Thermal adaptation of people and buildings in Nepalese cold, temperate and sub-tropical regions

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Abstract

Climate, cultures and geographical variation has reflected in the way that people create a suitable indoor thermal environment in residential buildings, depending on the outdoor climatic conditions. The people may have different thermal preference depending on the local characteristics of the climate from one region to another. Different region has its distinctive housing patterns, cultural differences including so called adaptive behaviours to avoid thermal discomfort from the local outdoor environmental conditions. Each year, Nepalese people living in the sub-tropical region faces extreme heat in summer, and living in cold region faces extreme cold in winter which causes various problems ranging from discomfort to illness and death. There are a few thermal comfort surveys conducted in specific places in Nepal. It is necessary to know about the adaptive thermal comfort of the people living in different regions especially in traditional houses. Preference of thermal environment varies with respect to different groups of people depending on their respective local climatic characteristics that elude their thermal histories on their own which need to investigate.

The objectives of this research are to clarify the real conditions of thermal environment of houses in cold, temperate, and sub-tropical regions, to investigate the adaptive thermal comfort of residents, to investigate the clothing adaptation of residents in traditional houses in respective climatic regions, and to investigate on adaptive thermal comfort considering thermal history of local and migrant peoples living in sub-tropical region of Nepal.

A series of surveys on indoor thermal environment and thermal comfort survey were conducted in three climatic regions; cold, temperate, and sub-tropical regions in winter and summer. The indoor thermal environment of 18 houses were continuously measured. Through thermal comfort surveys altogether 427 houses were randomly selected and data were collected from 1287 respondents.

The indoor air temperatures for all investigated houses are highly affected by outdoor air temperature. In the cold climatic region, the indoor air temperature tends to be lower than temperate and sub-tropical climatic regions in both seasons. The mean indoor air temperature is 15.6 °C, 25.7 °C and 29.9 °C in summer and 10.9°C, 15.4 °C and 18.4 °C in winter in cold,

temperate, and sub-tropical regions, respectively. The regional and seasonal difference of this in indoor air temperature may be due to the size of the windows, wall thickness and heat capacity of the materials used.

The mean comfort globe temperature was 13.8 °C in the cold region, which was 4.1 °C and 9.3 °C lower than that of the temperate and sub-tropical regions in winter, respectively. Similarly, in summer the mean comfort temperature was 16.6 °C in cold region, which was 10.3 °C and 14.3 °C lower than that of the temperate and sub-tropical regions in summer, respectively. The regional different in comfort temperature is quite large, and this is related mainly due to difference in the clothing adjustment of the residents. The mean clothing insulation was 1.63 clo, 1.32 clo and 1.15 clo in the cold, temperate and sub-tropical regions in winter, respectively. Similarly, in summer the mean clothing insulations was 1.4 clo in the cold region, which was 0.7 clo and 0.9 clo higher than that of the temperate and sub-tropical regions.

The upper limit of acceptable indoor globe temperature for local people was 32 °C which is 3 °C higher than that of migrant people. Preferred temperatures of local and migrant peoples were different under the condition of indoor globe temperature lower than 31 °C. Furthermore, perceived sweating level of migrant people was 66% and that of the local people was 26%. This implies that migrant people tend to perceive more sweating than local people. Thermal history of the local and migrant peoples is considered very likely to affect their thermal comfort levels indoors. Consequently, it is important to consider the diversity of thermal acceptability when creating an appropriate built environment.

Overall, the results showed that the regional difference and seasonal different are found in the indoor temperature, comfort temperature and clothing insulation. It is highly probable that the thermal history developed through past experiences affects the thermal adaptability of people. Therefore, it is necessary to recommend a solution for providing people with sufficiently comfortable built environment based on the thermal history of people. The findings of this study revel that a single standard or guideline for a uniform thermal environment and comfort may not be appropriate for the suitable building design.

ネパールの冷帯、温帯、亜熱帯地域における居住者と建物の熱的適応に関する研究

論文要旨

気候的、文化的、地理的な差異は、屋外気候変動に応じた適切な住宅温熱環境の構築に反映される。人々の好む温熱環境は、各地域の気候特性に応じて異なると思われる。さらに、地域によって住居形態や文化も異なり、これには屋外環境条件による熱的不快感を回避するための、いわゆる適応行動なども含まれる。毎年、亜熱帯地域に住むネパール人は夏の極度の暑さに直面する一方で、冷帯地に住む人々は冬の極度の寒さに直面しており、不快感だけでなく病気や死に至るまで様々な問題を引き起こしている。ネパールの特定の場所で実施された熱的快適性調査はいくつかあるが、特に伝統的住宅における適応的熱的快適性については様々な地域で解明する必要がある。温熱環境の好みは、居住者自身の熱履歴にかかわらず、それぞれの気候特性に応じて変化する。

本研究の目的は、寒帯、温帯、亜熱帯地域の住宅の温熱環境の実態を明らかにし、居住者の適応的熱的快適性や冬における居住者の着衣量の調整について明らかにする。また、ネパールの亜熱帯地域に住む地元民と移民が持つ熱履歴を考慮した適応的な熱的快適性についても解明する。

室内の温熱環境と熱的快適性に関する調査を、冷帯・温帯・亜熱帯の 3 つの気候の地域で夏と冬に実施した。熱的快適性調査を通じて合計 427 戸の住宅を調査し、1287 人の回答者からデータが収集した。その内、18 戸の住宅では室内温熱環境を継続的に測定した。

調査対象の全ての住宅の室内気温は、外気温の影響を大きく受けていた。寒冷気候地域では、両方の季節で室温が温帯および亜熱帯気候地域よりも低くなる傾向があった。平均室温は、夏において冷帯で 15.6°C、温帯で 25.7°C、亜熱帯で 29.9°C、冬に寒帯で 10.9°C、温帯で 15.4°C、亜熱帯で 18.4°C であった。室温に地域差や季節差があるのは、窓のサイズや壁の厚さ、使用する材料の熱容量が関係していると思われる。

冬の平均快適グローブ温度は寒帯地域で 13.8°C であり、温帯地域よりも 4.1°C、亜熱帯地域よりも 9.3°C 低かった。同様に、夏では冷帯地域で 16.6°C であり、温帯地域

よりも 10.3°C、亜熱帯地域よりも 14.3°C 低かった。また、冬の各地域の平均着衣量は、冷帯で 1.63 clo、温帯で 1.32 clo、亜熱帯で 1.15clo であった。夏の平均着衣量は、冷冷地域で 1.4 clo であり、温帯よりも 0.7clo および亜熱帯よりも 0.9clo 高かった。以上のことから、快適グローブ温度の地域差には着衣調整の差異も関係すると思われる。

地元の人々が許容できる室内グローブ温度の上限は 32°C で、移民の人々よりも 3°C 高かった。室内グローブ温度が 31°C 未満の条件下では、地元の人々と移民の人々の好まれる温度は異なっていた。さらに、移民の発汗レベルは 66%、地元の人々の発汗レベルは 26%であり、移民の人々の方が地元の人々よりも発汗を感じる傾向があることを意味している。このことから、地元および移民の人々の熱的履歴は、熱的快適性に影響を与える可能性が非常に高いといえる。従って、適切な構築環境を作成する際には、熱受容性の多様性を考慮することが重要である。

以上のことから、室内温度だけでなく快適温度や着衣量にも地域差や季節差がみられた。また、過去の経験を通じて得られた温熱履歴が人々の熱的な適応性に影響を与える可能性が高い。従って、人々の温熱履歴に基づいて快適な建築環境を構築するための改善策を推進する必要がある。この研究の成果は、温熱環境や熱的快適性のための単一の基準及びガイドラインでは建物を設計することが適切でないことを明らかにし。

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Chapter 1: Introduction

1.1 Overview of research

Nepal is a landlocked country which is located between India to the east, south, and west and China to the north. It has small land area of 1,47,181 km^2 with diverse climatic and geographical variations. It is broadly classified into three ecological regions: mountain, hilly and terai regions (Figure 1.1), all of which extend from east to west. Climatic features of the three regions can be seen in a short distance from south to north. Northern mountain, middle hilly and southern terai regions are highly dominated by cold, temperate and sub-tropical climate respectively. Each region has its distinctive housing patterns (Figure 1.2 Photos of study houses), cultural differences including so-called adaptive behaviours to avoid thermal discomfort from the local outdoor environmental conditions. The traditional skills of construction, one of whose major objectives must have been to mitigate indoor thermal conditions, have been handed over from one generation to another since old days with almost no modification, but they are being replaced by the contemporary ways of construction like modern design and technology including artificial materials (Rijal et al., 2010).

Every year new houses are being built in Nepal as a part of urbanization and modernization. Under this circumstance, it is important to know the state of thermal comfort as experienced by Nepalese people with the living condition in traditional houses, which has made the local people develop their respective unique culture. Although the surrounding countries, India and Pakistan, have their own thermal-comfort standards BIS (2005) and ENERCON (1990), the Nepalese government has not yet established any thermal-comfort standard. This study may direct the Nepalese government to establish the thermal-comfort standard and make rational policy and plans in the nearest future.

Each year, Nepalese peoples living in sub-tropical region have to face extreme heat in summer and the people living in cold region also have to face extreme cold in winter. Such a situation has caused various problems ranging from discomfort to illness and death (Rijal et al., 2010). Indoor environment is extremely hot, it directly affects human health, and mortality rate rises evidently with increasing hot stress (Regmi et al., 2008; Julio et al., 2006) resulted that the

45–64 years age-group is a risk group to be taken into account when it comes to considering the health-related effects of temperature extremes. The elderly and infants are more at risk from exposure to low temperature (David and Veronique, 2016). Exposure to high temperature can increase the risk of heat stroke (Bouchama and Knochel, 2002), and health problems such as respiratory and cardiovascular hospitalizations and deaths (Anderson et al., 2013). In Nepal, under a high emissions scenario heat-related death in the elderly (65+ years) is approximately 4 deaths per 100,000 annually between 1961 and 1990 as it has been reported by World Health Organization (2015). To avoid discomfort caused by hotness in sub-tropical region, people take a variety of actions such as staying on the top of roof, in semi-open spaces or front yards during the evening time, drinking a lot of cold drinks, taking showers often to get rid of sweat, using fans and wearing less clothing for the ease of releasing heat from their bodies. On the other hand, to avoid discomfort caused by coldness in cold region, people take a variety of actions such as staying near firewood, drinking a lot of hot tea or butter tea, closing the all openings and wearing heavy clothing for the easy of releasing cold from their body.

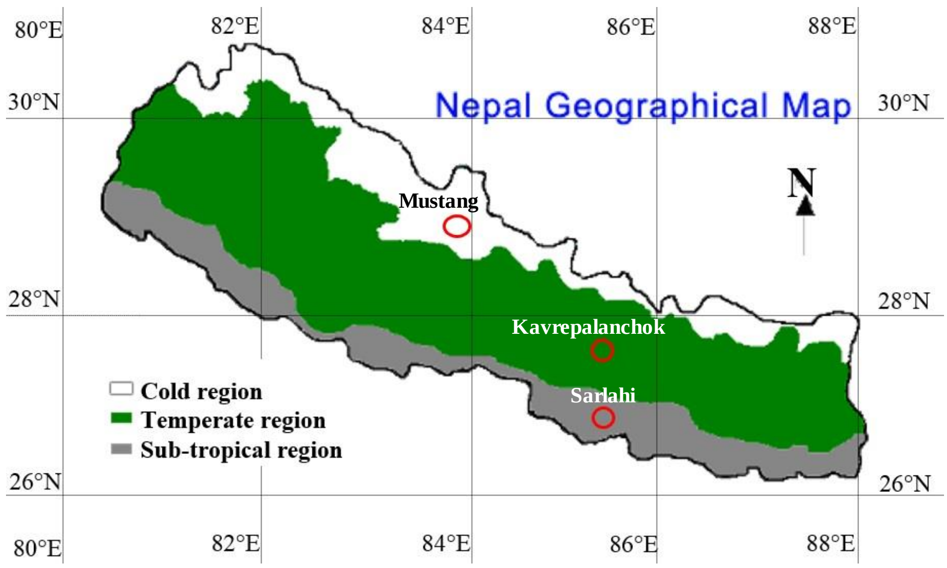

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Figure 1.1 Map of Nepal with three geographical features (https://en.wikipedia.org/wiki/Geography_of_Nepal).

Nepal has climatic variation from cold to sub-tropical regions. Climate affects the building type, thermal environment and human behaviours. These two things can be assessed by means of qualitative observation everybody. But this research has intended to investigate the two things: (1) to assess the effects of climate in the building's types, thermal environment and (2) to assess the effect of climate in human behaviours in quantitative way. We tried to know how the thermal environment indoor originally in people's houses in respective regions. Nowadays, in Nepal many people tend to move from temperate and cold climate to sub-tropical climate because of a variety of issues in the society and the desire of having easy life and so on. Hugged identified two types of people; local and migrant. Climate effects on people behaviours and buildings types. We wanted to know whether they could feel something different or same if they moved from one region to another. So, we tried to answer whether there is a difference or not. We found that there are some differences, for example, behaviours and also the limit of temperature value of performance and so on.

Two methods are generally used for the determination of thermal comfort. Present thermal comfort standards such as ASHRAE 55-1992 and ISO 7730 are based on climate chamber experiments performed in North America and northern Europe. These standards are only used for constant regular thermal conditions. Fanger (1970) also developed the Predicted Mean Vote (PMV) model, derived a thermal index which made it possible to predict thermal sensation for given combination of activities level, clothing insulation, air temperature, mean radiant temperature, air movement and relative humidity. In this experiment, people were arranged in a control condition inside a climate chamber. Their activity and clothing levels were observed and thermal sensation votes was collected. This model does not accurately predict the actual thermal sensation of occupants, particularly in field settings. This model was developed from laboratory-based studies and the effects of buildings types, using materials of buildings, cultures and environmental information inherited from the far past of which we are unknown were not investigated during its development. In fact, people live in changeable and dynamic environments. It could be a big problem when the standards are applied to people living in a real-world situation (Benton et al 1990). In general, human beings' body core temperatures are the same all over the world. The energy balance of the man or woman, local or migrant people is basically the same (Shukuya 2019). The thermal environment that is the defined air temperature, surface temperature, air velocity and so on should be identical. But they're missing is the culture; including the food we eat, the clothing we wear and what kind of houses we are living in. People have natural tendency to adapt to changing conditions in their environment. If a change occurs to produce discomfort, people respond in those ways that tend to restore their thermal comfort (changing clothing insulation, changing posture, opening or closing the openings, switching on or off the fans, increasing or decreasing the activities level). This kind of natural tendency of making people themselves comfortable is expressed in the adaptive thermal comfort. Whenever, we visited some places in different parts of Nepal, we came to feel that the way of living was quite different than developed countries. The buildings construction has been found different, especially the local houses were different (Rijal et al., 2010). Since local climate is different, the availability of the building's materials and the structure are also different (Gautam et al., 2019). Energy balance is also changed. Physically speaking, human being is the same that is one thing quite important (Shukuya 2019). There are different localities in which thermal environment and human behaviour are not well balanced. This is the reason why the adaptive thermal comfort approach has been used for doing field surveys and collecting votes.

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55; 2013). The human body can be viewed as a heat engine where food serves as input energy. The human body will generate excess heat into the environment, so the body can continue to operate. The heat transfer is proportional to temperature difference. In cold environments the body loses more heat to the environment and in hot environments the body does not exert enough heat. Both the hot and cold scenarios lead to discomfort (Yunus, 2015). Similarly, thermal comfort of a person is also dependent on his/her physical characteristics such as their fitness level, size and weight, age, sex, etc. Environmental factors, atmospheric temperature or air temperature will decide how hot or cold we feel, but so will do other factors such as radiant temperature, humidity and air velocity.

Two kind of thermal factors that affect temperature of the room and human comfort are called physical and personal factors. They have been presented in Figure 1.3. The physical factors include: air temperature, mean radiation temperature, relative humidity and air velocity. The indoor air temperature of a building will be changed depending on the temperature outside. The walls and insulations play important role to change the indoor temperature. It can be said that if indoor temperature is extremely low or high, it directly affects to human health. The mortality rate with increasing cold stress (Lachewski and Jendritzky, 2002). The elderly and infants are more vulnerable from exposure to low temperature (David, 2016). The body's reaction to low temperature includes thickening of the blood and hypertension (Woodhouse et al., 1993). The indoor environment is also affected by the residents inside the building and the activity they are doing. The mean radiant temperature also affects the human comfort. The mean radiant temperature is defined as the temperature of a uniform enclosure with which a small black sphere at the test point would have the same radiation exchange as it does with the real environment (Parsons, 2003). The radiation is averaged for all directions and so the resulting 'mean radiant temperature' has a single value for any particular point in the room, the distribution of radiation from different directions then the mean radiant temperature will be sufficient (Nicol et al., 2012). The relative humidity is another important factor that affects the human comfort. It is a considerable variable to measure only in warm and hot condition. The relative humidity is the percentage of water vapor saturation in the air. Although, most of the researchers suggested their research results about relative humidity; it is necessary that the water vapor pressure is an index of humidity, rather than relative humidity. The air movement is another important factor for human comfort. This is the movement of the air throughout a building or a room. In natural ventilated buildings, especially in a hot climatic region, air movement will have played most important role on the thermal comfort of the residents. Nicol (1974), and Rohles and Nevins (1971) estimated the effect of the air movement to be the equivalent of a drop in temperature of about 3°C.

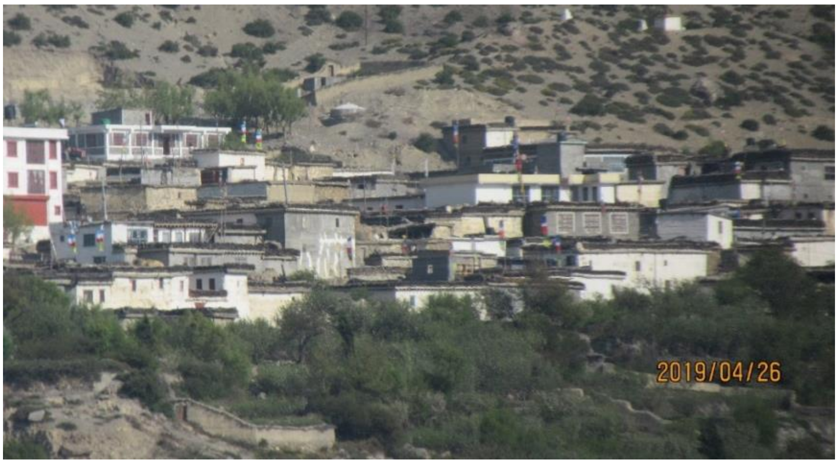
Personal factors can also affect the human comfort. Mainly, there are two personal factors; one is the clothing insulation and other is the metabolic rate that affect the human comfort. Thermal comfort is very much dependent on the insulating effect of clothing on the wearer. Wearing too much clothing may be heat stress even if the environment is not considered warm or hot. If clothing does not provide enough insulation, the wearer may be at the risk of cold injuries such as frostbite or hypothermia in cold conditions. Clothing is both a potential cause of thermal discomfort as well as a control for it as we adapt to the climate in which we work. It is important to identify how the clothing contributes to thermal comfort or discomfort. Metabolic rate is also important to note. When more physical work we do, the more heat we produce. If more heat we produce, the more heat needs to be lost so we don't overheat. The impact of metabolic rate on thermal comfort is critical. A person's physical characteristics should always be tolerated in mind when considering their thermal comfort, as factors such as their size and weight, age, fitness level and sex can all have an impact on how they feel, even if other factors such as air temperature, humidity and air velocity are all constant.

Figure 1.4 shows a schematic relationship between the types of built-environment technology and those of associated human behaviour. The horizontal axis in the figure represents technology and the vertical axis represents behaviour. The leftist extreme of the horizontal axis indicates a case of local traditional passive technology alone, while the rightist extreme indicates such a case which is equipped fully with active technology alone. The former must necessitate very active behaviour of the people for restoring their thermal comfort indoors, while the latter requires the least passive behaviour. It is because theoretically speaking the active technology can do everything. In this diagram, the present condition of the traditional houses and their lifestyle are positioned in the area "T", since it is hard to sustain the indoor environmental condition sufficiently with old and poor building envelope system alone. People need to do a lot of behaviours for avoiding thermal discomfort. Contemporary houses having mechanical systems for heating and cooling especially in the cities on developed countries are positioned in the area "U"; people may be less active; that is, passive in behaviour. In either area "T" or "U", they lack optimal health, since the active systems may provide too little opportunities of the occupants' behaviour, while the passive system alone may necessitate too much of occupants' behaviour (Shukuya, 2013). In order to clarify the conventional path and propose path for developing country as the future target for either of "T" or "U", it is essential to understand how the people try to restore their thermal comfort in traditional houses by changing clothes and doing other activities. It should be good to extract the positive aspects of traditional lifestyle and inherit them as the portion of futuristic lifestyle.

To preserve traditional constructing technology, we have to make such a policy that the traditional technology is to be improved with some modern skills. It is to be developed without deteriorating the cultural norm by keeping an eye on positive aspects of traditional houses that should be preserved and inherited into the future. One of the aspects to be improved while keeping the tradition skill must be the better thermal comfort. For this purpose, we need to know how the people living in different climatic regions of Nepal achieve their thermal comfort in their respective traditional houses. We need to do this by taking various adaptive behaviours such as using the fan, shitting under the shade, using light clothes, and swimming in summer and use of the firewood, drinking hot tea, sitting on the sun light, and using heavy clothing for winter to mitigate the thermal comfort.

Good indoor environment is important for the success of a building, not only because it will make the people comfortable, but also because it will decide the energy consumption of the building and in the long run influence of economy and sustainability. "Thermal comfort is the condition of mind which expresses satisfaction with the thermal environment" (ASHRAE stander 55; 2013). Thermal comfort standards are required by building designer and engineers to provide the indoor environment that the people dwelling in those buildings will find thermally comfortable. It gives people satisfactions. Mainly, there are two factors; environmental factors and personal factors that affect the thermal comfort of people as it has been shown in Figure 1.3. In addition, it is believed that the people to the warmth or cold depends on the combined effect of air temperature, mean radiant temperature, air movement and relative humidity besides the amount and level of the clothing and activity level. The entire temperature affects the thermal comfort of an individual. It was increasingly being felt by researchers such as Nicol, Humphreys, de Dear, Brager and Rijal that the thermal comfort of the people was greatly influenced by perception, expectations, and opportunities to change clothing level and change immediate indoor environment.

There are many field studies on so-called adaptive thermal comfort in various buildings around the world Rijal et al. (2017), de Dear et al. (2002), Indraghanti (2010), Nicol (1996), Thapa et al. (2018), Wang et al. (2006), Nicol et al. (2012). However, the climatic variation, living condition and building structures in Nepal are different from those studies. Although there are a few thermal comfort surveys which have been conducted in specific places in Nepal Rijal et al. (2010), Thapa et al. (2018), Shahi et al. (2020), Pokharel et al., (2020), this study was conducted in three different climatic regions especially focusing on traditional houses and their comfort temperature.



(a)

(b)

(c)

Figure 1. 2 The snaps of investigated houses in the study areas: (a) Cold climatic region (Mustang), (b) Temperate climatic region (Kavrepalanchok), and (c) Sub-tropical climatic region (Sarlahi).

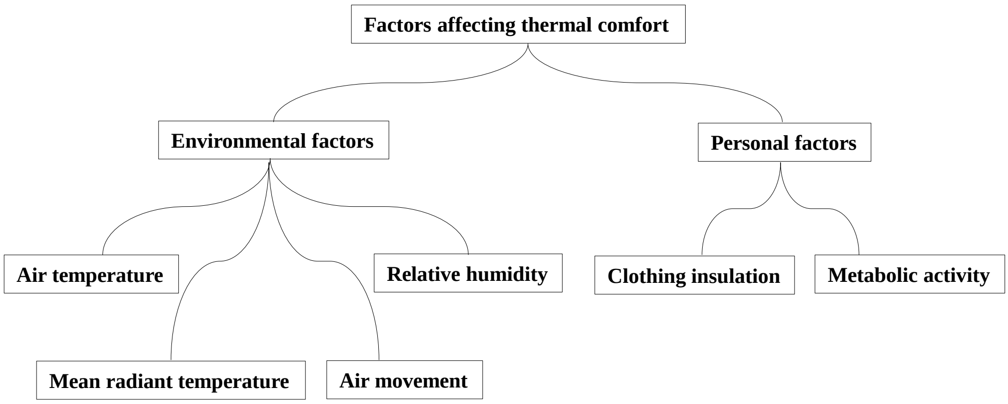


Figure 1.3 Six factors that affect thermal comfort.

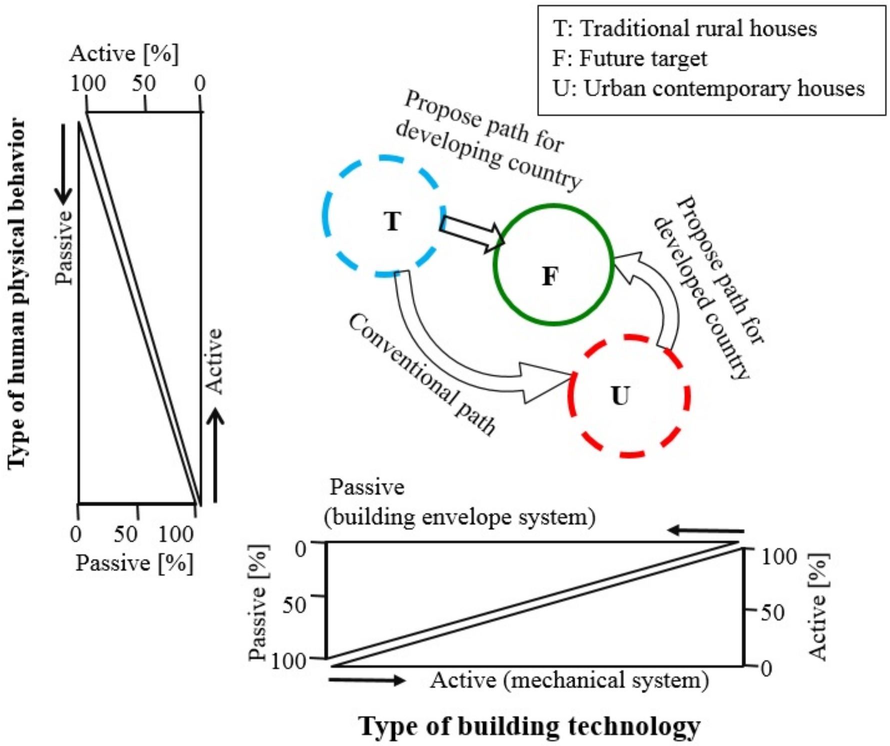


Figure 1.4 Schematic diagram of built-environmental technology and human behaviors.

1.2 Literature review

The aim of this section is to review what has been reported by other researchers in order to identify the research gaps, support, underpin, and justify the subject of investigation raised in the present study. A review of climatic regions and climate classifications of the regional studied have been presented. In this section, we have presented a review of related academic studies. It reviews the thermal environment of different types of buildings, houses, and adaptive thermal comfort of people in respective regions, climates, and houses. It addresses the thermal environment of the houses in the different climatic regions. The importance of residents' thermal comfort, thermal preference, and adaptive behaviours for their thermal comfort in the houses have been reviewed.

1.2.1 Thermal environment

Indoor thermal environment in the building is important because most of the people spend more than 90% of their time indoor (ASHRAE standard 55; 2010). The indoor temperature should not be too high or be too low since it is directly related to human health (Ponni and Basker, 2015). The variation in indoor temperature affects the thermal comfort of human beings. WBCSD, Geneva, (2009) presented that 40% of the energy is consumed in the buildings all over the world. Another researcher named Givoni (1967) said that in 2010 around 40% of all energy in US and 76% of electricity was used in building. Most of the people in rural and semi-urban areas are living with passive means of heating and cooling without mechanical heating and cooling. Therefore, their indoor thermal environment depends much on natural climatic patterns.

There are many field studies on so-called indoor thermal environment in various buildings around the world. Sarkar (2013) studied of climate responsive passive design features in traditional hill architecture of Khyah village in Hamirpur, Himachal Pradesh, India for indoor thermal comfort and concluded that the traditional architecture and construction method of the vernacular hill settlement were very dynamic relationship with climate condition. Similarly, Singh et al. (2009) also studied on bioclimatism and vernacular architecture of north-east India and concluded that the most of the houses have been solar passive features which relation to temperature control and enhancing natural ventilation. Likewise, Wang et al. (2003) studied on the thermal environment in residential building in Harbin and concluded that 91.7% of the occupants considered their thermal conditions acceptable. In the same way, Tuck et al. (2019) studied on effectiveness of free running passive cooling strategies for indoor thermal environments. The study presents an example from a two-stores corner terrace house in Malaysia and pointed out that the mean indoor temperature under FR was approximately 27 ~ 37 °C. Full ventilation and day ventilation recorded better correlation between outdoor and indoor temperature compare with no ventilation and night ventilation. In another research, Xu et al.

(2018) studied on thermal comfort and thermal adaptive behaviours in traditional dwellings: A case study in Nanjing, China. This study concluded that the traditional dwellers are more tolerant to harsh environments, and their thermal neutral temperature and thermal sensitivity are lower in winter and higher in summer, than those of the people that reside in modern dwellings.

People are living in different types of the buildings which is depending up on the climatic regions in the study areas. The concrete houses are called modern houses in the context of Nepal. Modern houses are made by artificial materials that are not necessarily produced locally. These materials are not only expensive but also environmentally and ecologically inappropriate than those of the natural materials. On the other hand, the wooden, stone, and mud houses are defined as a traditional house in the study areas. Traditional skill of construction, one of whose major objectives must have been to mitigate indoor thermal conditions, have been handed over from one generation to another since old days with almost no modification. According to National Population and Housing Census (2011), more than half of the population are living in traditional houses in rural area of Nepal. Under this circumstance, it is important to know the state of indoor thermal environment of the Nepalese traditional houses. To sustain traditional constructing technology, we have to make policies that improve traditional technology using modern skills without deteriorating the cultural norms by keeping an eye on positive aspects of traditional houses that should be preserved and inherited for the future.

However, the climatic variation, living condition and buildings structures in Nepal are different from those examined in previous studies. Although there are a few indoor thermal environments which have been conducted in a specific place in Nepal, Rijal and Yoshida (2005) conducted a field study on winter thermal improvement of a traditional house in Nepal. Their study concluded that the closing windows, doors, etc., to make the buildings airtight, and insulation of the roof using local building materials and technology are highly effective for thermal improvement and saving of firewood. Our study was conducted in both the traditional and modern houses of three different regions (cold, temperate and sub-tropical regions) as their winter and summer indoor thermal environment and adjustment would be totally different from one another. In this study, we examined the thermal environment (e.g., we compared relationship between indoor and outdoor air temperature, distribution of indoor air temperature, and relationship between indoor and outdoor relative humidity) in the cold, temperate, and sub-tropical climatic regions in winter and summer in Nepal. The findings of the study can be useful for the improvement of traditional and modern houses in three climatic regions in the future.

According to the previous study by Bajracharya (2013), the indoor air temperature of traditional buildings was 1 to 2 °C higher in winter and 1 to 2 °C lower in summer than that of modern house. This is due to the effect of thermal resistivity and capacity. Mostly, people are living with passive means of heating and cooling without mechanical means. Therefore, their indoor thermal environment depends much on natural climatic patterns. Fuller et al. (2009), in this regard, conducted a field measurement in a traditional house in northwest part of Nepal and found that indoor temperature is significantly lower and comfort of the people worsens in winter. In the same way, Susanne et al. (2014) analysed climate response building design strategies of vernacular architecture in Nepal and found that the openings are increasing natural ventilation that is essential during warm and humid season and people have been using passive solar design strategies widely in the study areas. Rijal (2009) studied entitled changes and improvements to traditional vernacular houses in a mountain area of Nepal and concluded that the traditional houses not only lost their inherent beauty but also created thermal environment problems. In order to solve these problems, thermal insulation for thatched, slate and corrugated iron roofs was proposed and constructed using local materials and techniques. Manandhar and Yoon (2015) investigated on passive cooling strategies for buildings in hot humid region of Nepal and concluded that thermo physical property of buildings has the maximum effect on the energy consumption. Every design strategy creates an average of 20% decrease in energy consumptions, whereas the thermal conductivity can have as much as 10 times more effect on the energy consumption than other design strategies. Gautam et al. (2019) carried a field study on regional differences of wintry indoor thermal environment of traditional houses in Nepal and concluded that the houses were found to be 80% of the time below 11 °C, 16 °C and 22 °C in cold, temperate and sub-tropical regions respectively. This result is well attributed to the regional climatic difference and the thermal characteristics of buildings materials used. The traditional houses surveyed are considered to be adapted to the climates because of the local availability of buildings materials. Likewise, Gautam et al. (2019) studied on wintry air temperature and humidity of traditional houses in three regions of Nepal and concluded that the indoor air temperature is highest in low altitude and vice versa in highest altitude. The indoor water vapor concentration was low in cold, intermediate in temperate, and high in sub-tropical regions. Gautam et al. (2019) also made a field study on the title comparison of the wintry and autumnal indoor thermal environment in Nepalese rural houses and concluded that in the modern houses, the temperature variation was larger than the traditional houses both in winter and autumn. The modern house is more responsive to outdoor thermal environment variation than that of the traditional house. Pokharel et al. (2020) carried out a field investigation on indoor thermal environment and its associated energy use in three climatic regions in Nepal. The study concluded that a substantial improvement of the indoor thermal environment by improving thermal insulations of building envelopes together with rationally small energy use must be required for the well-being of the people in all three regions.

Since last thirty/forty years in this context, in every regions of Nepal, the traditional construction skills of building housing system have been replaced with modern technologies and contemporary houses. We have to control such encroachment on traditional houses. However, there exist a question like: how people were able to sustain thermal comfort in such houses in different climatic regions in Nepal.

1.2.2 Adaptive thermal comfort

There are many field studies on indoor thermal comfort in different types of buildings, such as office buildings, school buildings, residential buildings, and so on around the world. Some of them have been reviewed here. de Dear and Barger (2002) studied on thermal comfort in natural ventilated buildings: revisions to ASHRAE standard 55 and suggested that adaptive comfort standard could be used for the design, operation, or evaluation of buildings, and for research applications. Nicol and Roaf (1996) conducted a field survey on thermal comfort in summer and winter seasons in the five climatic regions of Pakistan. They concluded that the variations in desired indoor temperature depended on climate and season. Wang (2006) conducted a field study of the thermal comfort in residential buildings in Harbin, northeast of China and concluded that the males are less sensitive to temperature variation than females, and the comfort operative temperature of males is 1 °C lower than that of females. Indraganti (2010) studied on using the adaptive model of thermal comfort for obtaining indoor neutral temperature. The field study was conducted in Hyderabad, India. The study was undertaken in May, June, and July in 2008, collecting 3962 datasets involving 113 subjects living in 45 flats belonging to five apartment buildings. The findings concluded that the indoor temperature in roof-exposed flats were higher than lower floors. The respondents living in top floor flats had a higher thermal sensation and thermal preference votes than those of the respondents who were living in lower floor flats. The study further concluded that the naturally ventilated apartment buildings in India determined neutral temperature and a wider comfort band than Indian standard. In the same country, another field study was conducted by Thapa et al. (2018) on the title of adaptive thermal comfort in different buildings of Darjeeling Hills in eastern India – effect of difference in elevation and concluded that the clothing insulation of the respondents were increased with the increased in the elevation. Similarly, Manu et al. (2016) conducted a field study on thermal comfort across multiple climate zones for the subcontinent: Indian Model for Adaptive Comfort (IMAC) and found that the Indian respondents are more tolerant towards the warmer temperature than cooler temperature. The study by Nicol and Humphreys (2010) reported derivation of the adaptive equations for thermal comfort in free running buildings in European standard EN15252 described that how the indoor comfort conditions were related to the running mean of the outdoor temperature, and addresses the effect of air movement and humidity. In the same pace of the study, Damiati et al. (2016) studied on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season in 2015. They collected 2049 responses from 325 occupants in 13 office buildings. Their study found that the comfort range differed for each group of occupants under the different ventilation modes.

Many field studies examined thermal comfort and adaptive behaviours in buildings around the world. One of them is the study by Nicol et al. (1996) on Pioneering new indoor temperature standard: the Pakistan project in Pakistan. This study concluded that the large variations in desired indoor temperature with climate and season. de Dear et al. (2002) also studied on thermal comfort in natural ventilated buildings, revision to ASHRAE standard 55 and summarized that adaptive comfort standard could be used for the design, operation, or evaluation of buildings, and for research applications. Similarly, Wang (2006) conducted a field study of thermal comfort in residential buildings in Harbin, China, and concluded that males are less sensitive to temperature variation than females; the neutral temperature of males 1 °C lower than that of females. Indraghanti (2010) also studied on title using the adaptive model of thermal comfort for obtaining indoor neutral temperature which was based on the findings from a field study in Hyderabad, India. This study concluded that the people living in top floor flats had a higher neutral temperature when the available adaptive opportunities were sufficient. Thapa et al. (2018) also studied adaptive thermal comfort in the different buildings of Darjeeling hills in eastern India. The effects of difference in elevation were examined in the study. The study concluded that the mean clothing insulations of the respondents were found increase with the increase in the elevation. In the same concern, Damiati et al. (2016) studied on adaptive comfort of office buildings in Malaysia, Indonesia, Singapore and Japan. The result shows that the comfort range differed for each group of occupants under the different variations modes. Singh et al. (2011) conducted a study on the adaptive model of comfort for different climatic zones in India and concluded that the occupants adopt different manners of adaptation based on the types of climatic zones. Likewise, Ning et al. (2016) conducted a study on thermal history and adaptation in Harbin, China and suggested that a thermally comfortable zone with a higher indoor temperature was formed in the case of people exposed to warmer climatic conditions. They also observed that the neutral temperature for people with warm exposure was 1.9 °C higher than that for people with cold exposure. Based on the conceptualization of adaptive thermal comfort introduced by the studies like: Humphreys and Nicol (1998) and, then by Barger and de Dear (1998), Nicol et al. (2012), and Rijal et al. (2018, 2019), it has been confirmed that people adapt their thermal environments by adopting various actions such as opening/closing windows, adjusting blinds and by using mechanical heating or cooling. People use the aforementioned adaptive actions to maintain their state of dynamic equilibrium under their surrounding environmental conditions (Humphreys et al., 2013).

However, current international thermal comfort studies and standards do not represent people living in different types of buildings, especially in traditional dwellings (Xu et al., 2018). The climatic variations, living conditions and building structures in Nepal are different from those examined in previous studies, although there are a few thermal comfort surveys conducted in specific places of Nepal. However, there are no studies that have explored how people adapt to local climate, which differs significantly from their original local climate in the past. With respect to Nepal, a few studies examined thermal comfort based on field investigations. For example, Rijal et al. (2010 and 2019) conducted a thermal comfort survey in six districts of Nepal with different climates. They conducted a thermal comfort survey by gathering respondents in various houses at 1-h intervals. They found that the seasonal difference could be resulted in clothing insulation, air velocity and the physiological or psychological adaptation from different seasons. However, it is unknown how it works, if we conduct the survey in many houses. Thapa et al. (2018) carried a thermal comfort survey, but it was related to temporary shelters after the 2015 earthquake. Although, Rijal et al. (2010, 2018 and 2019), and Thapa et al. (2018), conducted field investigations, they did not focus on the differences between local and migrant peoples in the sub-tropical region in Nepal. Therefore, it is important to examine the differences in the indoor thermal environment of local and migrant peoples and evaluate the differences or similarities in comfort temperature, preferred temperature, the upper limit of acceptable temperature, and behavioural responses to the thermal environment in summer. So that it is necessary to find out more about the adaptive thermal comfort of people living in traditional dwellings in cold, temperate and sub-tropical climatic regions in Nepal. This study was conducted in three climatic (cold, temperate, and sub-tropical) regions, in winter and summer particularly focusing on traditional houses and their comfort temperature in winter and adaptive thermal comfort considering the thermal history of local and migrant peoples living in sub-tropical region of Nepal.

1.3 Necessity of research

Research has its special significance in solving various problems along with the motivational one. Our research was based on field survey where we took data from indoor thermal environment and thermal comfort of the residents' residing in the buildings in cold, temperate and sub-tropical climatic regions. Before presenting the results of the empirical research, it is necessary to address some of the limitations of the study. The perspectives of people who are living in traditional and modern houses in three climatic regions are represented in this study as voter. The researcher conducted interviews with them, as well as measure the indoor and outdoor thermal environment parameters.

In order to develop a thorough understanding of outdoor miscellaneous environmental factors, we could conduct the social research in another context. In the case of developing countries like Nepal, the traditional houses built for living tend to be used for a longer period of time. Every year new houses are being built and it is necessary to them to be comfortable. Nepal is in the process of federal system, urbanization and modernization, and it is essential to find out the comfort temperature experienced by Nepalese people in the present living condition separately in contemporary houses. The types of housing and the way of clothing as a part of culture have been reflected by the differences in geographic variation. The traditional skills of construction, one of whose major objectives must have been to mitigate indoor thermal conditions, have been handed over from one generation to another since old days with almost no modification, but they are being replaced by the contemporary ways of construction like modern design and technology including artificial materials (Rijal et al. 2010). Every year new houses are being built in Nepal as a part of urbanization and modernization. Under this circumstance, it is important to know the state of thermal comfort experienced by Nepalese people with the living condition in traditional houses. Although the surrounding countries, India and Pakistan, have their own thermal-comfort standards (BIS. National Building Code, 2005 and ENERCON, Building Energy Code of Pakistan (1990), Nepalese government has not yet established any thermal-comfort standard. This study may support or direct the Nepalese government to establish the thermal-comfort standard and make rational policy and plans in the future.

Firstly, to preserve traditional constructing technology, skills, and its hand-over to new generation, we have to make such a policy that the traditional technology is to be improved with some modern skills without deteriorating the cultural norm by keeping an eye on positive aspects of traditional houses that should be preserved and inherited for the future. One of the aspects to be improved while keeping the traditional skills must be better thermal comfort. Secondly, there are a few researches works to relate thermal environment, for example, Rijal and Yoshida (2005), Fuller et al. (2009), Rijal (2009), Bajracharya (2013), Susanne et al. (2014), Manandhar and Yong (2015), Pokharel et al. (2020). Similarly, some studies have been done regarding the thermal comfort, for example, Rijal et al. (2010, 2018 and 2019), Thapa et al. (2018). In order to fulfil the research gaps, it is necessary to conduct field study. For this purpose, we need to know how the people living in different climatic regions of Nepal achieve their thermal comfort in their respective contemporary houses by taking various adaptive behaviours such as clothing adjustment, using fire wood, open/close the openings, using fans and so on. Similarly, it is also important to examine the quantity and the extents of how people sustain their thermal comfort during winter and summer in traditional houses through their choice of clothing, use fan, take shower, sit under the shade, and evaluate the differences or similarities in comfort temperature, preferred temperature, the upper limit of acceptable temperature, and behavioural responses to the thermal environment in both the winter and summer.

1.4 Research questions

The following research questions were addressed throughout the study:

1. Is the indoor thermal environment of the houses in cold, temperate, and sub-tropical regions similar?
2. What kind of living environment should be arranged by people in their houses for well living considering thermal comfort?
3. How does the people living in different climatic regions of Nepal achieve thermal comfort in their respective houses by taking various behaviours?
4. How does long-term thermal history of the people affect thermal adaptability and thermal comfort?
5. What kind of numerical analysis helps to concern their structure and improve the houses in those climatic regions for future planning to build the buildings?

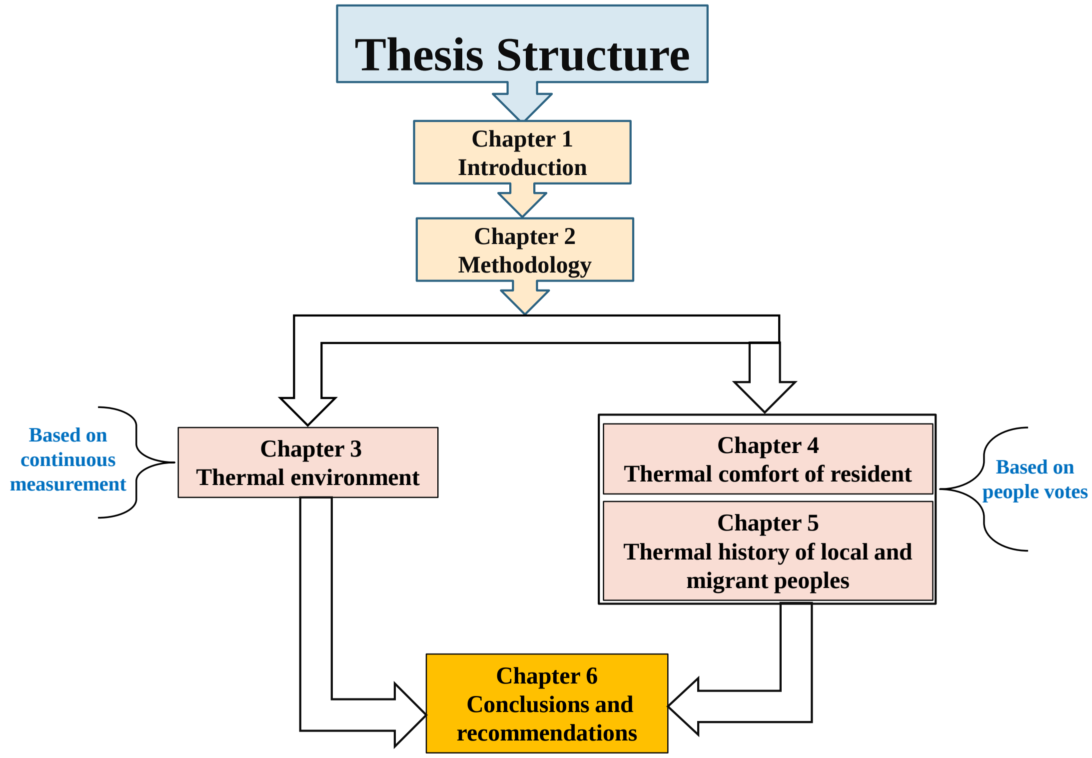
1.5 Objectives

The objectives of this research were as follows:

1. To find out the real condition of thermal environment of houses in cold, temperate, and sub-tropical regions.
2. To estimate the comfort temperature and preferred temperature based on the votes of people in respective regions.

3. To evaluate seasonal and regional differences of comfort and preferred temperature.
4. To observe and clarify the thermal comfort and clothing adjustment of residents in traditional Nepalese houses.
5. To investigate on adaptive thermal comfort considering thermal history of local and migrant peoples living in sub-tropical region of Nepal.

1.6 Thesis contents



Here, the thesis contents have been summarized:

Chapter 1: General Introduction

This chapter has included:

- Overview of the research information related on Nepal, traditional and modern houses and their indoor thermal environment.
- Literature review, rationale of the study and the objectives.

Chapter 2: Methodology

This chapter has included:

- Research areas and climate
- Plan view of the investigated houses
- Description of instruments used and thermal measurement
- Method of thermal comfort survey
- Equations used in the study

Chapter 3: Thermal environment of houses

Under this chapter the following contents have been included:

- Survey on 2016 winter and 2019 summer
- Analysis of indoor thermal conditions of respected houses (During voting time and continuous measurement)
- Discussion on winter and summer thermal environment, and regional and seasonal indoor thermal performance of traditional houses in respective regions.

Chapter 4: Thermal comfort of residents

This chapter outlines the:

- Seasonal and regional differences of comfort temperature of people residing in traditional houses.
- Comparison of comfort temperature of this study with other studies.
- The thermal adaptability of people and their strategies to adjust their regional and seasonal indoor thermal environment by adjusting clothing insulations.

Chapter 5: Thermal history of local and migrant people

This chapter presents:

- Thermal conditions of the investigated houses during the survey period.
- Thermal history of people that affect their thermal adaptability based on thermal acceptability, adaptive thermal comfort and thermal adjustment.

Chapter 6: Conclusions and recommendations

Here, the results of the above chapters have been summarized and discussed.

Chapter 2: Methodology

In this section, the research areas, their general climatic conditions, the profiles of investigated traditional houses and the measurement and thermal comfort survey method have been presented.

2.1 Research areas and climate

The land area of Nepal occupies1,47,181 km^2. Nepal has diverse climatic and geographical variations. It is broadly classified into three ecological regions: mountain, hilly, and terai, all of which extend from east to west. The climatic features of the three regions can be observed within a short distance from south to north. Northern Mountain, central Hilly, and southern Terai regions are dominated by cold, temperate, and sub-tropical climates, respectively. Each region has its distinctive housing patterns, cultural differences including the adaptive behaviours to avoid thermal discomfort from the local outdoor environmental conditions. There are six seasons in Nepal that is given in Table 2.1. Summer starts from April till August and November to February is winter. Climatic condition, on the other hand, is either 'extreme hot' or 'extreme cold'. Nepal is ranked as the fourth most climate vulnerable country in the world in the climate change vulnerability index (Government of Nepal, Ministry of Home Affairs, 2018). In the southern part of Nepal called Terai region (sub-tropical region), summer is extremely hot and winter is extremely cold. The middle part of the country has a mild climate almost the whole year. The northern part of the country is almost cold for the whole year.

Table 2.1 Seasons in Nepal with reference to English months

Nepali Ritus	Seasons in Nepal	English Month
Basanta	Spring	Mid-March to mid-May
Grishma	Early summer	Mid-May to mid-July
Barkha	Summer or monsoon	Mid-July to mid-September
Sharad	Early autumn	Mid-September to mid-November
Hemanta	Late autumn	Mid-November to mid-January
Shishir	Winter	Mid-January to mid-April

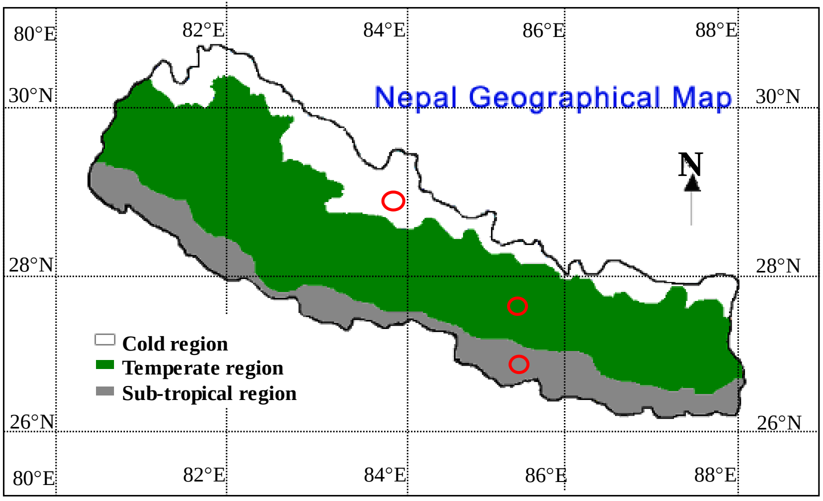


Figure 2.1 Map of Nepal including three regions for the survey and their general climatic characteristics.

Three climatic regions, i.e., cold (Mustang district), temperate (Kavrepalanchok district), and sub-tropical (Sarlahi district) have been chosen for the survey. Figure 2.1 shows the map of Nepal with three climatic regions. Figure 2.2 shows three investigated areas and the numbers in brackets denote the height above the sea level. The study areas were selected on the basis of altitude, climate and housing type. Figure 2.3 (a) shows monthly mean outdoor air temperature. The outdoor air temperature is highest in sub-tropical region (Sarlahi district), moderate in middle temperate region (Kavrepalanchok district), and lowest in cold region (Mustang district). Among all investigated areas, mean outdoor air temperature was maximum in the month of May [32 ºC], August [26 ºC], and July [18 ºC] in Sarlahi, Kavrepalanchok, and Mustang districts, respectively. The differences in monthly mean outdoor air temperature between the maximum (highest) and the minimum (lowest) was identical by 13 °C to 15 °C.

Figure 2.3 (b) shows monthly mean outdoor relative humidity. Relative humidity (RH) is the most usually used measure of the moisture content in the air. Relative humidity is defined as the amount of water vapor in the air at a specific temperature to the maximum amount that the air could hold at that temperature, expressed in percentage. Outdoor relative humidity fluctuates from one season to another. During January the air is cooled, so there will be a temperature at which the air cannot hold the water vapor as it saturates at that temperature. The relative humidity at this point will be 100%. The partial vapor pressure in the saturated air will depend upon the temperature of the air; higher air temperature can hold more vapor and which means greater partial vapor pressure. The outdoor relative humidity becomes high, although the water holding capacity in the cold air is less than the average. So, the air during the cold days gets saturated even with less moisture content in the air, and the relative humidity gets high, whereas during the rainy and warm monsoon season (June, July and August), the water holding capacity of the air is high and the moisture content in the air is also high.

(a)

(b)

(c)

Figure 2.2 Three investigated areas: (a) cold (2743m), (b) temperate (1451m), and (c) sub-tropical (157m) regions.

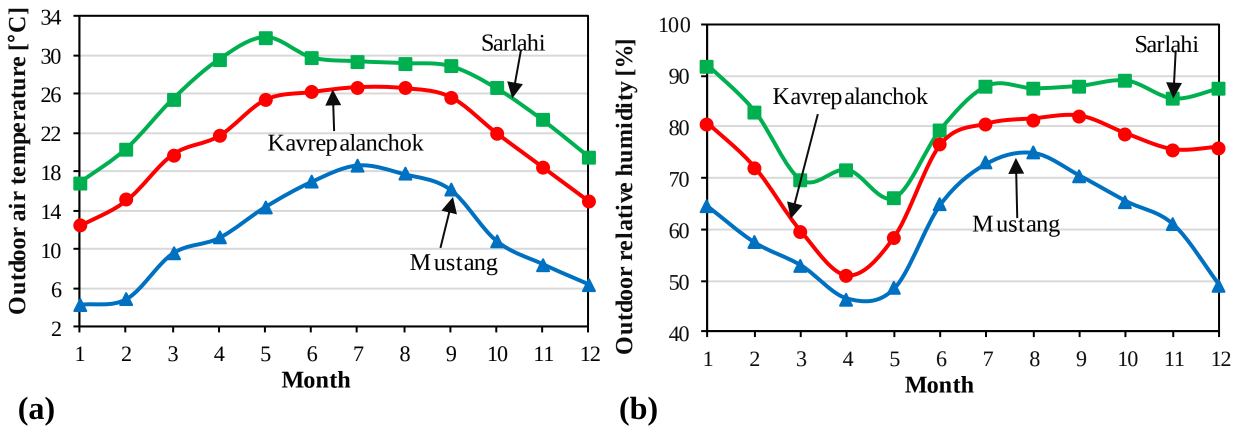


Figure 2.3 General climatic characteristics of research areas: (a) monthly mean outdoor air temperature, and (b) monthly mean outdoor relative humidity.

2.1.1 Mustang district

Mustang district covers an area of 3,573 km^2 and has a population of 13,452 according to CBS (2011). It headquarters is Jomsom. Jomsom has great potential in the national and internal tourism industry. It is the remotest area in Nepal and is second in terms of the sparsity of population. The elevation ranges from 1,372 to 8,167 meters (Mount Dhaulagiri, the 7th highest mountain in the world), with several peaks above 7,000 meters. Average elevation of Mustang is 13,200 ft. (https://www.imnepal.com/terai-region-nepal/Accesseddate:5July2019). Mustang is 196 km far away from Kathmandu. The area receives an average annual rainfall of less than 260 mm. Spring and autumn are generally dry, but some precipitation is brought by summer monsoons. In the study area, the houses are made by different types of materials used for foundation, walls and roofs which is shown in Table 2.2 as it is presented by CBS (2011). The mean minimum monthly air temperature falls to -2.7 °C in winter while the maximum monthly air temperature reaches 23.1 °C in summer. Both diurnal and annual variations in temperature are large. Agriculture and animal husbandry are the main occupations in Mustang. Thak Khola, Panchgaon, Baragaon, and Jomsom are famous places of Mustang district.

2.1.2 Kavrepalanchok district

Kavrepalanchok district covers an area of 1,396 km^2 and has a population of 381,937 according to CBS (2011). The elevation ranges of Kavrepalanchok; ranges from 1,000 to 9,800 ft. The place is shown in Figure 2.1 (https://www.imnepal.com/terai-region-nepal/Accesseddate:5July2019). Its headquarters is Dhulikhel, which is 28 km far away from Kathmandu. Dhulikhel has great potential in the tourism industry. Kavrepalanchok district is culturally rich with historical places like Dhulikhel, Panauti, and Banepa. The major tourist attraction places of the district include Dhulikhel, Banepa, Panauti, Bhakundeybesi. With mild climate the living standard is no different as houses are made by different types of materials used for foundation, walls and roofs which is shown in Table 2.2 as presented by CBS (2011).

Table 2.2 Description of houses-foundations in respective regions

Description	Districts		
Foundation of houses	Mustang	Kavrepalanchok	Sarlahi
Mud bonded brick/stone	3095	68449	8311
Cement bound brick/stone	146	5382	25207
RCC with pillar	3	5095	6966
Wooden pillar	31	613	87260
Other	7	146	3391
Not stated	21	966	1668
Outer walls			
Mud bonded brick/stone	2366	66,442	5300
Cement bound brick/stone	303	10997	29109
Wood/planks	29	418	8178
Bamboo	9	252	87492
Unbaked brick	565	1325	199
Other	10	198	790
Not stated	23	1018	1735
Roof of the houses			
Thatch/straw	31	8164	19301
Galvanized iron	192	45960	1859
Tile/slate	83	15238	95137
RCC	26	10062	12940
Wood/planks	20	265	1099
Mud	2903	103	0
Others	23	94	486
Not stated	28	1065	1999

2.1.3 Sarlahi district

Hariwon was selected as one of the study areas. It is at an altitude 157 m, which is just in the range of terai region from 60 to 600 m. The place is shown in Figure 2.1 (https://www.imnepal.com/terai-region-nepal/Accesseddate:5July2019). Sarlahi covers an area of 1,259 km2 and has a population of 769,729 according to CBS (2011). Figure 2.2 shows its monthly mean outdoor air temperature and relative humidity (HMG, 1995-96). In Nepal, the climate is dry in March, April, and May and rainy (hot-humid) in June, July, and August. The summer season in Nepal is from March to August. The mean outdoor air temperature is high from April to August and relative humidity is high from June to September. Sarlahi district is famous for tomato production and supply. With Malangwa as its' headquarter, Sarlahi is predominantly an agriculture dependent district. The historical Nunthar Pahad which is very famous among different religious groups because of its typical geographical location. This district has a total population of 769,729. It lies 138km far from Kathmandu. Sarlahi district has Bagmati, Balara, Barahathwa, Godaita, Haripur, Ishworpur etc as major places. In the study area the houses are made by different types of materials used for foundation, walls and roofs which is shown in Table 2.2 as presented by CBS (2011).

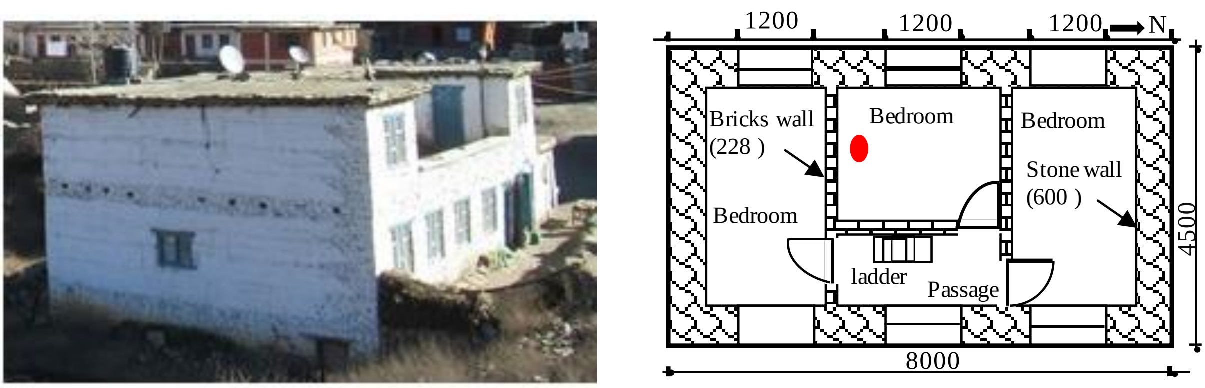
2.2 Plan view of the investigated houses

We had field investigation on thermal environment of the houses in winter 2016 and 2017, and in summer 2019 in cold, temperate, and sub-tropical regions of Nepal, respectively. We have randomly selected altogether 18 houses denoted from H1 to H18, for which nine were traditional houses (H1, H2, H3, H7, H8, H9, H13, H14, and H15) and nine were modern houses (H4, H5, H6, H10, H11, H12, H16, H17, and H18) (appendix 1). The houses of the study areas are made of by different materials. Traditional houses are made of wood, or bamboo, or stone and mud, and modern houses are made by concrete, rod and cement. Most of the selected traditional houses are rectangular-shaped and modern houses are square shaped in cold region Figure 2.4, temperate region Figure 2.5, and sub-tropical region Figure 2.6. Table 2.3 shows the number of traditional and modern houses and their percentage presented by CBS 2011. We observed and noted that, 95%, 86%, and 74% similar types of traditional houses and 5%, 14%, and 26% modern houses in

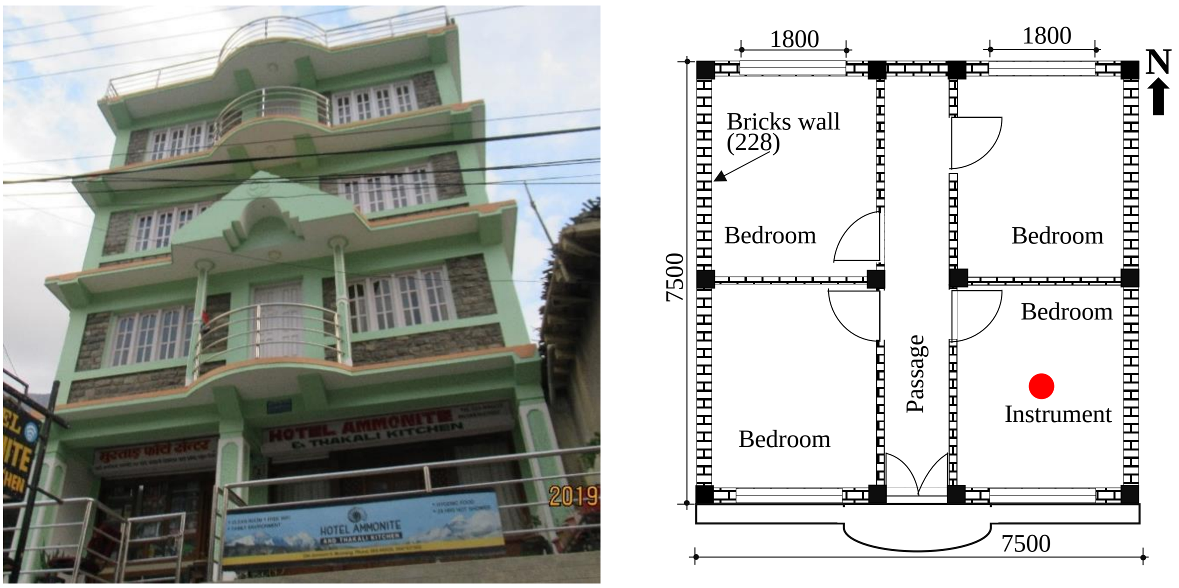
Mustang, Kavrepalanchok and Sarlahi districts, respectively.

Table 2.3 Number and percentage of traditional and modern houses in selected districts

House type	Mustang		Kavrepalanchok		Sarlahi	
	No of houses	Percentage [%]	No of houses	Percentage [%]	No of houses	Percentage [%]
Traditional	3126	95.4	69062	86.8	95571	74.8
Modern	149	4.6	10477	13.2	32173	25.2
Total	3275	100	79539	100	127744	100

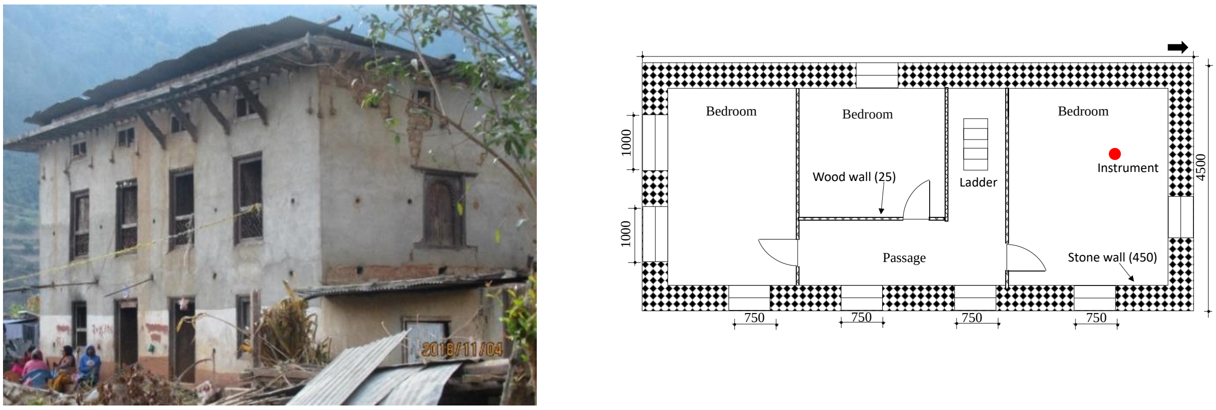


(a) H1

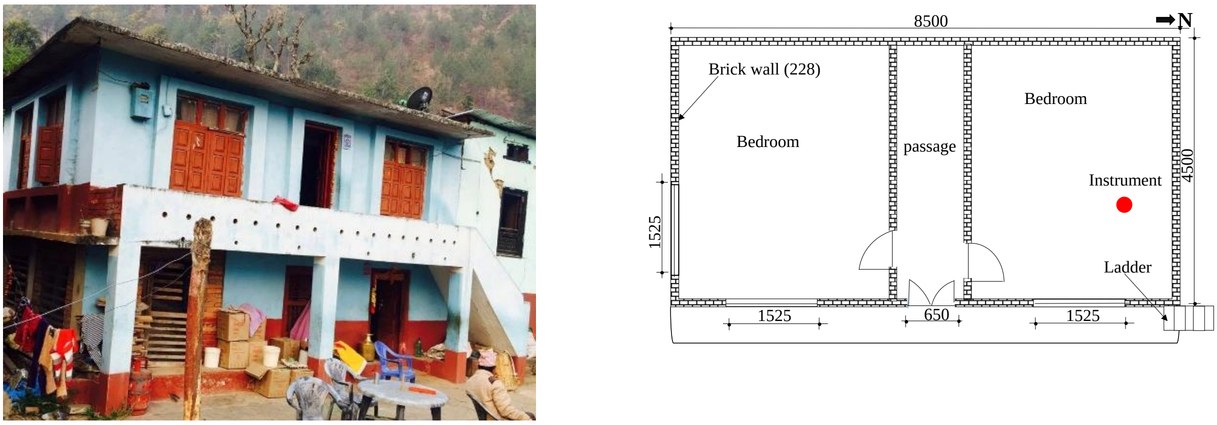


(b) H4

Figure 2.4 The sample houses that are investigated in cold region: external view and floor plan; (a) traditional and (b) modern houses.



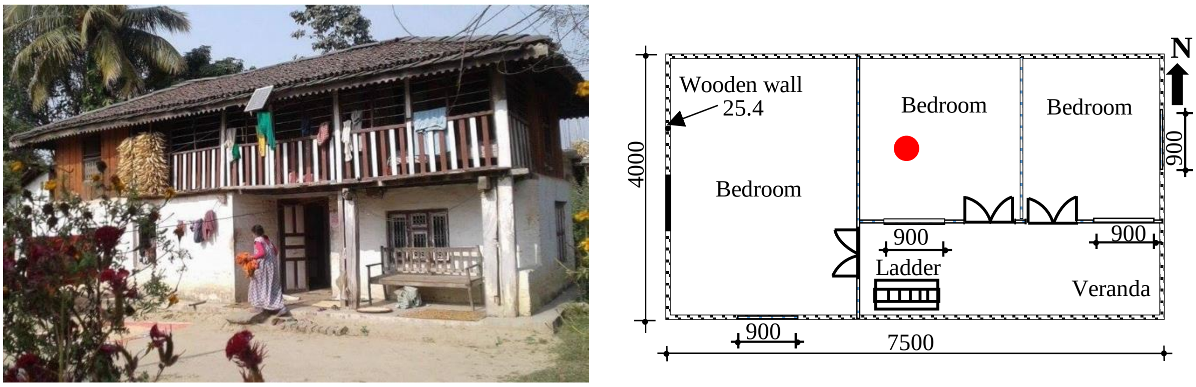
(a) H7



(b) H10

Figure 2.5 The sample houses that are investigated in temperate region: external view and floor plan; (a) traditional and (b) modern houses.

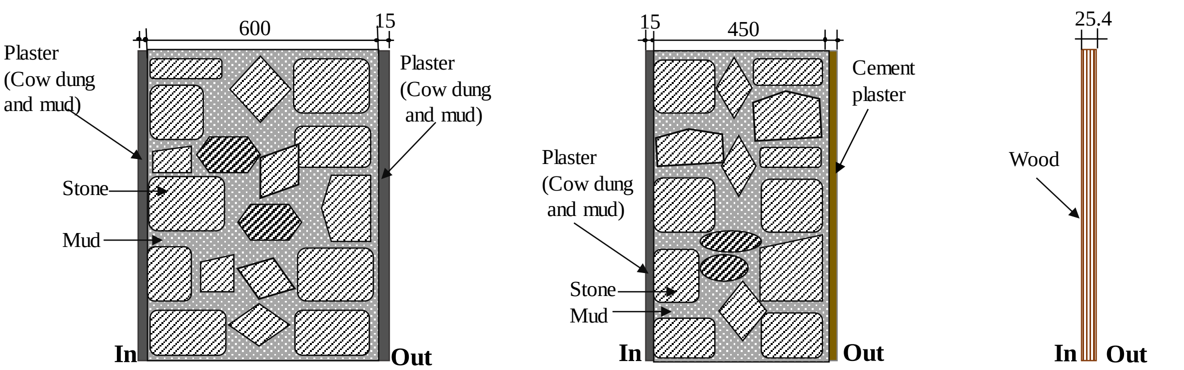
Overall, altogether 18 houses (9 mud and stone houses and 9 concrete houses) were included in the measurement of indoor air temperature, globe temperature and relative humidity in cold, temperate and sub-tropical climates respectively. Those houses were made with the foundation of mud and stone or wood houses, which were designed and constructed by local people with locally available materials. The concrete houses were designed by schooled engineers and constructed by market available materials. Table 2.4 shows the dimensions of these houses and their structure, finishing and the size of the windows. The cross-sectional views of an external wall with the materials and their thickness in houses in the three climatic regions are shown in above Figures 2.4, 2.5, and 2.6. Most of the houses are constructed with heavy walls in cold and temperate regions and lightweight walls in the sub-tropical region shown in Figure 2.7. The houses are one to three stories for stone, mud or wood houses and one to five stories for concrete houses. Generally, the kitchen and living room are on the first floor, bedrooms are on the second floor, and storerooms are on the top floor.



(a) H13

(b) H16

Figure 2.6 The sample houses that are investigated in sub-tropical region: external view and floor plan; (a) traditional and (b) modern houses.



(a) H1 (b) H7 (c) H13

Figure 2.7 Cross-section of external wall with material and the thicknesses of investigated houses: (a) Cold, (b) Temperate and (c) Sub-tropical regions (Unit: mm).

Table 2.4 Description of the six houses surveyed as presented in Figures 2.4, to 2.6

Climates	House code	Dimension [m]			No of floors	Walls			No of windows	Window height and width [m]
		Depth	Width	Height		Structure	Finishing	Thickness [m]		
Cold	H1	8.0	4.5	5.0	2	Mud and stone	Inside mud and cow dung plaster	0.600	12.0	1.2×1.2
	H4	7.5	7.5	12.0	4	Cement and bricks	Outside and inside cement plaster	0.125	12.0	2.0×1.5
Temperate	H7	10.0	4.5	7.5	3	Mud and stone	Outside cement, inside mud and cow dung plaster	0.450	10.0	1.5×0.75
	H10	8.5	4.5	6.0	2	Cement and bricks	Outside and inside cement plaster	0.125	5.0	1.2×1.2
Sub-tropical	H13	7.5	4.0	5.0	1	Wood	No plaster	0.025	9.0	1.2×0.75
	H16	8.0	7.0	2.3	2	Cement and bricks	Outside and inside cement plaster	0.125	6.0	1.2×1.2

2.3 Description of the instruments used and thermal measurement

During the field work in each climatic region, we measured the thermal environmental parameters as: indoor and outdoor air temperature, indoor globe temperature and indoor and outdoor relative humidity using the digital instruments which can be seen in Figure 2.8. Table 2.5 shows the details of measuring the instruments. We installed the instruments in the bedroom on the second floors for traditional houses and the first floor for modern houses. We also installed the instruments in the middle of each wall (four directions; east, west, north and south directions), middle of ceiling and middle of floor areas for measuring surface temperature that is seen in Figure 2.9. The data were recorded by data loggers for respective sensors at an interval of 10 minutes.

Continuous measurement of thermal environment was performed for one month from December 3rd 2016 to January 3rd 2017 for winter and April 18th to May 17th 2019 for summer which is displayed in Table 2.6. Indoor air temperature, outdoor air temperature, indoor globe temperature, indoor relative humidity and outdoor relative humidity were measured by respective regions and sensors with digital data loggers at the interval of 10 minutes. Table 2.5 shows the instruments used in this field measurement. The data loggers were installed in the bed room of respective investigated houses; they were set 1.1m above the floor level which is shown in Figure 2.8. The outdoor air temperature was measured just outside the house H3, H9, and H13 in cold, temperate, and sub-tropical regions, respectively. We assumed the same outdoor air temperature for other investigated houses because all of the investigated houses were located within the area of 2 to 4 km diameter from houses H3, H9, and H13 in respective regions.

Table 2.5 Details of the instruments used for measuring the environmental parameters

Parameter measured	Sensors	Range	Accuracy	Name of instruments
Air temperature and relative humidity	Thermistor and polymer membrane	0.55 ºC, 10–95%	± 0.5 ºC, ± 5%	TR-74Ui
Globe temperature	75-mm diameter globes, painted black	-60 to 155 ºC	± 0.3 ºC	Tr-52i, SIBATA, 080340-75
Air velocity	Hot-wire anemometer	0.01 to 5 m/s	± (2% of reading ±0.0125 m/s)	CLIMOMASTER (model 6501-00)
Surface temperature	Infrared sensor	-55 ºC to +220 ºC	±2% rdg or ±3 ºC	Custom, IR-300

(a) (b)

Figure 2.8 Sample scenes of continuous measurement installed the instruments in the bedroom: (a) Second floor in traditional house, and (b) First floor in the modern house.

(a) (b)

Figure 2.9 Sample scenes of installed the instruments for continuous measurement in the traditional house of surface areas; (a) four walls, and (b) celling.

Table 2.6 Details of the thermal measurement survey at interval of 10 minute

Season	Regions	House code	Survey period		
			Start date	End date	Total days
Winter	Cold	H1 to H3	12/5/2016	12/7/2016	3
	Temperate	H7 and H10	12/2/2016	1/2/2017	31
		H8 and H9	12/10/2016	12/16/2016	7
	Sub-tropical	H13 to H16	12/18/2016	12/21/2016	4
Summer	Cold	H1 to H6	4/22/2019	4/28/2019	7
	Temperate	H7 to H12	4/18/2019	5/18/2019	31
	Sub-tropical	H13 to H18	4/18/2019	5/18/2019	31

2.4 Method of thermal comfort survey

A series of surveys on indoor thermal environment and comfort was conducted in three climatic regions; cold (Mustang district), temperate (Kavrepalanchok district), and sub-tropical (Sarlahi district), in winter and summer. The measurement of thermal environment and survey of thermal comfort were conducted for twenty-one days from December 5^{th} to 26^{th} 2016 for winter survey and 22^{th} April to May 16^{th}, 2019 for summer survey. We measured the thermal environmental parameters; i.e., indoor air temperature, surface temperatures (ceiling, floor and walls), globe temperature, relative humidity, air movement, outdoor air temperature and relative humidity by using sensors with digital recorders. Table 2.5 shows the sensors used for this survey. Table 2.7 shows the details of thermal comfort survey and Figure 2.10 shows the photographs of field survey. Similarly, Figure 2.11 shows the description of age group of the people who has been participated in the study. Table 2.8 shows the basic information of the respondents such as; average age, height, and weight.

Table 2.7 Details of thermal comfort survey in three districts in winter and summer

Season	Survey period			No. of houses visited and No. of respondents asked							
	Starting date	Ending date	Total days	Mustang		Kavrepalanchok		Sarlahi		Total	
Winter	05/12/2016	26/12/2016	21	30	60	34	90	50	135	114	285
Summer	22/04/2019	16/05/2019	26	107	292	93	315	113	395	313	1002
Total			47	137	352	127	405	163	530	427	1287

Table 2.8 Basic information of the respondents

Seasons	Districts	No. of respondents		Age (years)		Height (cm)		Weight (kg)	
		Male	Female	Male	Female	Male	Female	Male	Female
Winter	Mustang	29	31	42	42	160	160	58	58
	Kavrepalanchok	46	44	43	43	160	160	59	59
	Sarlahi	74	61	39	39	157	157	59	59
Summer	Mustang	141	151	40	39	157	157	60	60
	Kavrepalanchok	145	170	39	39	157	157	59	59
	Sarlahi	180	215	37	38	158	158	57	57

As soon as we arrived in the houses that were surveyed, we first set the instruments for outdoors and then indoors. The measurements were performed only once in each house during the daytime from 7:00 to 19:30. The indoor sensors were placed approximately 1.1 m. above the floor surface and 1 m. away from the occupants. The outdoor sensors were placed 1.5 m. above the ground surface and approximately 3 m. away from the houses and were protected from direct solar radiation. We also measured the indoor air velocity with a hot-wired sensor and a digital recorder. Given the limited survey period and budget, we were unable to perform continuous measurements in the 427 houses that we visited. Therefore, we conducted a series of spot measurements in those 427 houses. The measured data was recorded 15 ~ 20 minutes after the instruments were set to ensure stabilized measurements. We assumed that the measured indoor thermal environmental data can be used for the analysis on the votes given by the respondents. This type of methodology is widely used in adaptive thermal comfort field surveys (Nicol et al., 1996, 2012; Humphreys et al., 2013; Rijal et al., 2010, 2019).

Although there are many survey methodologies for collecting the data, according to time limit, budget, availability of the respondents, after contacting majority of the houses in the study areas, the sample size was shaped on the basis of their availability. All voting was performed in living rooms, bedrooms or kitchens where residents were sitting, resting and working. To capture their daily lifestyle and minimize the activity level before voting, we did not fix specific rooms for voting. However, all the rooms were naturally ventilated to a good extent, and thus the temperature difference between the rooms was considered as very low. Additionally, some residents also used the kitchen room for living and sleeping purposes. Figure 2.11 (b) shows one of the interview scenes of data collection. We used the modified scale of thermal sensation (mTSV), thermal preference (TP), and thermal acceptance which is shown in Table 2.9. The same scale was used in the study of Rijal et al. (2010) Gautam et al. (2019, 2020). The scales were presented in local language as performed in previous studies at Rijal et al. (2010), Thapa et al. (2018), Khatri et al. (2019), Humphreys et al. (2016), Gautam et al. (2919, 2020) shown in appendix 2. We prepared a checklist of clothing insulation and recorded the clothing worn by the respondents during the time of survey shown in Table 2.10. Given the absence of data on the thermal insulation level of Nepalese traditional clothing, we applied the closest clothing insulation values available from ISO (2003) and referred to the data reported by Indraganti et al. (2015). We also asked questions on behaviours adopted for thermal comfort. The respondents were asked to choose only one of the behaviours and activity levels (the activity of the respondents performed in the last 15 min) from the list that was prepared, as shown in Table 2.9.

Figure 2.10 Sample snaps of thermal measurement and a scene of interview while performing thermal comfort survey: (a) instruments for thermal measurement; (b) Cold; (c) Temperate, and (d) Sub-tropical regions.

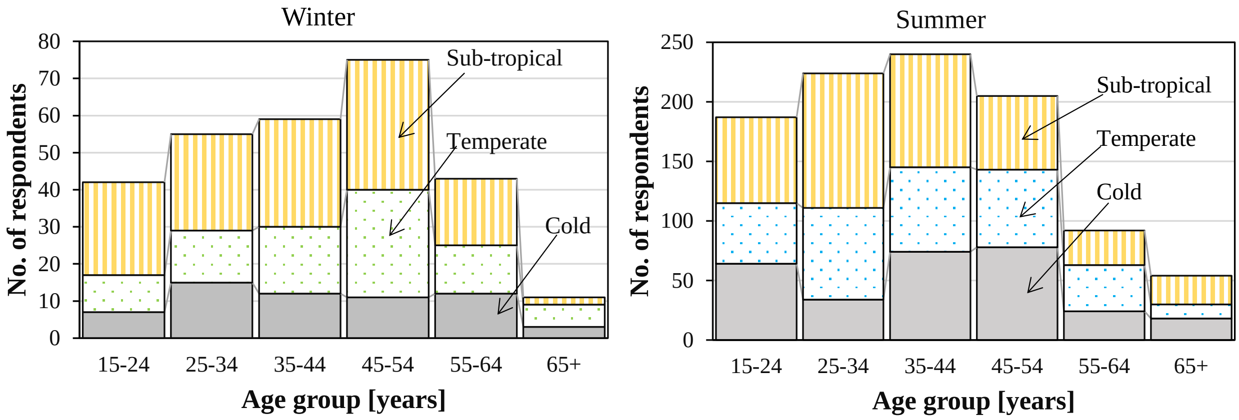
Table 2.9 Questionnaire used in the thermal comfort survey

English	Nepalese
Modify thermal sensation vote (mTSV)	**चिसो तातोको अनुभवः**
1. Very cold	१ जाडो।
2. Cold	२ चिसो।
3. Slightly cold	३ अलिकति चिसो।
4. Neutral (Neither cold nor hot)	४ ठिक्क (चिसो पनि छैन, तातो पनि छैन)।
5. Slightly hot	५ अलिकति तातो।
6. Hot	६ तातो।
7. Very hot	७ गर्मि।
Thermal preference	**तापक्रमको चाहनाः**
1. Much warmer	१ धेरै न्यानो चाहिन्छ।
2. A bit warmer	२ अलिकति न्यानो चाहिन्छ।
3. No change	३ एतिकै ठिक छ।
4. A bit cooler	४ अलिकति शितल चाहिन्छ।
5. Much cooler	५ धेरै शितल चाहिन्छ।
Thermal acceptance	**तापक्रम खप्न सक्नुः**
0. Acceptable	० खप्न सक्छु।
1. Unacceptable	१ खप्न सक्दिन।
Sweating perception	**शरिरमा पसिना:**
0. None	० छैन।
1. Slightly	१ अलिकति छ।
2. Moderately	२ केही मात्रामा छ।
3. Largely	३ धेरै छ।
Preferring behaviours for coolness	**सितलताको लागि चाहाना:**
1. Use fan	१. पंखाको प्रयोग।
2. Use light clothes	२. पातलो कपडाको प्रयोग।
3. Take a shower	३. नुहाऊन चाहान्छु।
4. Sit under the shade	४. छाहारीमा बस्न चाहान्छु।
5. Change posture	५. आसन (बसाई) परिबर्तन।
6. Nothing in particular	६. यतिकै ठिक छ।
Activity level (last 15 minutes)	**शरिरको कार्यशिलता**
1. Lying down	१. पल्टिरहेको।
2. Sitting resting	२. बसेर आराम गरिरहेको।
3. Sitting working	३. बसेर काम गरिरहेको।
4. Standing relaxed	४. उभिएर आराम गरिरहेको।
5. Standing working	५. उभिएर काम गरिरहेको।
6. Walking indoors	६. घरभित्र हिडी रहेको।
7. Walking outdoors	७. घरबाहिर हिडी रहेको।

Table 2.10 Check-list of clothing insulation used in thermal comfort survey

S. N	Clothes	Nepali name	ISO/WD9920	I_{cl} [clo]	ISO/WD9920
1	T-shirt half	टिसर्ट हाफ	T-shirt	0.08	P_58. No_30
2	T-shirt full	टिसर्ट फूल	Long sleeves	0.12	P_58. No_33
3	Hi-neck	हाईनेक	Shirt, long sleeves	0.25	P_58. No_45
4	Shirt full	सर्ट (फूल)	Shirt, long sleeves	0.16	P_58. No_42
5	Chaubandi (NTD)	चौबन्दी चोलो	Long sleeves	0.33	P_58. No_54
6	Blouse	ब्लाउज	Short sleeve	0.25	P_58. No_53
7	Trouser	ट्राउजर	Trousers	0.3	P_61. No_201
8	Suruwal	सुरुवाल	Shorts	0.08	P_59. No_83
9	Track	ट्र्याक	Straight, loose	0.22	P_59. No_86
10	Peticoat (NTD)	पेटिकोट	Thin strap	0.15	P_63. No_357
11	Sweater	सुईटर	Thick sweater	0.35	P_56. Table 1
12	Jacket	ज्याकेट	Work jacket	0.39	P_60. No_153
13	Bakhu	बख्खु	Jacket above knee	0.69	P_60. No_181
14	Coat	कोट/फुलकोट	Coat	0.63	P_60. No_179
15	Muffler	गलवन्दी	Arm protectors	0.11	P_62. No_271
16	Cap	ऊनको टोपी	Cap	0.01	P_61. No_259
17	Docha (NTD)	डोचा	Jacket above knee	0.69	P_60. No_181
18	Gown	कुर्था, म्याक्सी,	Long gown	0.29	P_62. No_350
19	Cap	उनीको टोपी,	Cap	0.01*0.03	P_61. No_259
20	Pacheura (NTD)	पछ्यौरी (मजेत्रो)	Arm protectors	0.11	P_62. No_271
21	Pant	पाईन्ट /सुरुवाल,	Sweat pants	0.28	P_62. No_291
22	Lungi (NTD)	लुँगी, लेहेगां	Thin strap	0.15	P_63. No_357
23	Shoes full	जुत्ता बुट	Thick shoes	0.11	P_61. No_252
24	Shoes half	जुत्ता हाफ	Shoes	0.05	P_61. No_258
25	Shocks	मोजा	Thick socks	0.05	P_61. No_256
26	Sandal	चप्पल	Slippers	0.03	P_61. No_261
27	Saree**	फरिया, सारी		0.54	

0.01*0.03 = 0.03 case of woolen cap, Saree** = 0.54 Indraganti, I_{cl}: Clothing insulation [clo]



(a) (b)

Figure 2.11 Distribution of age group; (a) winter and (b) summer.

2.5 Equations used in the study

In this section, we have discussed the equations/ formula applied to the analysis of data. To estimate the mean radiant temperature, we adopted operative temperature, comfort temperature, preferred temperature, and logistic regression methods with the bins of globe temperature.

2.5.1 Estimated mean radiant temperature and operative temperature

The materials used in the houses in cold, temperate and sub-tropical regions are relied on climate and culture. Different types of houses have used a variety of ways to mitigate indoor thermal conditions. The mean radiant temperature, T_{mrt} [°C] and operative temperature, T_{op} [°C] are estimated via using equations (2.1) to (2.3) from a formula given in Persons (2003). Equation (2.1) is used for v ≤ 0.15 m/s and equation (2.2) is used for v > 0.15 m/s. The calculation of T_{mrt} is used to confirm how much the radiation effect inside the houses in cold, temperate and sub-tropical regions in winter and summer seasons.

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{0.25 \times 10^8}{\varepsilon} \left(\frac{|T_g - T_i|}{d} \right)^{\frac{1}{4}} \times (T_g - T_i) \right]^{0.25} - 273 \quad (2.1)$$

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon d^{0.4}} \times (T_g - T_i) \right]^{0.25} - 273 \quad (2.2)$$

$$T_{op} = \frac{T_i + T_{mrt}}{2} \quad (2.3)$$

where, T_g denotes the indoor globe temperature [°C], T_i denotes the indoor air temperature [ºC], v denotes the air velocity [m/s], d denotes the diameter of the globe [m] (= 0.075 m), ε denotes the emissivity of globe surface (= 0.95).

2.5.2 Estimation of comfort and preferred temperature

The comfort temperature and preferred temperature were estimated by the Griffiths method (Nicol et al., 2012; Humphreys et al., 2013; and Griffiths, 1990). The method can be used to estimate comfort temperature with any single vote in the seven-point scale of thermal sensation given the assumption of equi-distance in points. It is considered as useful when linear regression is not reliable to estimate the comfort temperature. Based on the respondents' votes of thermal sensation and the corresponding values of measured indoor globe temperature, we estimated the comfort temperature by using the following equation:

$$T_c = T_g + \frac{(4 - \mathrm{mTSV})}{a^*} \tag{2.4}$$

where T_c denotes the estimated comfort temperature [ºC], number "4" indicates "Neutral (neither cold nor hot)" in the mTSV seven-point scale, which is assumed as linear from 1 to 7, mTSV which denotes the thermal sensation vote obtained from the survey, and a^* denotes the increment of thermal sensation vote with indoor globe temperature.

Thus, a* replaces the regression coefficient assumed as 0.50, which is equivalent to assuming that an interval of two adjacent votes corresponded to an increase in globe temperature by 2 ºC, as indicated by Humphreys et al. (2007, 2013, and 2016). Rijal et al. (2017) and Indraganti and Boussaa (2017) also observed similar slope. The slope is widely used to estimate the comfort temperature in previous studies, for example, the study of Nicol et al. (2012), Humphreys et al. (2013), Indraganti et al. (2017), Rijal et al. (2020), CEN (2007). We applied a similar procedure to estimate the preferred temperature from the votes. The equation used is as follows:

$$T_{per} = T_g + \frac{(3 - TP)}{a^{**}} \tag{2.5}$$

Where T_{per} denotes the estimated preferred temperature [ºC], number "3" indicates "No change" in the thermal-preference five-point scale from 1 to 5, *TP* denotes the thermal preference vote obtained from the survey and a** denotes the assumed increment of preference vote corresponding to an increase of 3 ºC in globe temperature. The value of a** was assumed as 0.33 (= 4/6×0.50) Gautam et al. (2019) due to which the range of the seven-point thermal sensation scale and that of the five-point scale of preference corresponded to each other.

2.5.3 Estimation of logistic regression equation

Logistic regression analysis was performed to quantify the relationships between the number of respondents in terms of certain levels of thermal sensation or preference and indoor globe temperature.

$$\ln\left(\frac{P}{1-P}\right) = ax + \mathrm{b} \tag{2.6}$$

where "ln" denotes the natural logarithm, P denotes the probability of assumed level of thermal sensation or preference; a denotes the slope of the regression line, b denotes the intercept of the regression line, and x denotes the variable to be related to the probability. In the study, x corresponds to indoor globe temperature.

Chapter 3: Thermal environment

3.1 Introduction

Although Nepal is a land locked and small country, the climate varies from sub-tropical to very cold due to the broad range in elevation. Indoor environment has a significant impact on health and well-being, not only due to the time spent for indoors during our natural life, but also due to the combination of health and safety threats encountered on a daily basis (Charles, 2009). The indoor temperature should not be too high or too low, since it is very much related to human health which is concluded by the study of Ponni et al. (2015). Similarly, Saeki et al. (2014) presented that indoor environment is directly related to human health because most of the people spent around 90% of their time indoors ASHRAE Standard 55 (2010). Therefore, a good and comfortable thermal indoor environment is necessary for optimal health (Zhang, 2003). The traditional houses could be the main issue for acceptable building design for different regions and socio-cultures. The different construction of traditional houses, using a variety of ways to mitigate indoor thermal conditions, can be found such as inner court-yard, verandah, use of eaves or roofs cutting down sunshine, semi-open spaces and increasing thermal mass by applying local materials such as wood, stone, mud and the stalk of wheat or barley. People are well adapted to the climates and socio-cultural contexts by using local building materials and techniques. However, traditional constructions are decreasing day by day, being replaced by artificial materials, modern design and new technology which is shown in Figure 3.1. It is necessary to draft strong policies and good research is must in order to sustain the idea and possibility of traditional architecture. Indoor environment and living conditions of the traditional houses in different climatic regions need to be preserved, from practices of modern (concrete) houses for future generations. Nowadays people are gradually using market building materials in increasing pace which is not easily accessible to all people. The market-based materials cannot guarantee healthy indoor environment.

As we discussed earlier in the chapter 1; section 1.1, Figure 1.4 presents a schematic relationship between types of human physical behaviour and the types of the building environment technology. Figure 3.2 shows schematic relationship between types of human physical behaviour and the types of the building environment technology in the respective regions. All together five circles representing traditional houses (T) in cold, temperate, and sub-tropical regions, contemporary urban houses (U) and future target (F) are placed in a two-dimensional space in Figure 3.2. We already discussed about the horizontal axis, vertical axis, conventional path, proposed path for developing country, proposed path for developed country in the beginning of the first chapter. In this diagram, the current conditions of traditional houses and people life style are positioned in the area "T". The area "T" there are three circles with three dots points in the centre representing the condition of traditional houses, in cold, temperate and sub-tropical regions. As we mentioned in chapter 2; section 2.3, Table 2.3 presented the number and the percentage of traditional and modern houses in cold, temperate, and sub-tropical regions. There are 95.4%, 86.8% and 74.8% of the traditional houses are built in cold, temperate, and sub-tropical regions, respectively. This means that the traditional houses in cold region are based on passive building envelopment system and people are required to restore their thermal comfort with human physical behaviour, and more than 25% of the houses use active mechanical system for thermal comfort of people in the sub-tropical regions.

Figure 3.1 Traditional house is replaced by modern house.

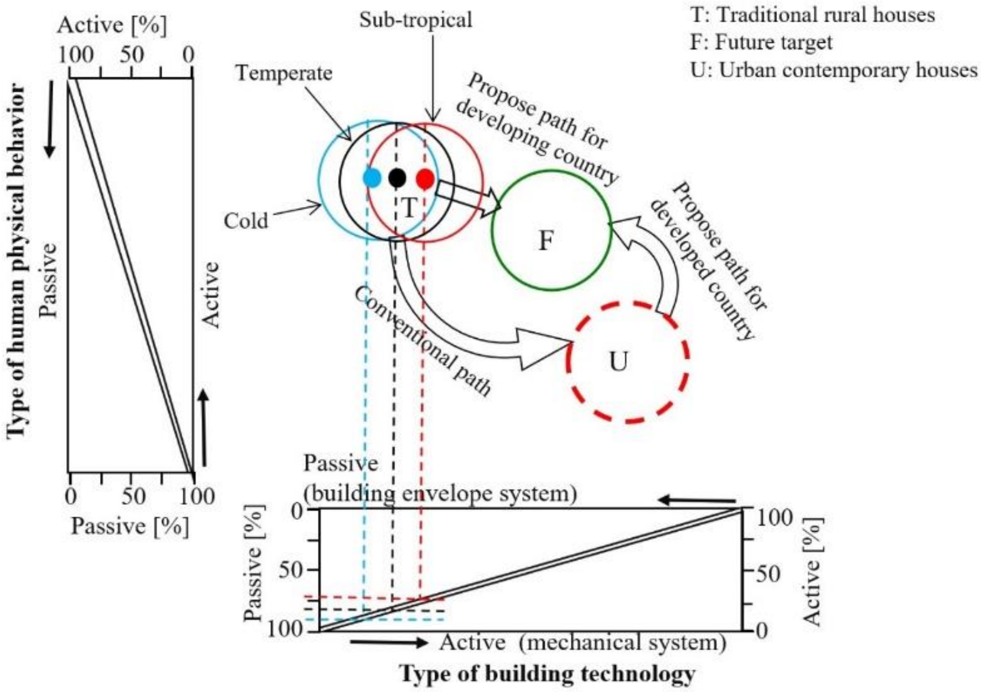


Figure 3.2 Schematic diagram of built-environment technology and human behaviors.

3.1.1 Modern houses in Nepal

Nepal has a rich tradition of culture, religions, languages, as well as buildings made of local materials such as mud, stone, wood, bamboo, and straw. These traditional materials, are cheaper, more ecological, and safer than those of the modern or concrete based materials. Because of our education system, we try to copy everything from the western countries and the case is sane in the selection of building materials and design. Nepal has climatic variations. The traditional houses have been made according to climate and culture but the concrete houses have been made up with the same materials in different climatic regions which is shown in Figure 3.3, being irrespective to the health and environment. Most of the concrete homes are neither sustainable nor environment friendly. Nepal imports nearly 70% of cement from India and its manufacture has a huge carbon footprint. The structures made of cement are energy-intensive because they are cold in winter and hot in summer. Bajracharya (2013) concluded that compare to traditional buildings, the concrete buildings were 1 to 2 °C chill in winter and 1 to 2 °C hot in summer. Gautam et al. (2019) also concluded that the temperature of the modern houses was lower at night time than the traditional houses in winter.

Figure 3.3 A sample of modern house.

3.1.2 Traditional houses in cold region

The traditional houses are very compact. They are based on traditional architecture. The buildings are often attached to each other creating small alleys that are protected from the cold wind and snowstorms. The traditional house volumes with rectangular building shapes are dominant in the cold climatic region (Gansach et al., 2004; Toffin (1991 and NTNC, 2008). Most of the houses in Mustang district have square and rectangular shape with ground floor plain. Houses are situated on the southern slope to enhance solar heat gains (Toffin, 1991 and NTNC, 2008). In this way, the high thermal mass of the traditional houses can be heated by the strong solar radiation during the day. The space arrangement within these houses is mainly organized vertically. The ground floor and top floor of the houses are allocated to secondary use and have the effect of a thermal buffer to keep the main living area on the first floor as warm as possible. Animals are housed on the ground floor leading to increase indoor temperature due to their bodily heat. The main living area on the second floor is horizontally surrounded by rooms which serve for storage, a family treasure, and so on which is creating horizontal thermal buffer zones. In the study area, narrow streets and high walls around the houses marking the alleyways have the same purpose. Most of the walls of the houses are traditionally built of stone and sun-dried mud bricks with 45 to 60 cm. thickness (Boch-Isaacson, 1987). Due to the insufficient rainfall, roofs of traditional houses in cold climates are generally flat (Gansach et al., 2004; Toffin, 1991; and NTNC, 2008) which is seen in Figure 3.4. Using locally available material, the roofs are typically made of mud and stone laid on a timber post and beam structure has developed different techniques to make the roof waterproof. This technique protects from the wet snow that typically falls in the early winter months.

Figure 3.4 A sample of flat roof house.

Traditional houses in the cold climatic region have several more features to protect from the coldness. Settlements and building volumes are integrated and are denser than in other climatic regions. The houses have smaller and fewer openings in order to reduce heat losses. The internal space arrangement is enhanced to create thermal comfort zones. The use of window shutters has the effect to increase the tightness of the building. Roofs are flat as far less rain is falling than in cool temperate climate. The buildings have a high thermal mass that helps to balance large diurnal temperature range in different seasons. In nutshell, the traditional design of house is very much adapted to the local climatic conditions in this region.

To preserve traditional construction technology, it is important to make policies such that traditional technology can be improved with modern skills without diminishing cultural norms, by looking at the positive aspects of traditional houses that should be preserved and inherited for the future. One aspect which can be improved while keeping traditional skills is better thermal comfort. For this purpose, we need to know how people living in different climatic regions of Nepal achieve thermal comfort in their respective traditional houses by examining various adaptive behaviours such as clothing adjustment.

3.1.3. Traditional houses in temperate region

The traditional houses typologies range from different ethnic groups and locations. They are built around the traditional architecture in the temperate climate of Nepal. The settlement of this climate is rather of scattered and dispersed character. There are several types of building forms strongly depending on settlement density and ethnicity. Most of the traditional houses in Kavrepalanchok district have rectangular shape ground floor plan seen in Figure 2.5 (a) and Figure 3.5. The plan is situated on the sunny slope of the hills with the longer façade facing toward the south, south-east or south-west. It was observed that traditional houses in Kavrepalanchok have more than two or three stores. The low room height being between 1.6 to 1.9 m. makes it easier to heat the house during winter season. In most of the houses, the ground floor is also big open space designated for different activities like cooking, dining, meeting, and worshipping which are sometimes visually divided by lower walls (Toffin, 1991). The first floor is basically used as sleeping rooms and the second floor is used for granary and storage for family's valuables.

Figure 3.5 A sample of zinc roof house.

The walls of the traditional houses in temperate climate of Nepal are mostly made of locally available stones and clay or earth with 40 to 50 cm. thickness which leads to a high thermal mass of the buildings. The walls are mostly plastered inside and outside using white or red mud and cow dung. The typical roof type applied in traditional houses in the temperate climate of

Nepal is the pitched roof supported by timber structure and covered by local available thatch, tiles and zinc which is seen in Figure 3.5. The windows in these houses are rather small, but larger than those found in the cold climatic region's houses. The windows are basically located in the longer facade. In short, it can be said that the traditional houses in temperate climate are very well adapted to the local climate condition.

3.1.4 Traditional houses in sub-tropical region

The sub-tropical region has fertile land, plain topography, easy access to various infrastructures such as educational and health facilities (CBS, 2011). Thus, people living in cold and temperate regions migrate to the sub-tropical regions. The number of migrants who are migrated from cold and temperate regions to sub-tropical regions was 410,064 in 1971 and it increased by 3.1 times over a 40-year period and reached 1,273,599 in 2011 (CBS, 2011; and Gartaula, 2013). This indicates that migration towards sub-tropical region is one of the major movements of human activities in Nepal.

The traditional houses are very dense in sub-tropical climate. Different castes have made the traditional houses representing their own respective culture in this region. Most of the traditional houses were composed of with bamboo walls and tile roof for local people and wooden walls with tile roofs for migrant people which is given in Figure 3.6, and a few houses were also composed of brick walls and concrete roof for both groups of peoples (Gautam et al., 2020). The houses of the local people were connected with each other, while the houses of the migrant people were significantly separated from each other. Generally, the house size of local people was smaller than that of the migrant people. These houses were designed and constructed by local people with locally available materials such as wood, sun dried bricks, and cement. Generally, the kitchen, storeroom, and living room are on the ground floor, and the bedrooms are on the first floor. The space arrangement within these houses is mainly organized horizontally. Most of the local traditional houses are almost undivided for natural ventilation.

The traditional house volumes with rectangular building shapes are dominant in the sub-tropical climatic region (Gansach et al., 2004; Toffin, 1991; NTNC; 2008; and Gautam et al., 2019, 2020). Most of the traditional houses in Sarlahi district have rectangular shape ground floor plans enclosed with light walls. The longer facade is usually oriented north-south which reduces the exposure to the sun (Gartaula, 2013). The houses in this reason have one to two stores with high ceilings for increasing the ventilation effect necessary especially in hot and humid climates. In short, it can be said that the traditional houses designed in the sub-tropical region of Nepal are very climate responsive. The main strategies such as increasing air movement within the building and protecting from the strong solar radiation are considered.

Figure 3.6 A sample of bamboo walls and tile roof.

3.2 Wintry thermal environment

3.2.1 Variation of indoor and outdoor air temperature

Outdoor air temperature has affected the indoor air temperature in all study areas. Figure 3.7 shows the results of three days' variation of indoor and outdoor air temperature in the selected houses of three climatic regions of Nepal. In the cold-climatic region, the average indoor and outdoor air temperatures tend to be lower than that of the temperate and sub-tropical regions. The mean outdoor air temperature is 8.6 °C in a cold region, which is 4.4 °C and 9.5 °C lower than temperate and sub-tropical regions, respectively. The diurnal range of the indoor air temperature in the cold region is smaller than that of the temperate and sub-tropical regions. The diurnal range is 3.9 °C in cold region, 6.1 °C in temperate region and 14.4 °C in sub-tropical region. The cause of this difference in indoor air temperature may be due to the size of the windows, wall thickness and heat capacity of the materials used.

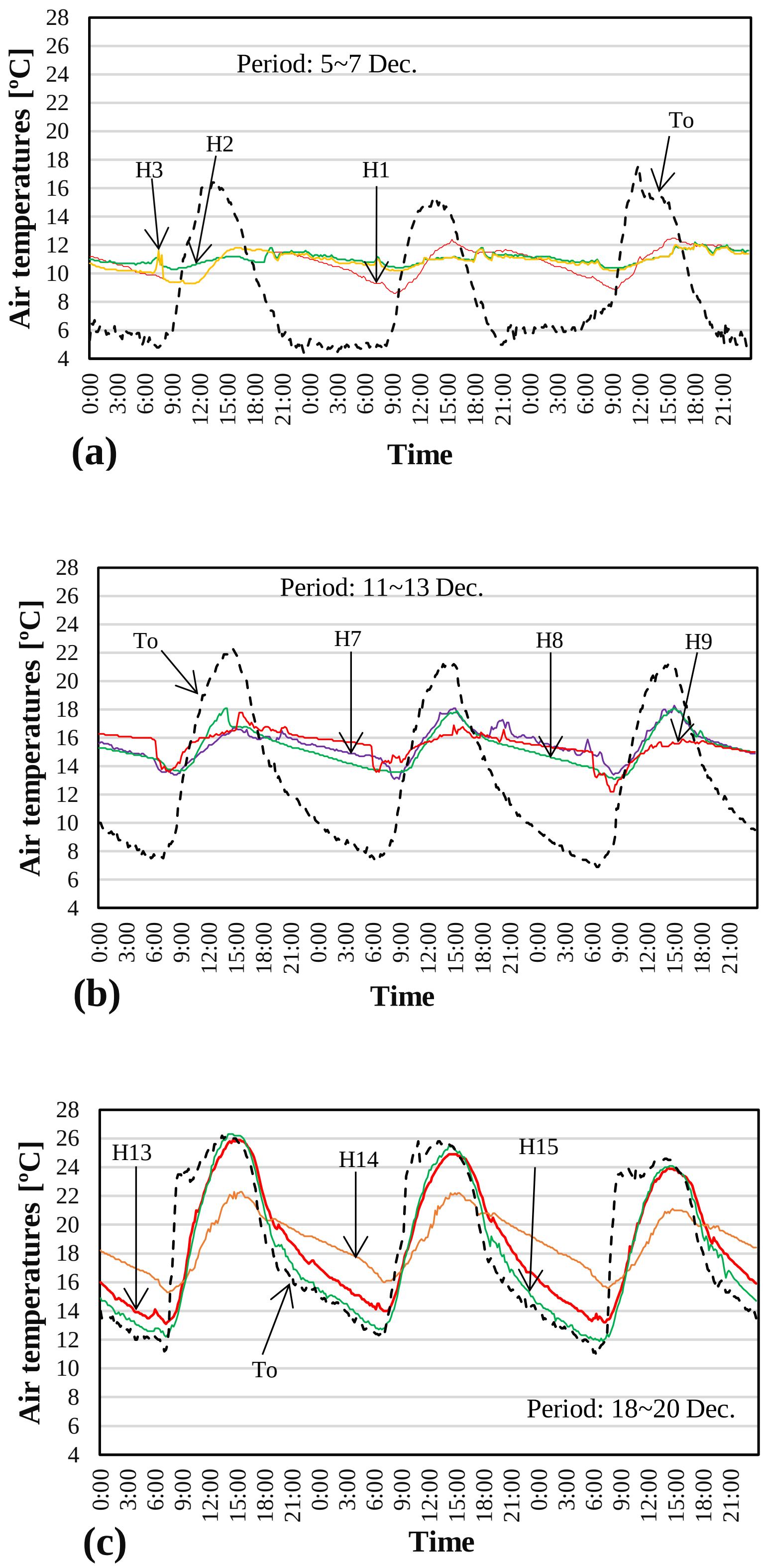


Figure 3.7 Three days' variation of indoor and outdoor air temperature: (a) Cold region, (b) Temperate region, and (c) Sub-tropical region.

Figure 3.8 and Figure 3.9 show the results of temperature variation of indoor and outdoor air temperature in traditional and modern houses; in the temperate region for one-month and sub-tropical region for three days. Unfortunately, we did not measure the continuous measurement data in modern houses in cold region. Outdoor air temperature has affected the indoor air temperature in the study areas. The indoor air temperature of the traditional house ranged between 12.1 to 20.0 °C and the modern house ranged between 9 to 21.7 ºC but the average temperature is the same as each other as like the findings of previous research works by Bajracharya (2013), and Rijal et al. (2010). The study of Bajracharya (2013) concludes that in traditional residential buildings, indoor air temperature is 1 to 2 °C lower in the summer and 2 °C higher in winter than in modern residential buildings. The range of indoor air temperature variation in traditional houses is narrower than that of in modern house in temperate climate. In temperate climate, the diurnal range of traditional and modern house is 2.7 °C and 8.7 °C respectively. The result is opposite in sub-tropical climate than in temperate climate. In the sub-tropical climate, the diurnal range of traditional and modern house is 14.4 °C and 7.1 °C respectively. The average indoor air temperature in a traditional house is 1.7 °C higher than the modern house. The cause of this difference in indoor air temperature may be due to the size of the windows, walls thickness and heat capacity of the materials used in the houses.

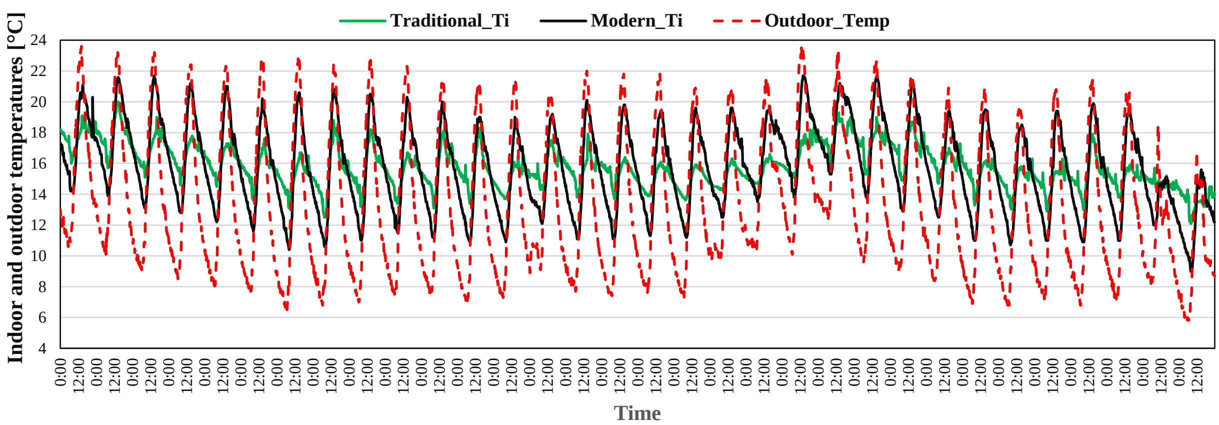


Figure 3.8 One-month variations of indoor and outdoor air temperature in temperate region.

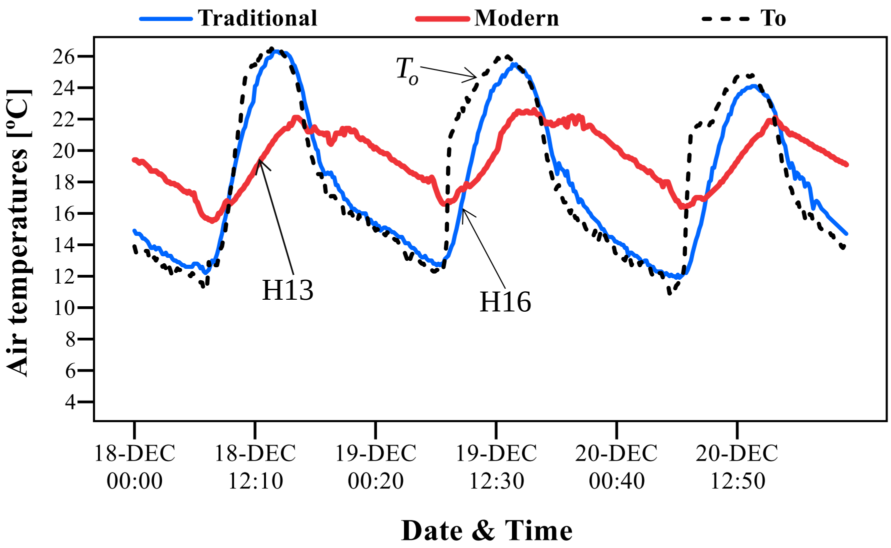


Figure 3.9 Three-days' variations of indoor and outdoor air temperature in sub-tropical region.

3.2.2 Distribution of indoor air temperature

Figure 3.10 shows cumulative frequency of indoor air temperature in the measured houses of respective regions. Among the three regions, in most of the time the indoor air temperature was lower in the cold region, middle in the temperate region and highest in the sub-tropical region. The 80% of the data given below shown 11 °C in house H2 and H3 but house H1 data are below 11.5 °C in the cold region. The indoor air temperature is similar in these houses. The 80% of the data is below 16 °C in temperate region. Likewise, 80% of the data are below about 22 °C in houses H13 and H14 but house H15, the 80% of the data are below the 20 °C in sub-tropical region. This is probably because of solar radiation absorbed by the walls and roof, heat generation, and together with the light materials. It is shown in Figure 2.6 (a).

Figure 3.11 shows cumulative frequency of traditional and modern houses. In temperate climatic region, H1 (traditional) house was found 80% of time below 16.5 °C while H4 (modern) house to have only 80% of time below 18.2 °C. But the result is opposite in sub-tropical climatic region. In sub-tropical climate, 80% of time in the H13 (traditional) house was found to be below 22.8 °C while H16 (modern) house had only 80% of time below 21.0 °C. It proves that modern house is better than traditional house in sub-tropical climate in winter. It is due to the difference in house materials used, heat generation and wall thickness.

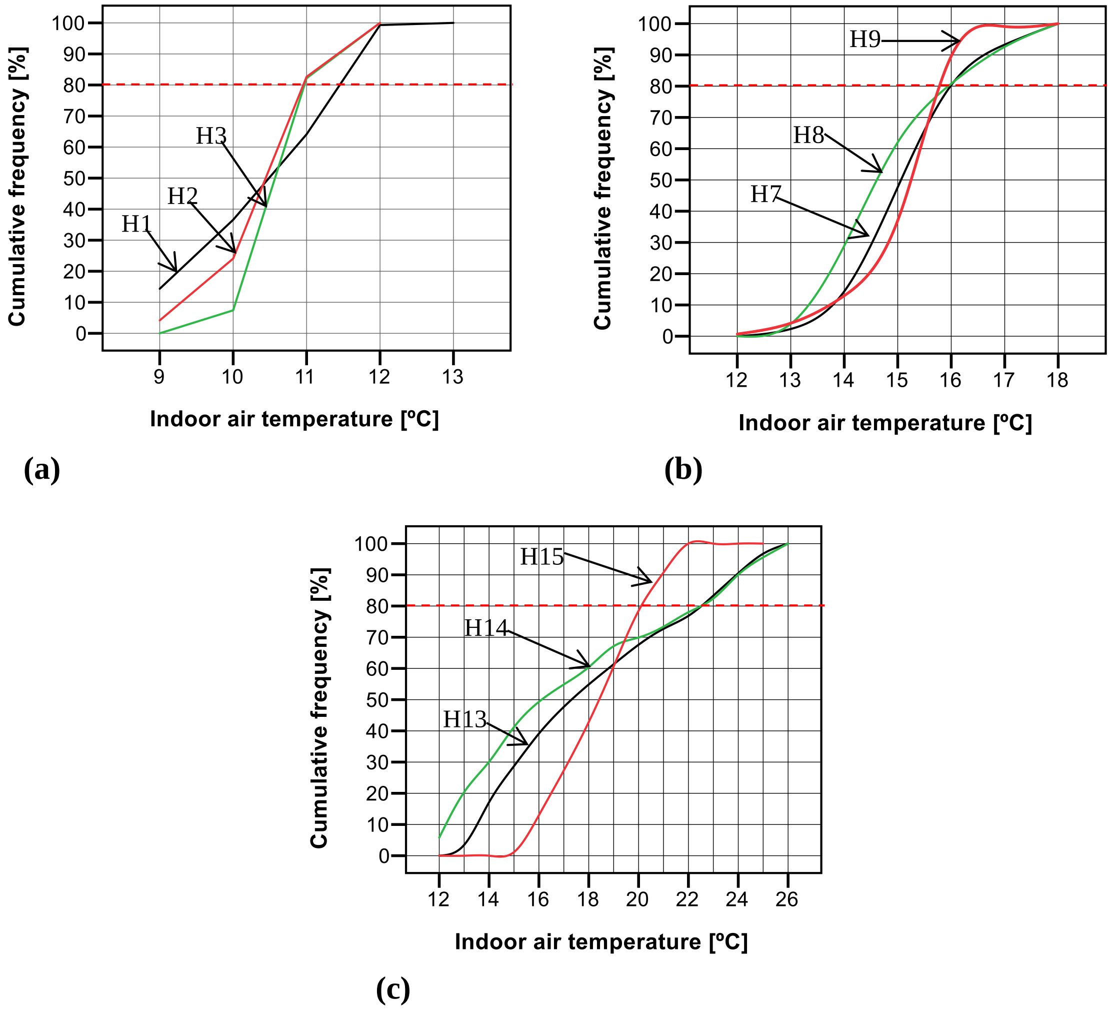


Figure 3.10 Distribution of indoor air temperature: (a) Cold region, (b) Temperate region, and (c) Sub-tropical region.

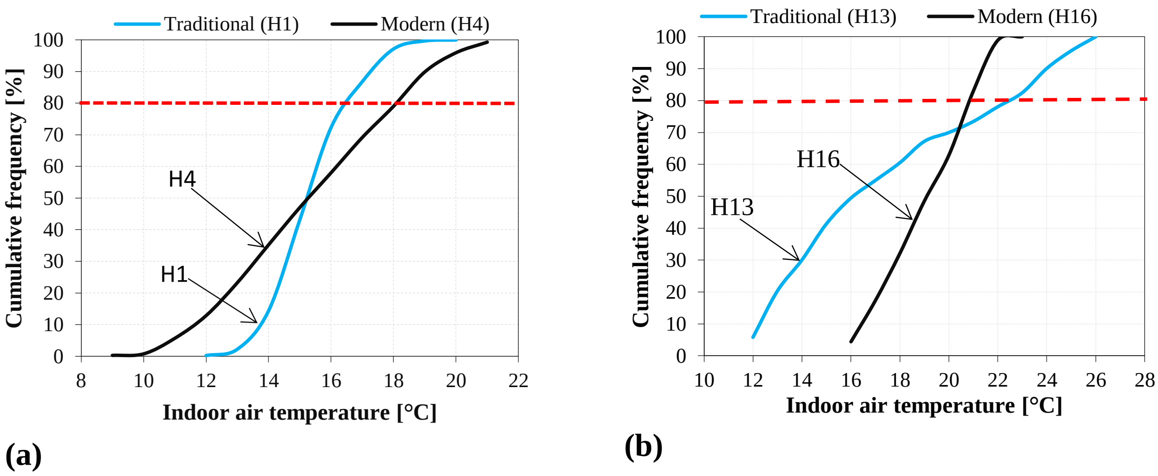


Figure 3.11 Distribution of indoor air temperature in traditional and modern houses: (a) Temperate region, (b) Sub-tropical region.

3.2.3 Relationship between indoor and outdoor air temperature

When the outdoor air temperature increased the indoor air temperature also got increased. It means, outdoor air temperature has affected the indoor air temperature in all study areas. Figure 3.12 shows the relationship between the indoor air temperature and outdoor air temperature. We have found the following regression equations for temperate and sub-tropical climatic regions:

Temperate $T_i = 0.150T_o+13.5$ (n = 1296, $R^2 = 0.406$, S.E. = 0.005, $p<0.001$) (3.1)

Sub-tropical $T_i = 0.538T_o+8.6$ (n = 1296, $R^2 = 0.572$, S.E. = 0.013, $p<0.001$) (3.2)

where, T_i is the indoor air temperature, T_o is the outdoor air temperature, n is the number of data, S.E. is the standard error of the regression coefficient and p is the significance level of the regression coefficient.

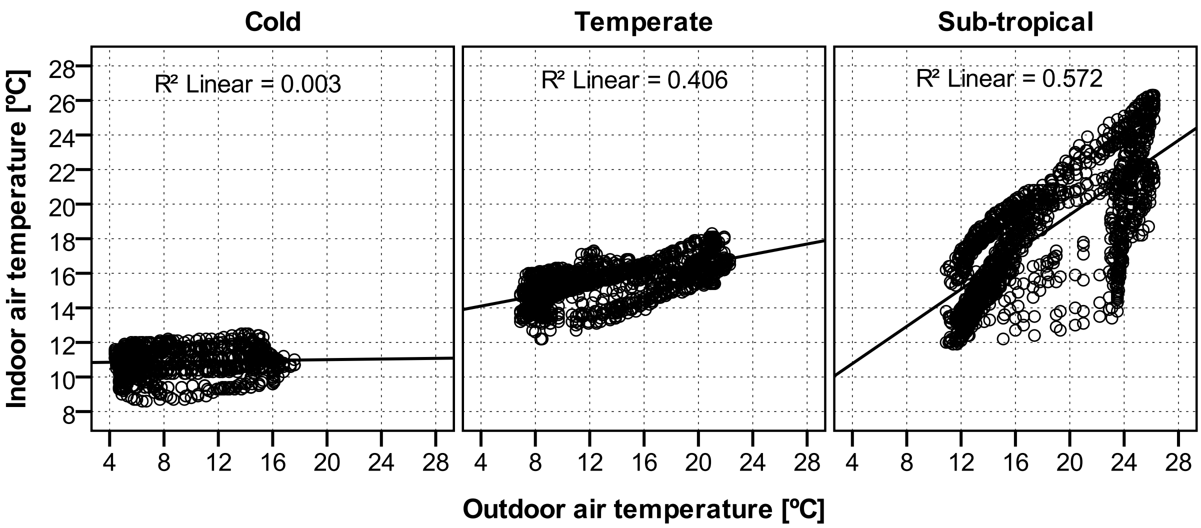


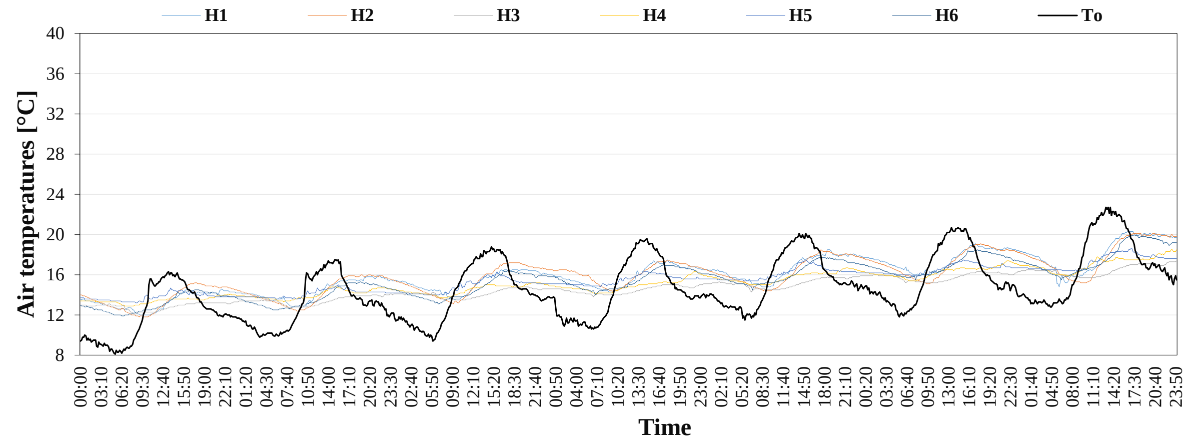
Figure 3.12 Relationship between indoor and outdoor air temperature.

Since the regression coefficient for cold region was found very small. The regression equation was not presented here. The regression coefficient (the slope of the line) of the temperate region is smaller than that of the sub-tropical regions. This difference must be due to the effect of thermal mass of materials used. In the temperate climatic region, the houses are made of stones and mud with thick walls (450mm) which is seen in Figure 2.5 but in sub-tropical climatic region, the houses are made up of wooden with thin walls (25mm). For both temperate region and sub-tropical region, there are data plots between 10 °C and 22 °C. According to the regression lines shown above, indoor air temperature, T_i = 16.6 °C for temperate region and T_i = 19.9 °C for sub-tropical region, with assumption of outdoor air temperature being 21.0 °C. The regional difference of indoor air temperature ΔT_i = 3.3 °C. These tendencies are similar to the findings of previous studies by Rijal (2012), Bajracharya (2013), Rijal et al. (2010), and Nicol et al. (2012).

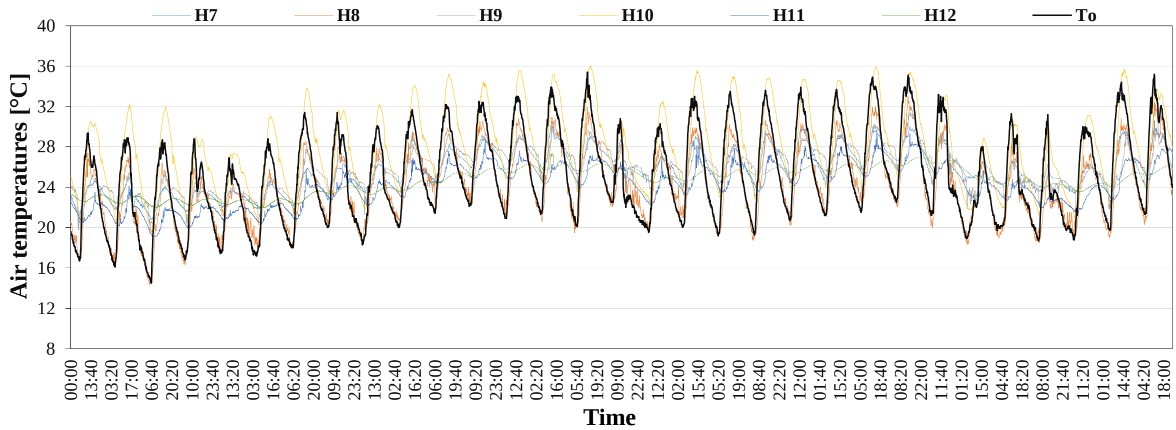
3.3 Summer thermal environment

3.3.1 Variations of indoor and outdoor air temperatures

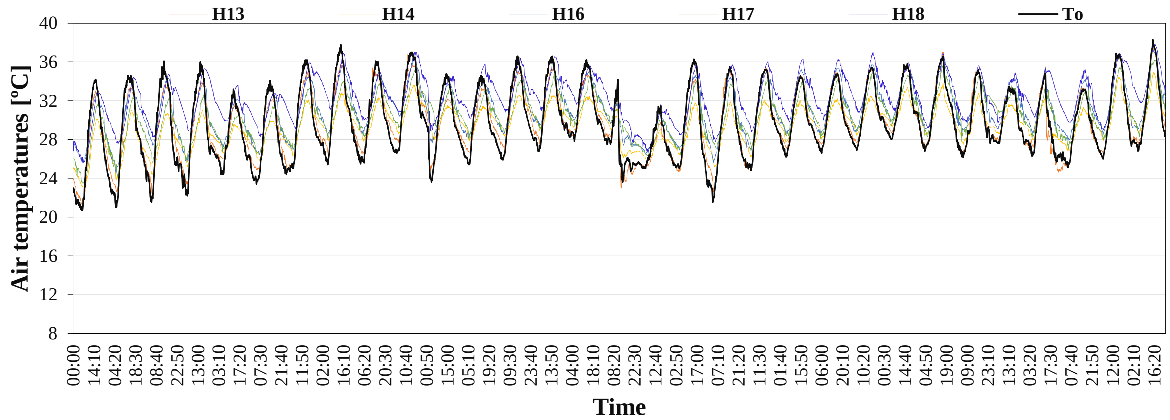
In order to understand the indoor air temperature variation of different climatic regions, we observed for seven days and for one-month indoor air temperature variations of cold region, and temperate and sub-tropical regions, respectively. Outdoor air temperature has affected the indoor air temperature in all study areas. Figure 3.13 shows the profile of indoor air temperature and outdoor air temperature in cold, temperate, and sub-tropical climatic regions in the months of April and May. In the cold region we measured only for seven days of selected houses H1 to H6 as it has been seen in Figure 3.13 (a). In temperate and sub-tropical regions, we measured one-month data of the selected houses H7 to H18 as it has been in Figure 3.13 (b) and (c). The result shows that the temperature decreased in the morning time; gradually increased in day time and again decreased in the evening time. In the cold climatic region, the indoor and outdoor air temperatures tend to be lower than temperate and sub-tropical climatic regions. Within the range of indoor air temperature between 11.8 °C to 20.3 °C in cold region, 20.5 °C to 36.0 °C in temperate region, and 21.3 °C to 38.6 °C in sub-tropical regions. The mean indoor air temperature is 15.6 °C, 25.7 °C, and 29.9 °C in cold, temperate, and sub-tropical regions, respectively. Therefore, the difference between indoor air temperature (ΔT_i) for temperate and cold region is 10.1 °C, sub-tropical and temperate region is 4.1 °C, and sub-tropical and cold region is 14.2 °C. These findings are consistent with those of the previous studies. For example, Rijal et al. (2010) found that the indoor temperature has large regional differences, and Nicol and Roaf (1996) also observed that the temperature is different depending on the climate.



(a)



(b)



(c)

Figure 3.13 Variation of indoor and outdoor air temperature: (a) Cold, (b) Temperate, and (c) Sub-tropical climates in summer.

3.3.2 Estimation of comfort temperature by regression method

The regression analysis of thermal sensation and indoor air temperature was conducted to estimate the comfort temperature in three climatic regions as it is seen in Figure 3.14 The following regression equation is obtained for the thermal sensation and indoor air temperature.

Temperate $C = 0.194T_i+0.3$ (n = 85, $R^2= 0.241$, S.E. = 0.040, $p<0.001$) (3.3)

When the comfort temperature was estimated by substituting “4 Neutral” in the equation 3.3, the comfort temperature would be 19.1 ºC in the temperate climate. However, the regression equations for the cold and sub-tropical climates are not statistically significant. This means that a reliable estimate of the comfort temperature is not possible using regression analysis as it has been found in previous researches, e.g., Rijal et al. (2013) and Nicol et al. (1999). To avoid this problem, we have estimated the comfort temperature by using Griffiths’ method (Griffiths, 1990) in the next section.

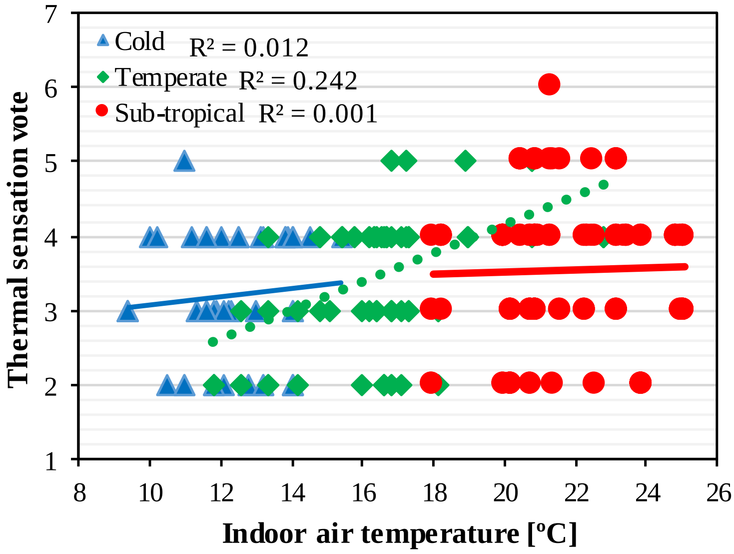


Figure 3.14 Relationship between thermal sensation vote and indoor air temperature.

3.3.3 Relationship between indoor and outdoor air temperature

Figure 3.15 shows the relationship between indoor and outdoor air temperature in cold, temperate, and sub-tropical regions in summer. As expected in general, a high outdoor air temperature results in a high indoor air temperature. When the outdoor air temperature increased, the indoor air temperature also got increased. It means, outdoor air temperature has affected the indoor air temperature in all study areas. We noted the following equations from the regression analysis.

Cold : $T_i = 0.30T_o+11.07$ (n = 6048, $R^2 = 0.32$, S.E. = 0.006, $p<0.001$) (3.4)

Temperate : $T_i = 0.49T_o+13.19$ (n = 22320, $R^2 = 0.47$, S.E. = 0.003, $p<0.001$) (3.5)

Sub-tropical : $T_i = 0.60T_o+12.21$ (n = 22320, $R^2 = 0.62$, S.E.= 0.003, $p<0.001$) (3.6)

The indoor air temperature is correlated well with outdoor air temperature in all three regions but the slope of the regression line for cold region is rather flatter than those for other two regions. This is due, highly probable, to the heat-capacity effect of the houses having thick walls in cold region. In the cold region, the houses are made of stones and mud with thick wall (60 cm. but in sub-tropical region, the houses are made of wood with thin wall (2.5 cm.) as it is seen in Figure 2.7. By comparing with the previous studies, done by Rijal et al. (2010), Nicol et al. (1996), and Thapa et al. (2018), the indoor air temperature in this study is the lowest in high altitude.

Within the range of outdoor air temperature between 14 °C and 23 °C, there are data points for all cold, temperate and sub-tropical regions. According to the regression lines shown in Figure 3.15, indoor air temperature (T_i) becomes 17.7 °C, 24.0 °C and 25.4 °C for cold, temperate and sub-tropical regions, respectively, when assuming the outdoor air temperature 22 °C; that is, the regional difference of indoor air temperature (ΔT_i) is 6.3 °C, for cold and temperate, (ΔT_i) is 1.4 °C, for temperate and sub-tropical, and (ΔT_i) is 7.7 °C for cold and sub-tropical regions. These findings are consistent with those of the previous studies. The indoor air temperature in the study is the lowest at high altitude, which is similar to those studies that was found in Rijal et al. (2012), Nicol and Roaf (1996), and Thapa et al. (2018).

Figure 3.16, Figure 3.17, and Figure 3.18 show the relationship between indoor and outdoor air temperature of traditional and modern houses in cold, temperate, and sub-tropical climatic regions. Outdoor air temperature has affected the indoor air temperature in both traditional and modern houses. We found the following equations from the regression analysis:

Cold region;

Traditional : $T_i = 0.35T_o+10.76$ (n = 1008, $R^2 = 0.34$, S.E. = 0.015, $p<0.001$) (3.7)

Modern : $T_i = 0.25T_o+11.53$ (n = 1008, $R^2 = 0.38$, S.E. = 0.010, $p<0.001$) (3.8)

Temperate region;

Traditional : $T_i = 0.37T_o+16.32$ (n = 4464, $R^2 = 0.63$, S.E. = 0.004, $p<0.001$) (3.9)

Modern : $T_i = 0.75T_o+8.76$ (n = 4464, $R^2 = 0.75$, S.E. = 0.007, $p<0.001$) (3.10)

Sub-tropical region;

Traditional : $T_i = 0.45T_o+15.34$ (n = 4464, $R^2 = 0.74$, S.E. = 0.004, $p<0.001$) (3.11)

Modern : $T_i = 0.69T_o+10.54$ (n = 4464, $R^2 = 0.74$, S.E. = 0.006, $p<0.001$) (3.12)

Figure 3.16 shows the relationship between measured indoor and outdoor air temperature in both traditional and modern houses in cold region. There are 2016 plots from both traditional and modern houses. As expected in general, the higher the outdoor air temperature, the higher the indoor air temperature will be. The regression coefficient (the slope of the line) of traditional house is slightly bigger than that of modern house shown in equations 3.7 and 3.8. This is due, highly probable, to the heat-capacity of the materials used in the houses. Within the range of outdoor air temperature between 11 °C and 23 °C, there are data points for both traditional and modern houses. According to the regression lines shown in the Figure 3.16, indoor air temperature (T_i) becomes 18.5 °C for traditional house and 17.03 °C for modern house, when assuming the outdoor air temperature 22 °C; that is the difference of indoor air temperature ΔT_i is 1.5 °C. This means that the traditional house is 1.5 °C warmer than that of the modern house in cold region in summer.

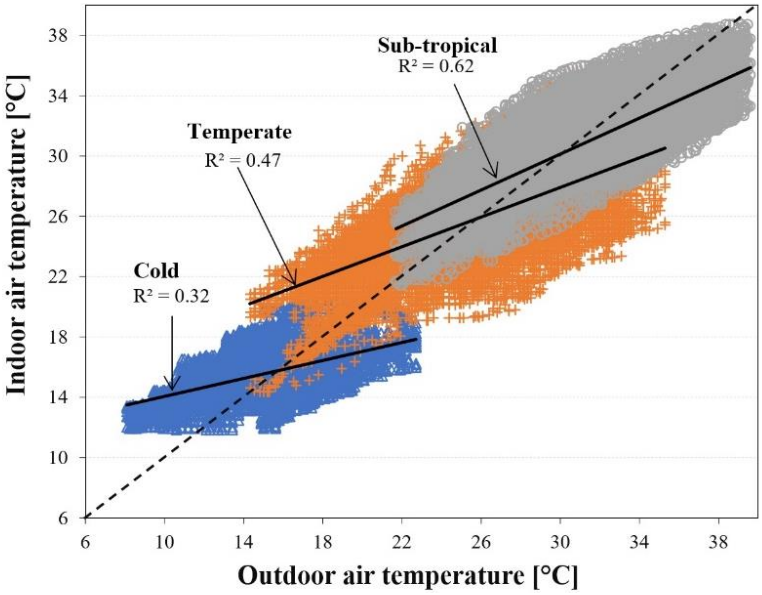


Figure 3.15 Relationship between indoor and outdoor air temperature in summer.

Figure 3.17 shows the relationship between measured indoor and outdoor air temperature in both traditional and modern house in temperate region. There are 8928 plots from both traditional and modern houses. Within the range of outdoor air temperatures between 14 °C and 35 °C, there are data points for both houses, traditional and modern in temperate region. According to the regression lines shown in equations 3.9 and 3.10, indoor air temperature (T_i) becomes, 28.5 °C for traditional house and 33.5 °C for modern house, when assuming the outdoor air temperature is 33 °C; that is the difference of indoor air temperature (ΔT_i) is 5.0 °C. This means that the traditional house is 5.0 °C cooler than modern house in temperate climatic region.

Similarly, there are 8928 plots from both traditional and modern houses in sub-tropical climatic region. According to the regression lines shown in equations 3.11 and 3.12, the slope of regression line for traditional house is smaller than that of the modern house. This is due to the heat-capacity effect of materials used in the house. Within the range of outdoor air temperatures between 21.3 °C and 39.6 °C, there are data points for both houses, traditional and modern in Figure 3.18. Accordingly, indoor air temperature (T_i) becomes, 32.4 °C for traditional and 38.8 °C for modern, when assuming the outdoor air temperature is 38 °C; that is the difference of indoor air temperature (ΔT_i) is 4.4 °C. This means that the traditional house is 4.4 °C cooler than that of the modern house in sub-tropical climatic region. This indoor air temperature is higher than that of the international standard. The difference must be due to the effect of thermal mass of materials used. In conclusion, traditional houses are 4 °C to 5 °C cooler than that of the modern houses.

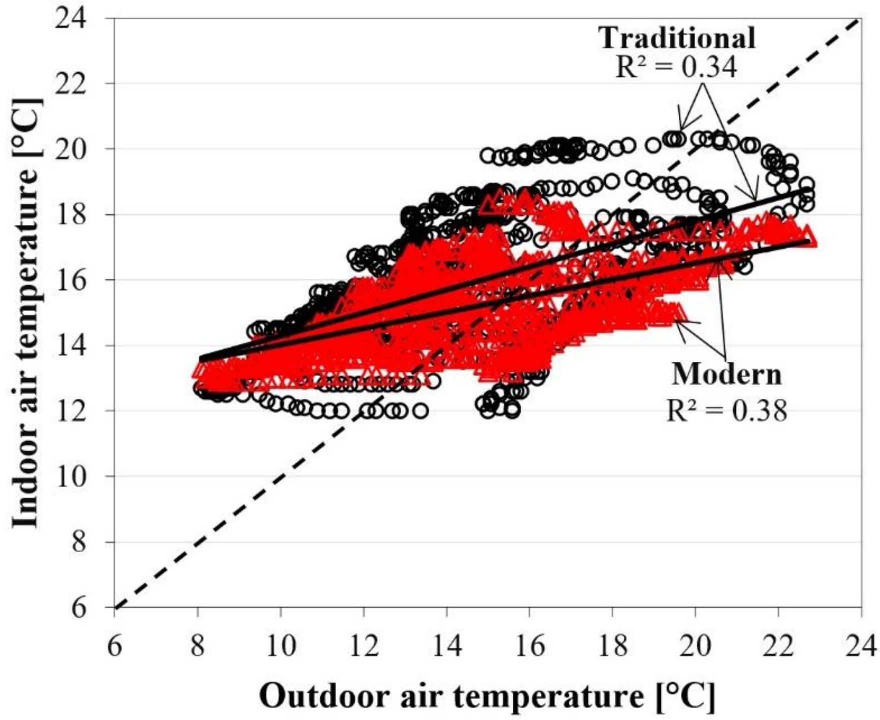


Figure 3.16 Relationship between indoor and outdoor air temperature of traditional and modern houses in cold region.

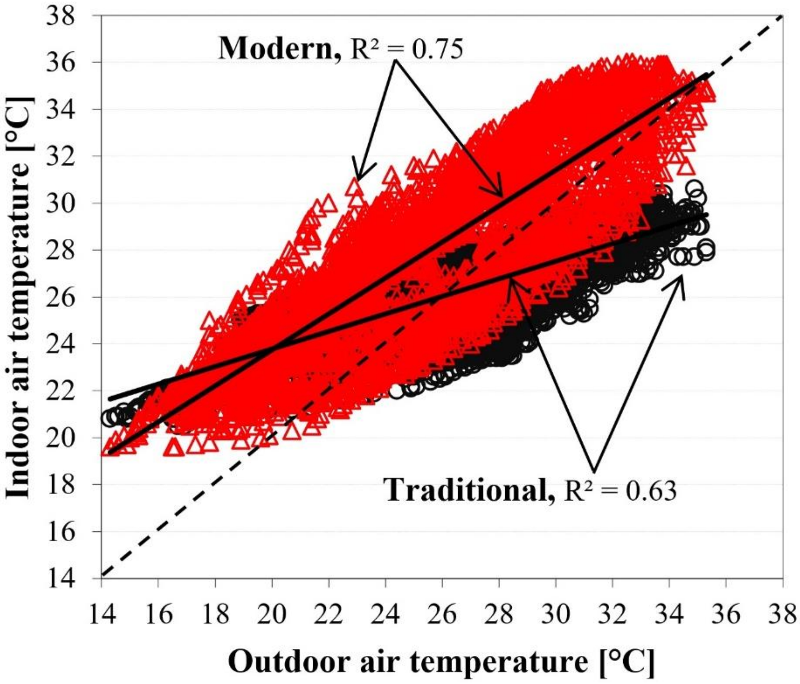


Figure 3.17 Relationship between indoor and outdoor air temperature of traditional and modern houses in temperate region.

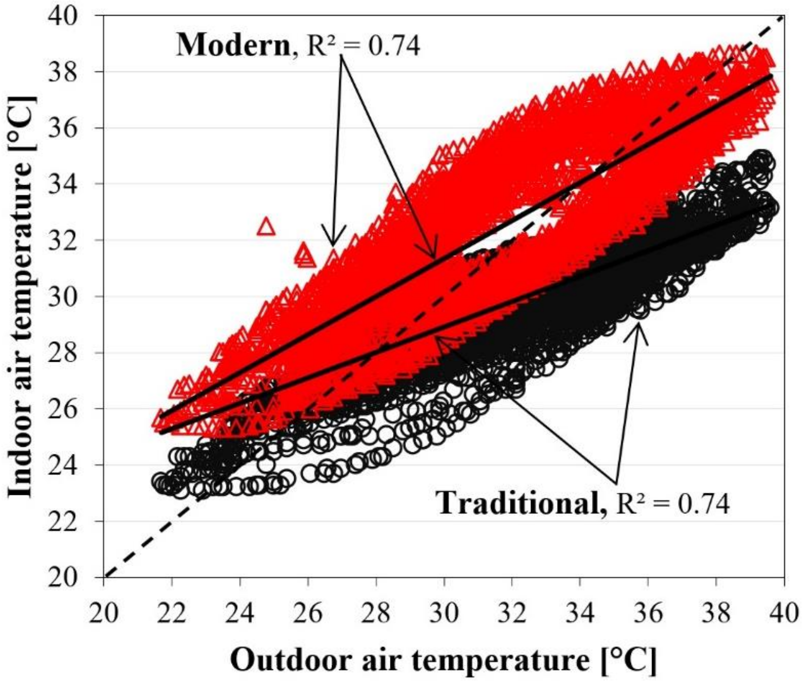


Figure 3.18 Relationship between indoor and outdoor air temperature of traditional and modern houses in sub-tropical region.

3.3.4 Relationship between relative humidity and temperature

In order to clarify the relationship between the indoor relative humidity and indoor air temperature, the regression analysis has been made. Figure 3.19 shows the relationship between the measured indoor relative humidity and indoor air temperature during the summer time. We have found the following regression equations for respective climatic regions.

Cold	$RH_i = -1.46T_i + 79.3$ (n = 6048, R^2 = 0.089, S.E. = 0.060, p<0.001)	(3.13)
Temperate	$RH_i = -1.78T_i + 97.4$ (n = 24784, R^2 = 0.053, S.E. = 0.046, p<0.001)	(3.14)
Sub-tropical	$RH_i = -2.49T_i + 133.1$ (n = 22320, R^2 = 0.332, S.E. = 0.024, p<0.001)	(3.15)

where, RH_i denotes the indoor relative humidity, T_i denotes the indoor air temperature, n denotes the number of data, S.E. denotes the standard error of the regression coefficient and p denotes the significance level of the regression coefficient.

As it is seen in Figure 3.19, the indoor relative humidity is negatively correlated with indoor air temperature. The coefficient of determination of sub-tropical region is much higher than that of cold and temperate regions. There is a tendency for indoor relative humidity to be lower as the indoor air temperature increases. Within the range of indoor air temperature between 14.0 °C and 21.0 °C, there are both the data plots for cold and temperate regions. According to the regression lines shown in equations 3.13 and 3.14, relative humidity (RH_i) becomes 53% for cold region and 65% for temperate region, when assuming the indoor air temperature being 18 °C; that is, the regional difference of indoor relative humidity (ΔRH_i) is 12%. Similarly, within the range of indoor air temperature between 21 °C and 35 °C, there are both the data plots for temperate and sub-tropical regions. According to the regression line shown in equations 3.14 and 3.15, RH_i becomes 48% for temperate region and 63% for sub-tropical region, assuming the indoor air temperature being 28.0 °C; that is, the regional difference of indoor relative humidity (ΔRH_i) is 15%. However, it is difficult to understand the level of thermal environment by observing the relative humidity only concluded by Ogawa (1999). So, we tried to observe the amount of water vapor concentration of the houses in three climatic regions.

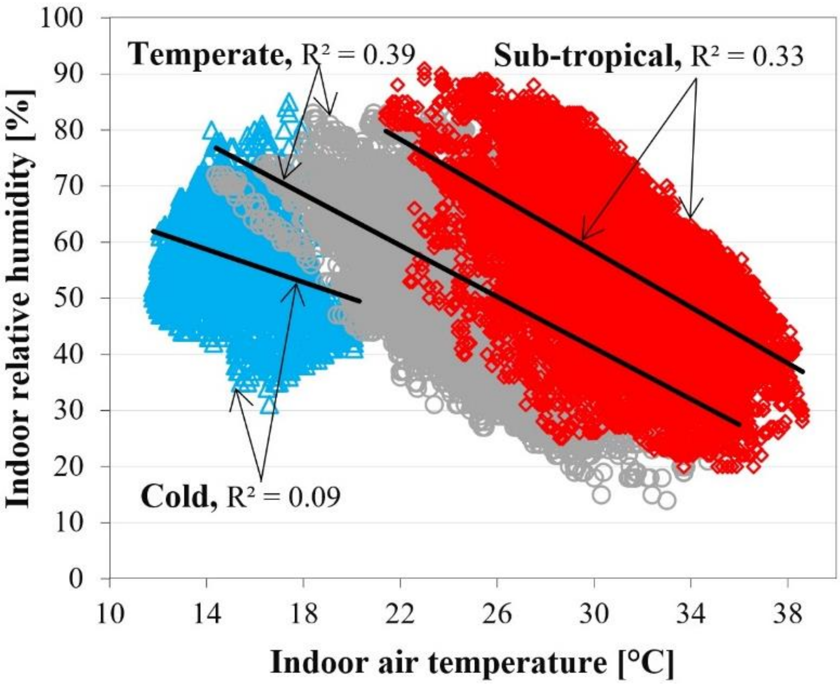


Figure 3.19 Relationship between indoor relative humidity and indoor air temperature.

3.3.5 Summer water vapor concentration

Based on the measured indoor and outdoor air temperature and relative humidity, we estimate the water vapor concentration values from the following equation given in the book of Bio-climatology for Built Environment by Shukuya (2019).

$$C_{wv} = 2.167 \times P_{wv}/T \quad (3.16)$$

where, C_{wv} denotes water vapor concentration (g/m^3), P_{wv} denotes water vapor pressure (Pa) and T denotes temperature in Kelvin scale (K).

Figure 3.20 shows the relationship between estimated indoor water vapor concentration and outdoor water vapor concentrations of the investigated houses in three climatic regions in summer. There are 6048 plots for cold region, 22320 for temperate region, and 22320 plots for sub-tropical region. The linear regression equations for cold, temperate, and sub-tropical regions are as follows.

Cold $C_{wvi} = 0.65C_{wvo}+3.04$ (n = 6048, $R^2 = 0.030$, S.E. = 0.013, $p<0.001$) (3.17)

Temperate $C_{wvi} = 0.80C_{wvo}+2.19$ (n = 22320, $R^2 = 0.66$, S.E. = 0.004, $p<0.001$) (3.18)

Sub-tropical $C_{wvi} = 0.94C_{wvo}+0.48$ (n = 22320, $R^2 = 0.94$, S.E. = 0.030, $p<0.001$) (3.19)

where, C_{wvi} denotes indoor water vapor concentration and C_{wvo} denotes outdoor water vapor concentration.

The trend of indoor water vapor concentrations looks quite similar to outdoor water vapor concentrations in all investigated areas; low, middle and high in cold, temperate, and sub-tropical regions, respectively. The cross points of regression lines to diagonal line in respective regions are 9 g/m^3, 11 g/m^3, and 10 g/m^3 from cold to sub-tropical regions. The mean value of the indoor water vapor concentration is 6.7 g/m^3, 11.9 g/m^3, and 17.5 g/m^3 in cold, temperate, and sub-tropical regions, respectively. The regional difference in the summer mean indoor water vapor concentration is 4.5 g/m^3 between temperate and cold regions, 5.6 g/m^3 between sub-tropical and temperate regions, and 10.1 g/m^3 between sub-tropical and cold regions. These differences might be the effect of the lower indoor air temperature in the cold region and higher indoor air temperature in the sub-tropical region and another reason could be that the cold region (Mustang district) is very dry compared to other two regions.

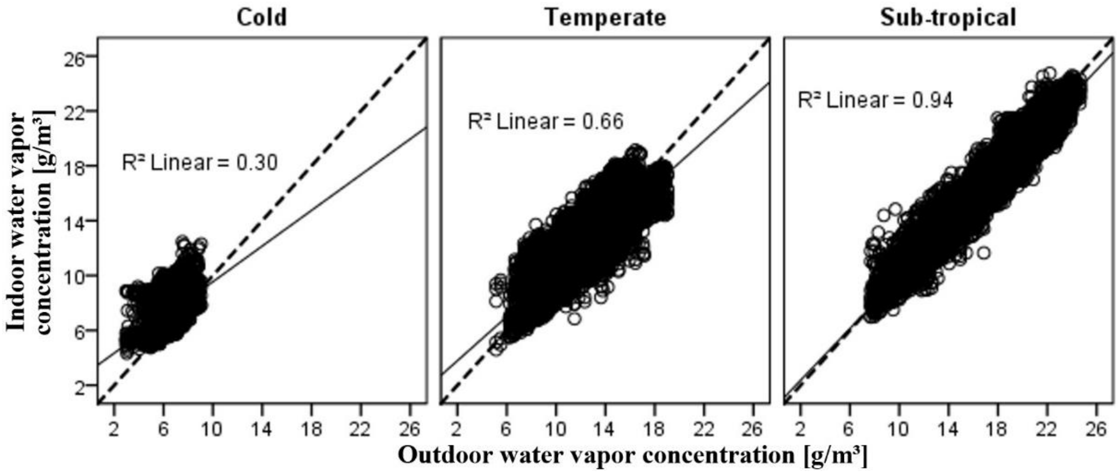


Figure 3.20 Relationship between indoor and outdoor water vapor concentration.

Figure 3.21 shows the relationship between the estimated indoor water vapor concentration and outdoor water vapor concentration in traditional and modern houses in cold region. The cross points of the regression lines to the diagonal in H1 (traditional house) is 8.5 g/m^3 but the position of the data point in H4 (modern house) is much higher than that of the diagonal line. Such tendency suggests that the indoor water vapor concentration of H4 is higher than of the H1. Figure 3.22 also shows the relationship between the estimated indoor water vapor concentration and outdoor water vapor concentration in traditional and modern houses in temperate region. The cross points of the regression lines to the diagonal in H7 (traditional house) and H10 (modern house) are 8.5 g/m^3 and 14 g/m^3. In H7 (traditional house), the indoor water vapor concentration is higher than outdoor water vapor concentration below 9 g/m^3, above 9 g/m^3 the outdoor water vapor concentration, the indoor water vapor concentration is lower than that of the outdoors and vice versa in H10 (modern house). Similarly, Figure 3.23 shows the relationship between indoor water vapor concentration and outdoor water vapor concentration in traditional and modern houses in sub-tropical region. In both, H13 and H16 houses, the indoor water vapor concentration is almost similar.

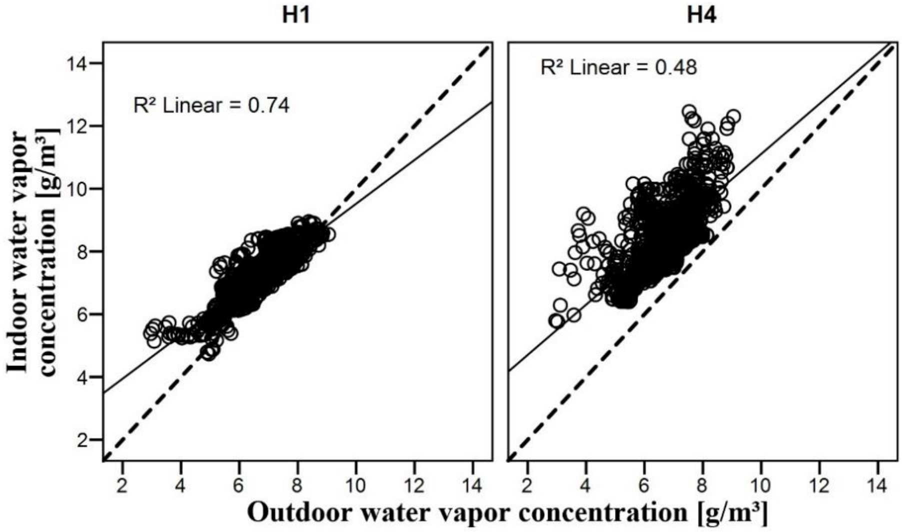


Figure 3.21 Relationship between indoor and outdoor water vapor concentration of traditional and modern houses in cold region.

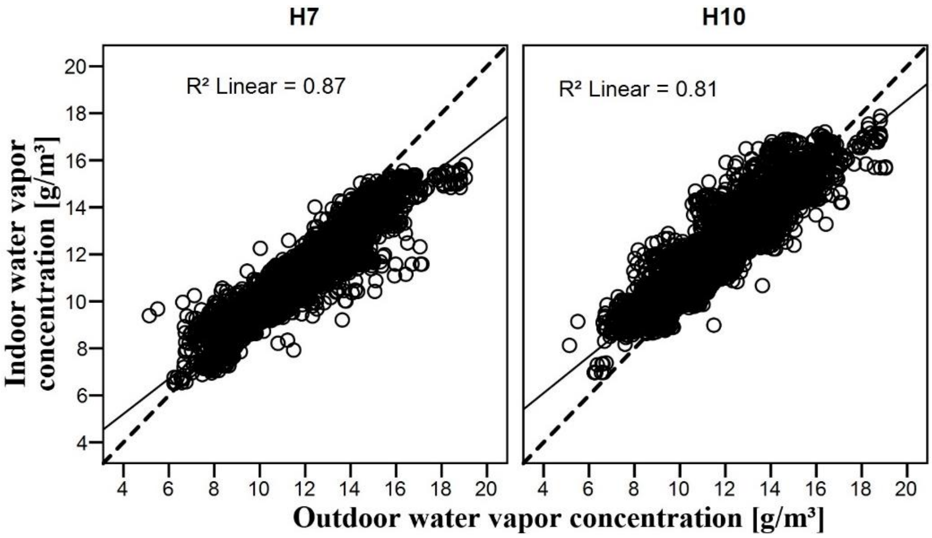


Figure 3.22 Relationship between indoor and outdoor water vapor concentration of traditional and modern houses in temperate region.

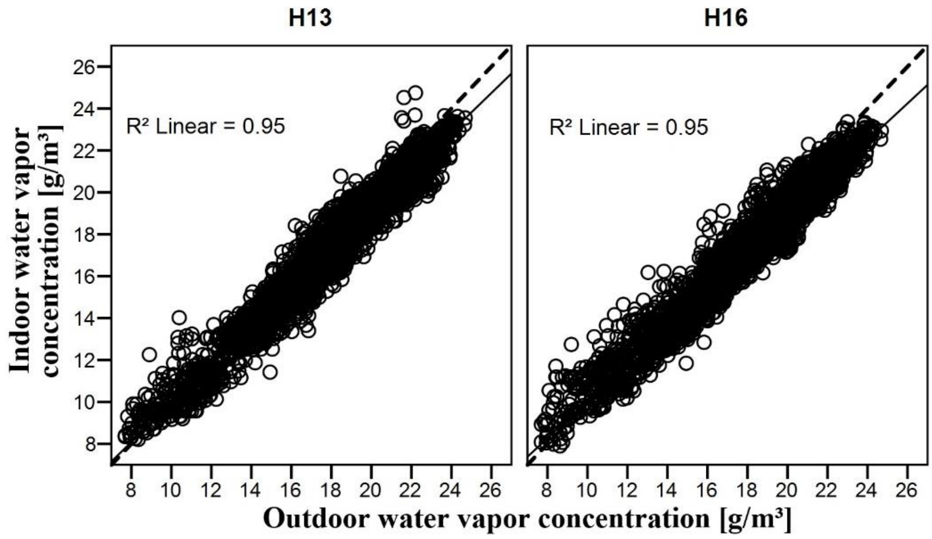


Figure 3.23 Relationship between indoor and outdoor water vapor concentration of traditional and modern houses in sub-tropical region.

3.4 Conclusions

A series of surveys on indoor thermal environment were conducted so far in three climatic regions: cold, temperate, and sub-tropical regions in winter and summer seasons. Continuous measurement of thermal environment was performed for a month from December 3rd 2016 to January 3rd 2017, for winter and April 18th to May 17th 2019, for summer. Indoor air temperature, outdoor air temperature, indoor globe temperature, indoor relative humidity and outdoor relative humidity were measured in respective regions. Sensors with digital data loggers at the interval of 10 minutes were used. From the study, we have come up with the following results:

1. The indoor air temperature for all investigated houses is highly affected by outdoor air temperature.
2. Among all three climatic regions; the range of outdoor air temperature is narrower in cold region than that of the temperate and sub-tropical regions in both seasons.
3. The mean indoor air temperature in winter is 10.9 °C, 15.4 °C and 18.4 °C in cold, temperate, and sub-tropical regions, respectively. However, the mean indoor air temperature in summer is 15.6 °C, 25.7 °C and 29.9 °C in cold, temperate, and sub-tropical regions, respectively. The cause of this in indoor air temperature could be due to the size of the windows, wall thickness and heat capacity of the materials used.
4. The seasonal differences of mean indoor air temperature are 4.7 °C, 10.3 °C, and 11.5 °C in

cold, temperate, and sub-tropical regions, respectively.

5. The regional differences between indoor air temperature (ΔT_i) for temperate and cold regions is 8.8 °C in summer.
6. Similarly, the regional differences between indoor air temperature (ΔT_i) for sub-tropical and temperate climate is 3.1 °C in summer.
7. However, the regional differences between indoor air temperature (ΔT_i) for sub-tropical and cold regions is 11.5 °C in summer, which is far different than that of other two regions. This is the reason that of differences in elevations.
8. In the winter, 80% cumulative frequency of indoor air temperature is 11 °C, 16 °C, and 22 °C in cold, temperate, and sub-tropical regions, respectively.
9. In the temperate climatic region, it has been found 80% of the time below 16.5 °C and 18.2 °C in H1 (traditional house) and H4 (modern house). However, 80% of the time below 22.8 °C and 21.0 °C in H13 and H16 has been noted. It is concluded that the indoor air temperature is not only depend into outdoor air temperature but also depend on thickness of the walls, materials used in houses, and size of the windows.
10. Compare to modern houses, the traditional houses were 3.8 °C, and 2.5 °C cooler in temperate and sub-tropical regions in summer but not vice-versa in cold region because still cold region has low indoor air temperature, this means traditional house is better than modern house in cold region.
11. The indoor water vapor concentration looks quite similar to outdoor water vapor concentrations in all investigated areas.
12. The mean indoor water vapor concentration is low in cold (7.4 g/m^3), middle in temperate (11.9 g/m^3), and high in sub-tropical (17.5 g/m^3) regions, respectively.
13. The regional difference in the summer mean indoor water vapor concentration is 4.5 g/m^3 between temperate and cold regions, 5.6 g/m^3 between sub-tropical and temperate regions, and 10.1 g/m^3 between sub-tropical and cold regions. These differences may be due to the effect of the lower indoor air temperature in the cold region and higher indoor air temperature in the sub-tropical region.

Chapter 4: Thermal comfort of the residents

4.1 Introduction

Nepal is a landlocked country, with geographic variations which have led to the local people developing a range of unique cultures. The type of housing and clothing as a part of local culture has been influenced by the differences in geographic variation. Traditional construction skills, one of whose objectives is to mitigate indoor thermal conditions, have been continued from one generation to another for a long period of time with almost no modification. However, they are now being replaced by contemporary construction methods such as modern designs and technology including artificial materials (Rijal et al., 2010). Every year new houses are being built in Nepal as a part of urbanization and modernization. Under these circumstances, it is important to know the state of thermal comfort as experienced by Nepalese people living in traditional houses. Although the surrounding countries, India and Pakistan, have their own thermal comfort standards BIS (2005) and ENERCON (1990), the Nepalese government has not yet established any such thermal comfort standard. This study may encourage and direct the Nepalese government to establish a thermal comfort standard and make rational policy and plans for the future.

To preserve traditional construction technology, it is important to make such a policy that traditional technology can be improved with modern skills without diminishing cultural norms, by looking at the positive aspects of traditional houses that should be preserved and inherited for the future. One aspect which can be improved while keeping traditional skills is to provide better thermal comfort. For this purpose, we need to know how the people living in different climatic regions of Nepal achieve thermal comfort in their respective traditional houses by taking various adaptive behaviours such as clothing adjustment.

We have already discussed schematic relationship between building environment technology and types of human physical behaviour are in horizontal axis, vertical axis, conventional path, and in proposed path for developing country, proposed path for developed country in the beginning of chapter 1 in section 1.1, and in Figure 1.4. The Figure 4.1 shows schematic relationship between types of human physical behaviour and the types of the building environment technology in the cold, temperate and sub-tropical regions. The horizontal axis represents the types of building technology and the vertical axis represents the types of human physical behaviour. The left side of the horizontal axis indicates that only basic passive technology is used, while the right side indicates that only active technology is used. The former suggests that when occupants are required to restore their thermal comfort, they do everything manually using muscular power; thus, they have a very active behaviour. The latter requires no manual activity or muscular power; it means that people rely on active technology for thermal comfort. In this diagram, the current conditions of traditional houses and occupant life style in the cold, temperate, and sub-tropical regions are positioned in the area "T". This is due to the difficulty in regulating and sustaining the indoor environmental conditions in old and poor buildings; thus, occupants need to take more thermal activity to avoid thermal discomfort. The area "T" are three circles with three dots points in the centre representing the condition of traditional houses, in cold, temperate and sub-tropical regions. As we mentioned in chapter 2; section 2.3, Table 2.3 presented the number and the percentage of traditional and modern houses in cold, temperate, and sub-tropical regions. There are 95.4%, 86.8% and 74.8% of the traditional houses built in cold, temperate, and sub-tropical regions, respectively. The traditional houses in cold region are in passive building envelopment system and people are required to restore their thermal comfort with active behaviour. But the result is quite opposite in the sub-tropical region. More than 25% of the houses use active mechanical system and less active human physical behaviour for their thermal comfort in the sub-tropical regions is required. This mean that, the active systems may provide the occupants with not much opportunities for adjusting the thermal environment; on the other hand, the passive systems do require too many actions in order to achieve comfort (Shukuya, 2013).

There are many field studies, for example, de Dear et al. (2002), Indraganti (2010), Nicol et al. (1996, 2012), Thapa et al. (2018), and Wang (2006) regarding thermal comfort. However, current international thermal comfort standards do not represent people living in different types of buildings, especially in traditional dwellings (Xu et al., 2018). The climatic variations, living conditions and building structures in Nepal are different from those examined in previous studies, although there are a few thermal comfort surveys conducted in specific places of Nepal, for example, the study of Rijal et al. (2010, 2019), Thapa et al. (2018). Rijal et al. (2010, 2019) conducted a thermal comfort survey in six districts of Nepal with different climates. They conducted a thermal comfort survey by gathering respondents in various houses at 1-h intervals. It is unknown how it works, if we conduct the survey in many houses. Thapa et al. (2018) also conducted a thermal comfort survey, but it was related to temporary shelters after the 2015 earthquake.

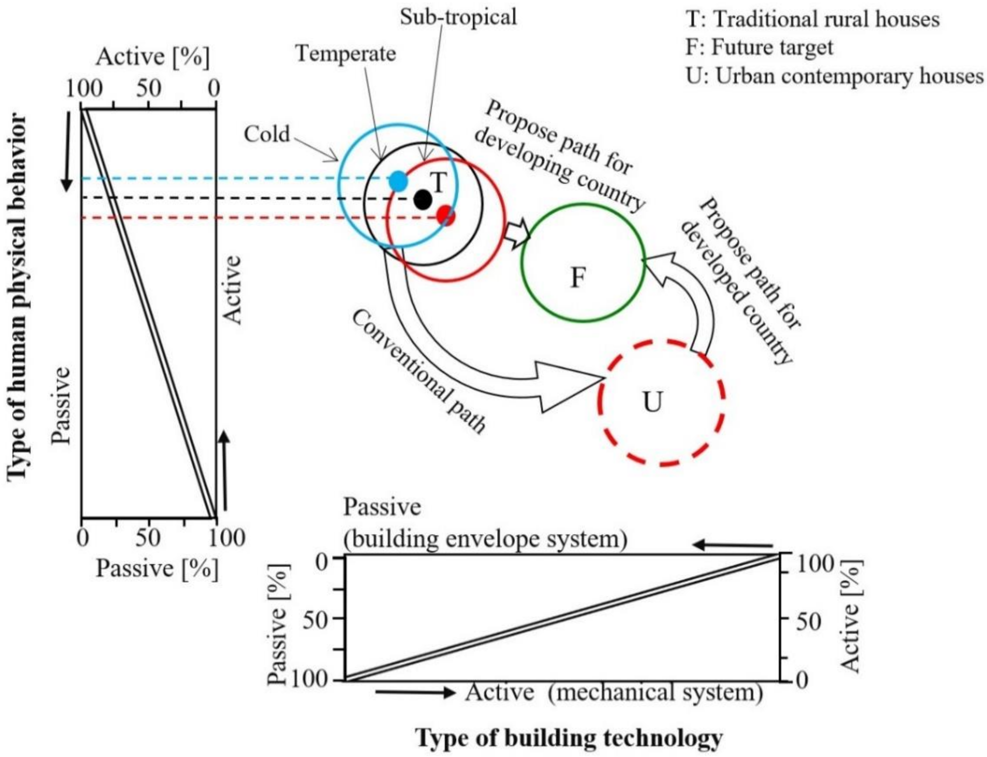


Figure 4.1 Schematic diagram of human physical behavior and types of the building technology.

Thermal comfort studies based on field surveys are limited, so that it is necessary to find out more about the adaptive thermal comfort of people living in traditional dwellings. Our study was conducted in three different climatic regions, particularly focusing on traditional houses and their comfort temperature. This study aimed at clarifying quantitatively how people sustain their thermal comfort during winter in traditional houses through their choice of clothing, on the basis of data collected in a series of field surveys. Putting on or removing clothing is one of the immediate adaptive behaviours that people usually take to restore their thermal comfort conditions. The study of Watanabe et al. (2013). Humphreys and Nicol (1998), and KC et al. (2018) indicated that people take a variety of behaviours such as opening windows, using fans and changing clothes to restore their thermal comfort. Rijal et al. (2010) also indicated that Nepalese people take hot drinks and burn firewood in winter for thermal comfort. People are free to adjust their clothing at home without limitations. Changing clothing insulation is the most immediate adaptation for thermal comfort adjustment. In particular, people wear heavily insulated clothing (1.2~2.7 clo) in winter for thermal adaption (Yu et al., 2017). In the studied areas too, we noted it as a significant means of restoring thermal comfort. Thus, we focus on the comfort temperature, preferred temperature and clothing insulation level estimated from the survey data obtained from people living in traditional houses in three climatic regions of Nepal.

4.2 Winter thermal comfort during voting time

We have, first, presented the indoor thermal environment measured during the voting time and the perception of the people as well as comfort temperature and preferred temperature estimated from the votes given by them in three climatic regions. Then, we have discussed the clothing insulation value and its relation to preferred temperature in the three climatic regions.

4.2.1 Thermal conditions of the investigated houses

Despite differences in languages, cultures, religions, and festivals between different castes, the people living in similar or different types of houses not only have similar but also different climatic conditions. Figure 4.2 shows the range of measured indoor air temperature (T_i), globe temperature (T_g), estimated mean radiant temperature (T_{mrt}), and operative temperature (T_{op}) with measured outdoor air temperatures during the voting time (T_o) by using the method of box-plotting. The daily mean indoor air temperature ranged in cold, temperate, and sub-tropical regions, from 9.4 to 15.4 °C, 11.8 to 22.8 ºC, and 18.0 to 25.1 ºC, respectively. This was similar to the values observed in Nepalese traditional houses in winter (i.e., in the study of Rijal, 2018) and also those observed in the central southern part of China by Han et al. (2007). The mean indoor air temperature is close to the indoor globe temperature, operative temperature, and mean radiant temperature in respective climatic regions of the respondents' houses, and thus we used globe temperature for further analysis. The measured indoor globe temperatures at 25% and 75% within the ascending order from the lowest value in the houses of cold region corresponded

11.1 °C and 13.8 °C, temperate region corresponded 15.7 °C and 17.4 °C, and sub-tropical region corresponded 21.2 °C and 23.6 °C, respectively. A few circles point in the figure is outliers. The fluctuating range of indoor globe temperature in the houses of sub-tropical climatic region exceeds than in the houses of cold and temperate climatic regions. The differences can be due to the size of the windows, wall thickness, and heat capacity of the materials used in the houses.

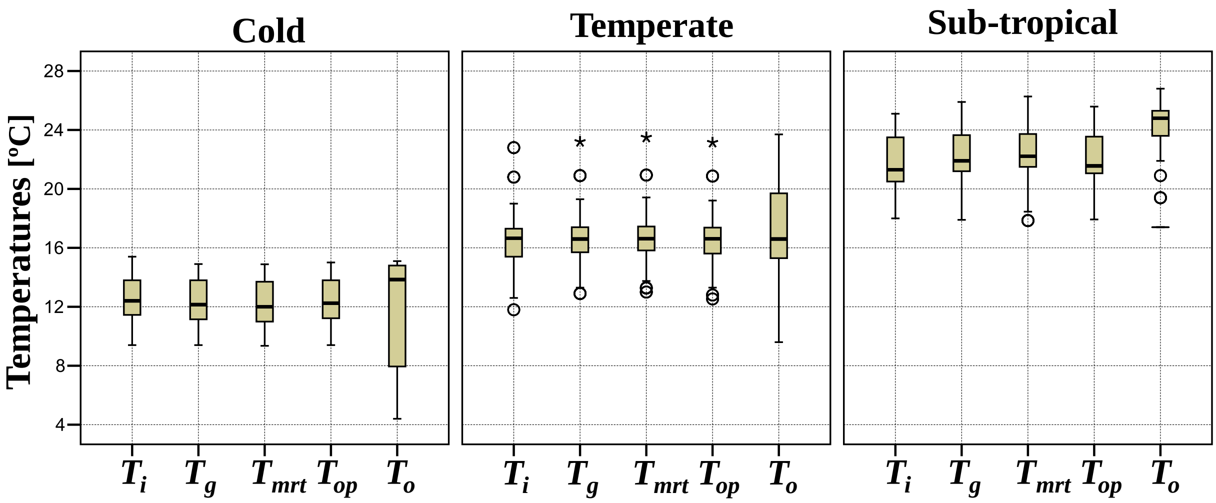


Figure 4.2 Temperature measured in the houses of cold, temperate, and sub-tropical regions (lower edge of box denotes 25% from the lowest temperature and upper edge denotes 75% from the lowest temperature).

The indoor relative humidity was recommended as 40 ~ 70% by Ogawa (1999). Table 4.1 shows the range of measured indoor and outdoor relative humidity, and air movement during the voting time. Due to naturally ventilated rooms, the indoor relative humidity was similar to that of outdoors, and thus in all regions, the people were considered as exposed to similar humidity conditions. The maximum indoor air movement was 0.14 m/s during the voting time. More than 92% votes were collected below 0.12 m/s of air movement.

Table 4.1 Descriptive statistics of relative humidity and air movement in cold, temperate, and sub-tropical regions

Climates	No. of respondents	Items	RH_i (%)	RH_o (%)	V_i (m/s)
Cold	60	Mean	25	21	0.05
		S.D.	6	4	0.03
Temperate	90	Mean	59	59	0.04
		S.D.	7	14	0.03
Sub-tropical	135	Mean	60	53	0.03
		S.D.	8	8	0.01

4.2.2 Relationship between operative temperature and globe temperature

The mean radiant temperature, T_{mrt} [°C] and operative temperature, T_{op} [°C] are estimated by using equations (2.1) to (2.3) from a formula given in Persons (2003). Figure 4.3 shows the relationship between operative temperature and indoor globe temperature. The operative temperature and globe temperature are very well correlated in this series of survey. Nicol and Roaf (1996), Singh et al. (2017) and Humphreys et al. (2013, 2016) used the globe temperature as a thermal comfort indicator. Therefore, we also used the globe temperature to evaluate the thermal comfort in this study because it includes both the effects of radiation and convection in the houses.

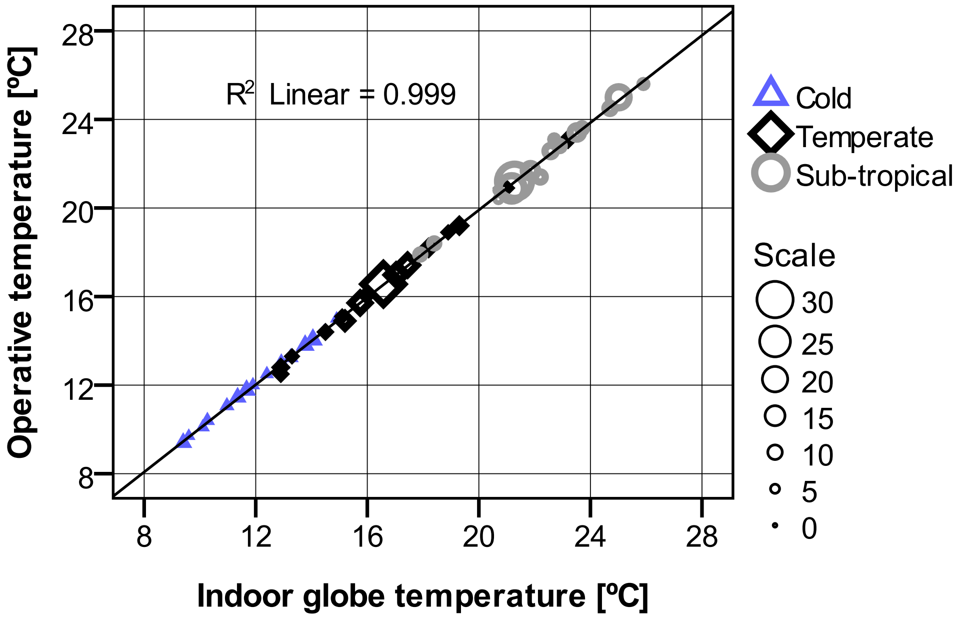


Figure 4.3 Relationship between operative temperature and indoor globe temperature.

4.2.3 Relationship between indoor globe and outdoor air temperature

Figure 4.4 shows the relationship between the measured indoor globe temperature and outdoor air temperature at the time of voting. There are 285 plots from all three regions which is exposed in Table 2.7. As expected in general, a higher outdoor air temperature also results in a higher indoor globe temperature. For this relationship, we have found the following equations:

Cold: $T_g = 0.33T_o + 8.8$ (n= 60, R^2= 0.63, S.E.= 0.03, $p<0.001$, $4.4 \leq T_o \leq 15.1$) (4.1)

Temperate: $T_g = 0.47T_o + 9.1$ (n= 85, R^2= 0.66, S.E.= 0.04, $p<0.001$, $9.6 \leq T_o \leq 23.7$) (4.2)

Sub-tropical: $T_g = 0.59T_o + 7.9$ (n= 130, R^2= 0.40, S.E.= 0.06, $p<0.001$, $17.4 \leq T_o \leq 26.8$) (4.3) where T_o denotes the outdoor air temperature, n denotes the number of data points, R^2 denotes the coefficient of determination, S.E. denotes the standard error of the regression coefficient, and p denotes the significance level of the regression coefficient.

The indoor globe temperature is moderately correlated (r = 0.63~0.81) with outdoor air temperature in all three regions. The values of the correlation coefficient are higher than those of mentioned in previous studies by Shing et al. (2017), Ioannou et al. (2018), KC et al. (2019), Toe and Kubota (2013) and Imagawa et al. (2016). Many factors affect the field survey data and it is not possible to eliminate all the noise effects (Nicol et al., 2012). Thus, the correlation coefficients obtained from the field survey data are usually lower than those obtained from climate chamber studies (Garcia et al., 2019). The slope of the regression line for the cold region is rather flat than those of the other two regions. This is likely to be due to the heat-capacity effect of the houses, which have thick walls in the cold region. In the cold region, the houses are made of stones and mud with thick walls (60 cm.), but in the sub-tropical region, the houses are made of wood with thin walls (2.5 cm.) as it is seen in Figure 2.7. Comparing to the previous studies by Rijal et al. (2010), Nicol et al. (1996), and Thapa et al. (2018), the indoor air temperature in this study is the lowest at high altitude.

Within the range of outdoor air temperature between 10 ºC and 16 ºC, there are data points for both the cold and temperate regions. According to the regression lines displayed above, T_g is 13.8 ºC for the cold region and 16.2 ºC for the temperate region, when assuming the outdoor air temperature is 15 ºC; that is, the regional difference of the indoor globe temperate (ΔT_g) is 2.4 ºC. Similarly, within the range of outdoor air temperatures between 17 ºC and 23 ºC, there are data points for both temperate and sub-tropical regions. According to the regression lines, T_g is 19.4 ºC for the temperate region and 20.9 ºC for the sub-tropical region, when assuming the outdoor air temperature is 22 ºC. Thus, the regional difference of the indoor globe temperature (ΔT_g) is 1.5 ºC. These tendencies are similar to findings of previous study by de Dear et al. (1997). In the same way, the study of Rijal et al. (2010) found that the indoor temperature has large seasonal and regional differences, and Nicol and Roaf (1996) also found that the temperature is different depending on the climate.

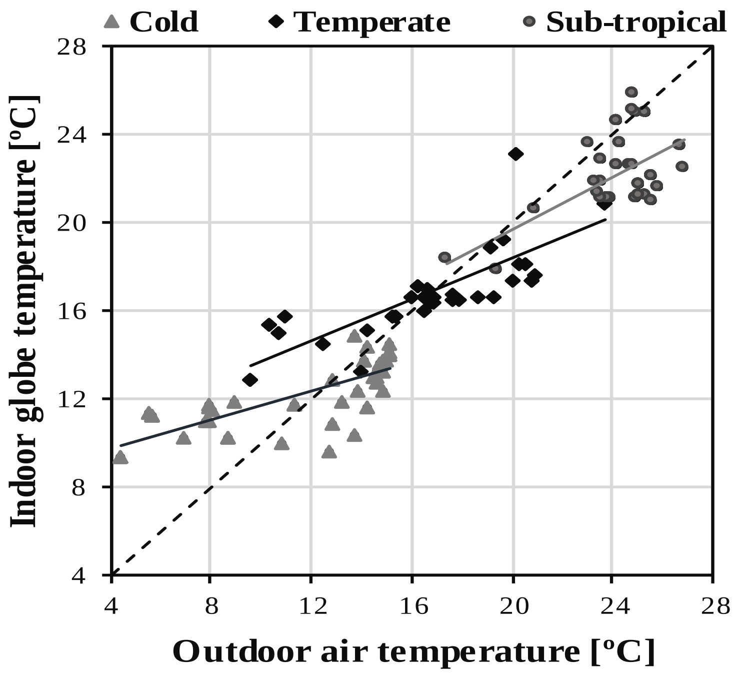


Figure 4.4 Relationship between indoor globe and outdoor air temperature.

4.2.4 Relationship between indoor air and mean radiant temperature

To identify the differences in the thermal characteristics between houses in the three climatic regions, the relationship between the calculated mean radiant temperature and the measured indoor air temperature was established. Figure 4.5 shows that in the cold region, the mean radiant temperature tends to be lower than the indoor air temperature, particularly when the value of the indoor air temperature is lower than 14.9 ºC. This is likely happened because outdoor radiant and air temperature is low and that the thick building walls are thermally well conductive. Further, it is likely that the effect of the cold outdoor temperature dominates in the establishment of the indoor surface temperature. In the temperate region, the mean radiant temperature and indoor air temperature are quite similar to each other. In the sub-tropical region, the mean radiant temperature tends to be higher than the indoor air temperature, particularly when the indoor air temperature is lower than 26.8 ºC. This is probably because of solar radiation absorbed by the walls and roof, together with the light materials used. It is seen in Figure 2.6 (a).

In all the three regions, there is always some amount of internal heat generation which also affects the formation of mean radiant temperature. This effect is considered to be more significant in the sub-tropical region than in the cold region. The trend shown in Figure 4.5 is similar to the finding of Singh et al. (2017). For further analysis, we use the measured globe temperature as the representative value of the indoor thermal environment, since the effect of radiation alone is not discussed in detail in this study.

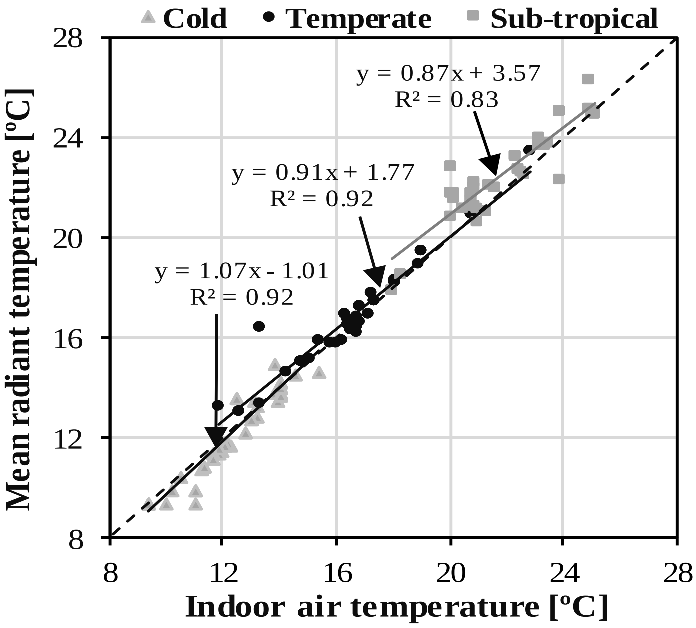


Figure 4.5 Relationship between mean radiant temperature and indoor air temperature.

4.3 Thermal sensation vote and thermal preference

Figure 4.6 (a) shows the frequency distribution of the thermal sensation votes obtained in the respective regions. We received the largest number of votes for "4. Neutral" in all regions. If the thermal sensation votes 3, 4 and 5 are grouped as "comfort zone" then 76.8% of the votes are in the "comfort zone" in the cold region, 82.6% in temperate and 84.7% in sub-tropical regions. The people seem to adapt to the given indoor environment in all three climatic regions. If we focus on the thermal sensation votes for "4. Neutral" alone, they comprise 40% of all votes in the cold region. This percentage is higher in other two regions as: 52.9% in temperate and 46.9% in sub-tropical regions. The number of votes from 1 to 3 are most numerous (58.3%) in cold region; this number is 19.5% and 16.0% more than the temperate and sub-tropical regions. This is probably due to indoor globe temperatures of lower than 10 °C occurring in the cold region, and such low values of globe temperature never occurring in temperate and sub-tropical regions.

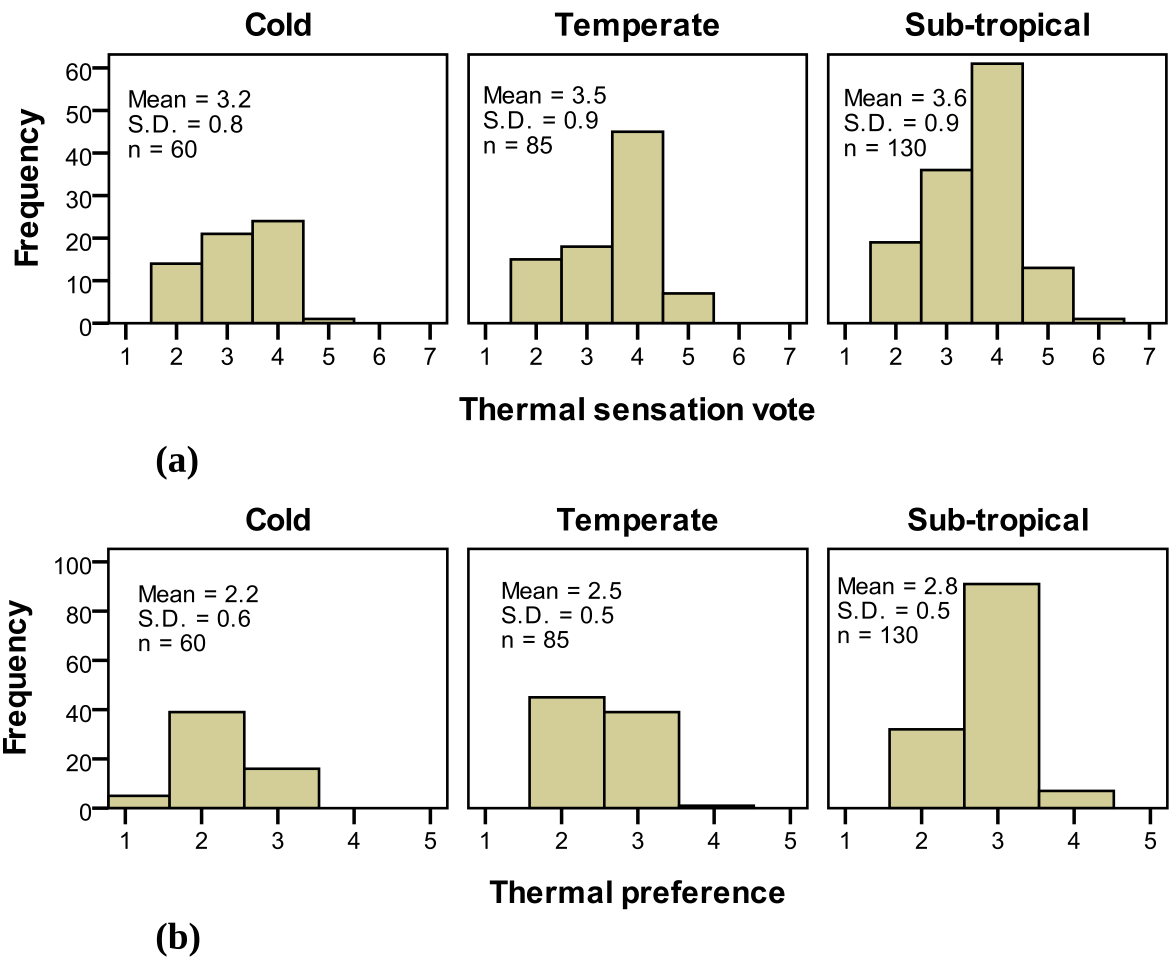


Figure 4.6 Frequency distribution of the votes of thermal sensation (a) and thermal preference (b).

Figure 4.6 (b) shows the frequency distribution of the thermal preference votes. We received the largest number of preferred votes “2. A bit warmer” in cold and temperate regions, which indicates that the occupants prefer to change their indoor environment to be perceived to be a little warmer. However, in the sub-tropical region we received the largest number of preferred votes for “3. No change”, indicating that the occupants are satisfied with their given indoor thermal environment. The relative number of votes corresponding to the two categories (vote “1. Much warmer” and “2. A bit warmer”) were 73.3% in the cold region, 52.9% in the temperate region and 24.6% in the sub-tropical region, respectively. Although, the largest number of mTSV votes are in the “4. Neutral” in all climatic regions as it is seen in Figure 4.6 (a), most of the respondents prefer a bit warmer in cold and temperate climatic regions. It can be concluded that the occupants experience cold indoor environments in their everyday life in winter in cold and temperate regions.

4.4 Comfort temperature and preferred temperature

4.4.1 Estimation of the comfort temperature by Griffiths' method

Based on the votes of thermal sensation and thermal preference, together with the corresponding values of the measured indoor globe temperature, we estimate the comfort temperature and the preferred temperature values from the equations (2.4 and 2.5), known as Griffith's method (Nicol et al., 2012; Humphreys et al., 2013; and Griffiths, 1990). It is necessary to think carefully that what value of Griffiths' constants is suitable for the 7-point thermal sensation scale. In applying the Griffiths' method, Nicol et al. (1994), and Humphreys et al. (2013), investigated the effect of using various values for constants a* (0.25, 0.33 and 0.50) to observe the change in comfort temperature.

Figure 4.7 shows the relationship between indoor air temperature when voting neutral and estimated indoor comfort temperature by Griffiths' method. The mean neutral temperature calculated using 0.50 constant is nearest to the mean indoor air temperature while voting neutral. Therefore, the comfort temperature calculated with Griffith's constant of 0.50 is assumed for the further analysis which is similar to the study of Humphreys et al. (2013). Based on the votes of thermal sensation and thermal preference, together with the corresponding values of the measured indoor globe temperature, we estimate the comfort temperature and the preferred temperature values from the equations (3.4 and 3.5), known as Griffith's method (Nicol et al., 2012; Humphreys et al., 2013; and Griffiths, 1990).

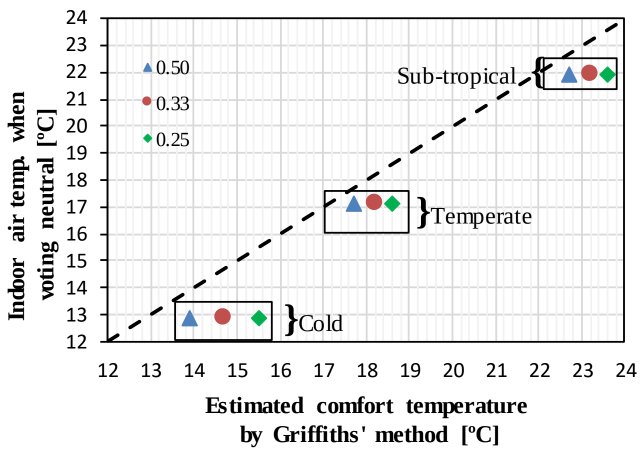
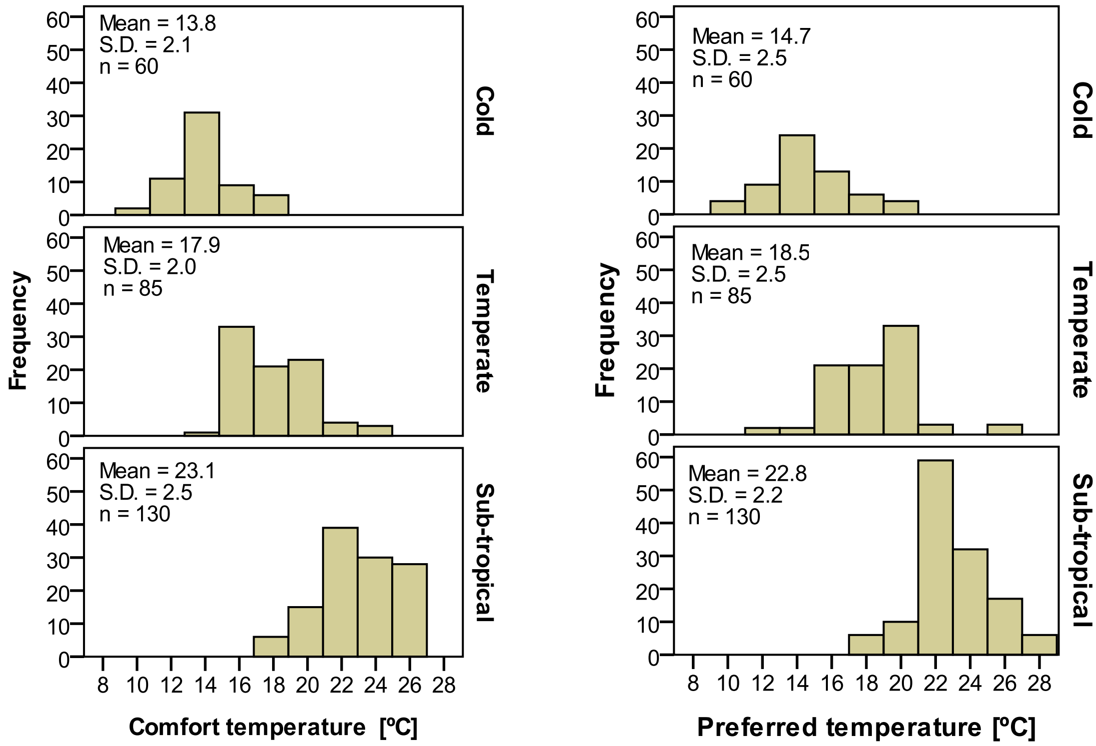


Figure 4.7 Relation between mean indoor air temperature while voting '4 Neutral' in thermal sensation vote and indoor comfort temperature by Griffiths' method.

4.4.2 Regional differences in comfort temperature

Figure 4.8 (a) shows the frequency distribution of the estimated comfort temperature in each climatic region. In the three investigated regions, the estimated mean comfort temperature is lowest in the cold region, middle in the temperate region and highest in the sub-tropical region. The mean value of the comfort temperature is 13.8 ºC, 17.9 ºC, and 23.1 ºC as indicated in the graph. The comfort temperature ranges from 10 ºC to 18 ºC in the cold region, from 15 ºC to 24 ºC in the temperate region and from 18 ºC to 26 ºC in the sub-tropical region. The regional difference in the winter comfort temperature (ΔT_c), is 4.1 ºC between the temperate and cold regions, 5.2 ºC between the sub-tropical and temperate regions and 9.3 ºC between the sub-tropical and cold regions. Nicol and Roaf (1996) found that the comfort temperature was lower at high altitude and higher at low altitude. Rijal (2010) found that the indoor neutral temperature is the highest in sub-tropical climate, moderate in temperate climate, and lowest in cold climate areas and also found a large seasonal difference in comfort temperature, from 3.5 °C to 13.8 ºC. These differences may be attributed to the difference in clothing insulation, as we will discuss later. The values of comfort temperature obtained here are found to be similar to those obtained in previous study of Humphreys et al. (2013).

As it can be seen in Figure 4.8 (b), the estimated mean preferred temperature is also the lowest in the cold region (14.7 ºC), middle in the temperate region (18.5 ºC) and the highest in the sub-tropical region (22.8 ºC). Considering the mean value of the comfort temperature and preferred temperature and their corresponding values of standard deviation (S.D.), the preferred temperature is quite close to the comfort temperature. This tendency is similar to that observed in previous studies by Griffiths (1990) and Hwang (2018). In all the three regions, the preferred temperature is higher than the comfort temperature. The difference between them is the largest at 0.9 ºC in the cold region compared with 0.6 ºC and 0.3 ºC in the other two regions. Although the largest number of respondents in cold and temperate regions voted in the scale of mTSV "4 Neutral", they wanted to shift the thermal environment to be 'a bit warmer'. The cold region investigated in this study was at an altitude of higher than 2700 m. The values of comfort temperature found in previous research by Rijal et al. (2010), Nicol and Roaf (1996, and Thapa et al. (2018) is similar to the finding of this study.



(a) **(b)**

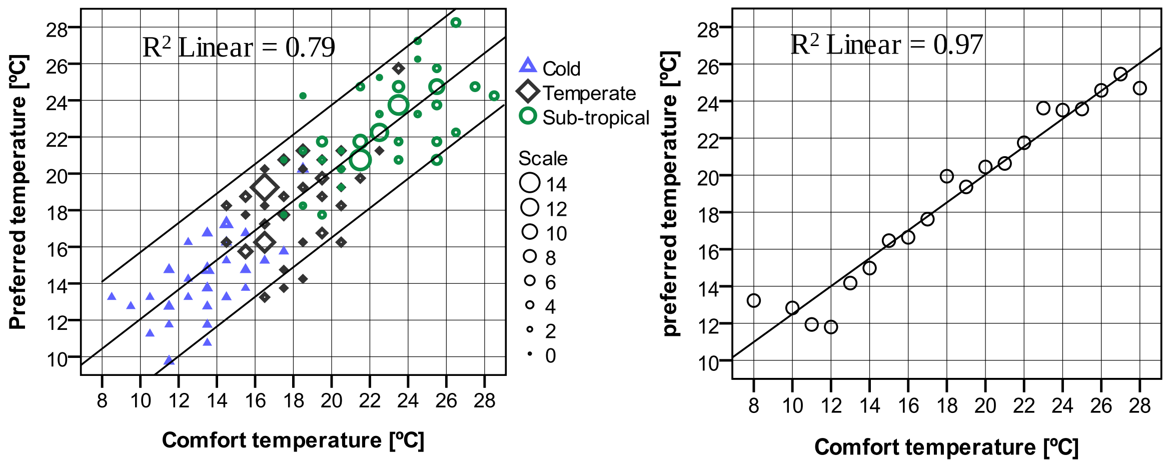
Figure 4.8 Frequency distribution of estimated comfort and preferred temperatures: (a) comfort temperature and (b) preferred temperature.

Figure 4.9 shows the relationship between the estimated comfort temperature and preferred temperature for raw data and binned data at 1 ºC intervals. To reveal trends in the scattered plots of the raw data, we have also analysed the binned data, as performed in previous studies, for example, in the study of Humphreys et al. (2016), de Dear et al. (2019), Xu et al. (2018), and Dili et al. (2011). We found the following equations from the regression analysis. We applied the weighted regression analysis for the binned data.

Raw data: $T_p = 0.81T_c+4.0$ (n = 275, $R^2 = 0.79$, S.E. = 0.03, $p<0.001$) (4.4)

Binned data: $T_p = 0.81T_c+4.0$ (n = 275, $R^2 = 0.97$, S.E. = 0.03, $p<0.001$) (4.5)

As expected, the coefficient of determination of the binned data is higher than the raw data. Interestingly, the slopes and constants of both equations are the same. Thus, it makes little difference with the method used to derive a regression line. Such a trend suggests that the respondents of the cold region in particular desire a warmer indoor environment condition in cases where the comfort temperature is low. Similar tendencies can be seen for the indoor temperature and cognitive temperature, which is the temperature value imagined by the respondents based on their respective indoor environmental conditions (Nagai et al., 2014). For indoor thermal environments with high temperatures during summer, there is a tendency for the cognitive temperature to be lower than the measured values of indoor temperature.



(a) (b)

Figure 4.9 Relationship between preferred temperature and comfort temperature: (a) raw data (95% of the data points are within the band) and (b) binned data.

4.5 Adaptive model

The relationship between comfort temperature and outdoor air temperature is called an adaptive model (Humphreys et al., 2016) which has been standardized in ASHRAE 55 (2013) and CEN 15251 (2007) by compiling the data sets provided for various seasons in various countries. Figure 4.10 (a) shows the relationship between the estimated comfort temperature and the measured outdoor air temperature. We have checked the regression model produced from the raw data with the regression model produced from the binned data of the temperatures at 2 ºC intervals as it is shown in Figure 4.10 (b). The number of raw data plots is the same as in Figure 4.3, that is, 285 plots from all three regions. The estimated comfort temperature is again lowest in the cold region, middle in the temperate region and high in the sub-tropical region. We have found the following equations from the two types of regression analysis. We applied the weighted linear regression analysis for the binned data.

Raw data: $T_c = 0.62T_o + 7.6$ (n = 275, $R^2 = 0.72$, S.E.= 0.02, $p<0.001$) (4.6)

Binned data: $T_c = 0.61T_o + 7.8$ (n = 275, $R^2 = 0.95$, S.E. = 0.04, $p<0.001$) (4.7)

The regression model shows a coefficient of determination of the binned data which is higher than the raw data. The slopes and constants of the raw data and binned data are very similar. The results indicate that both regression models are appropriate for evaluation of thermal comfort. However, the raw data is suitable to show the actual conditions of people in everyday life.

We have also compared the present result with the results derived in previous studies. Figure 4.11 shows equation (4.7) together with the lines from four sources i.e., Dhaka et al. 2015, Thapa et al. (2018), Nicol and Roaf (1996) and the ASHRAE standard (2002). Equation (4.7) obtained from the present study shows the lowest comfort temperature. This may be due to winter data and the inclusion of a cold region at high altitude in this study. The cross point of the regression line with the diagonal line in this study is at about 19 ºC, which is the lowest among the lines compared here. The steepness of the slope tends to become less for the range of data inclusive of higher outdoor air temperature. The most likely reason that the comfort temperature obtained in the present study is the lowest in the choice of clothing. The effect of clothing insulation is discussed in the following section.

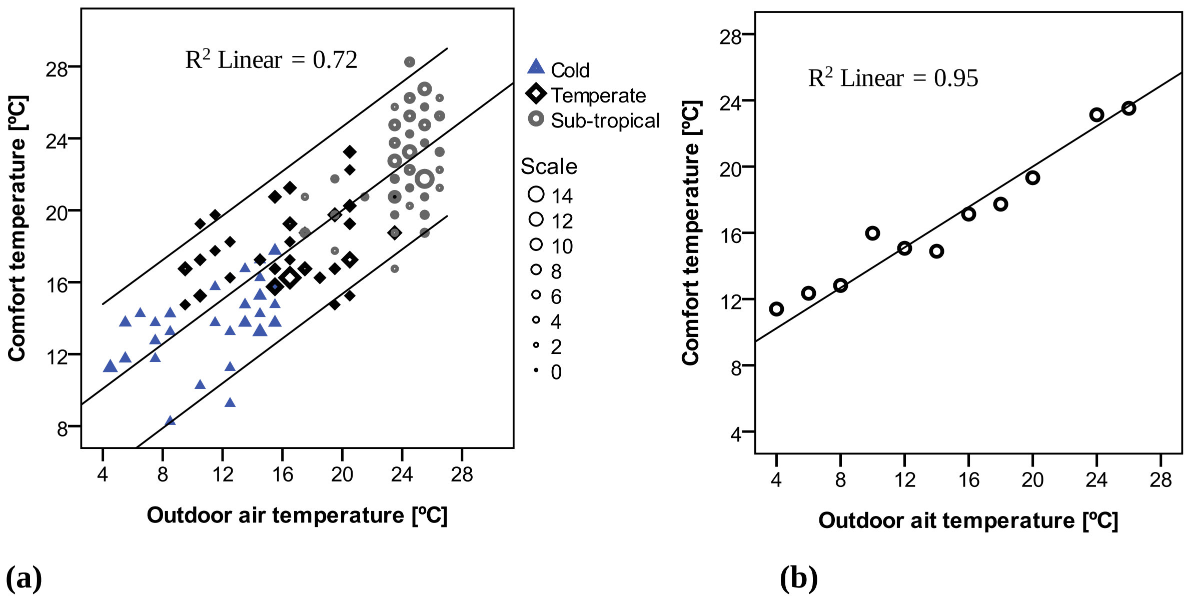


Figure 4.10 Relationship between the estimated comfort temperature and the measured outdoor air temperature: (a) raw data (95% of the data points are within the band) and (b) binned data.

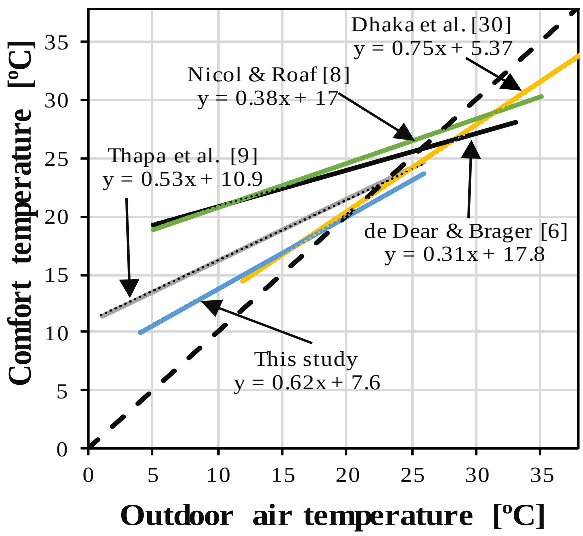


Figure 4.11 Comparison of adaptive model of this study in all with those of earlier studies.

4.6 Clothing insulation

We have natural tendency to adapt for varying circumstances in our environment. The natural tendency is expressed in the adaptive approach to thermal comfort. The comfort temperature is a result of the collaboration between the people and the buildings or with the other environment that they are inhabiting (Nicol and Humphreys, 2002).

Due to the climatic variations, differences in socio-culture life style in different regions and seasons in Nepal, people wear different types of clothing for their thermal comfort. In the cold climatic region, temperature is very low almost all the time of year. People wear thick and warm clothes for their thermal comfort. In the sub-tropical region, temperature is extremely hot or very high, and people wear thin and light clothes for their thermal comfort. In general, Nepalese women often wore traditional clothing such as saris, blouses, and Kurta-shawls, while Nepalese men especially young generation wore western-style clothing such as T-shirts, shirts, jackets, and trousers. The study of Rijal et al. (2010) reported that, in the cool climate, people wore layers of thick clothing and, until they went to bed, they wore shoes indoors in winter. In the sub-tropical climate, people wore light clothing and men often wore only shorts in summer.

4.6.1 Distribution of the clothing insulation

Clothing insulation directly affects the heat exchange between the human body and the surrounding environment. It plays a key role in obtaining personal thermal comfort of the respondents in different thermal environment. Therefore, clothing adjustment is an important behaviour in rural areas of Nepal. We took clothing value from ISC, 2003 which is given in Table 2.10. Figure 4.12 shows the mean clothing insulation with 95 % confidence interval for both genders. Figure 4.13 shows the frequency distribution of clothing insulation in respective regions. We observed high clothing values in the cold region, intermediate values in the temperate region and low values in the sub-tropical region, as expected. The mean clothing insulation is 1.63 clo in cold region, which is 0.31 clo and 0.48 clo higher than the temperate and sub-tropical regions, respectively. It is higher than the 1.38 clo founded by Jiao et al. (2017) in Shanghai, 0.90 clo in northeast India pointed by Thapa et al. (2018) and 0.77 clo in Korea founded by Yang et al. (2016). As presented in the previous section, the indoor globe temperature in the cold region was lower than the temperate and sub-tropical regions. Thus, it is reasonable that the respondents in the cold region have higher clothing insulation than temperate and sub-tropical respondents. The people do not wear less than 1 clo in cold region or more than 2 clo in the sub-tropical region. This trend is similar to the results of Rijal et al. (2010) in Nepal, Watanabe et al. (2013) in Japan, and Jiao et al. (2017) in China.

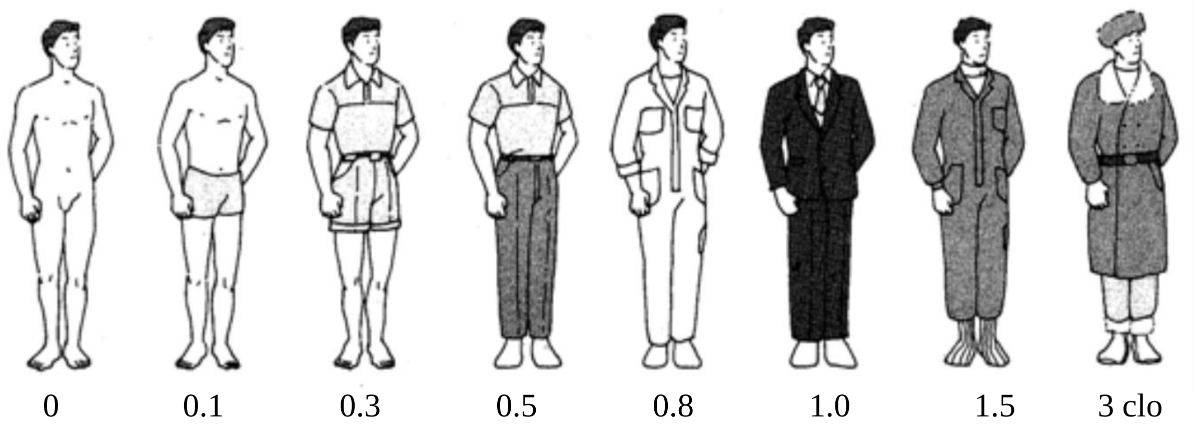


Figure 4.12 Clothing value (ISO, 2003).

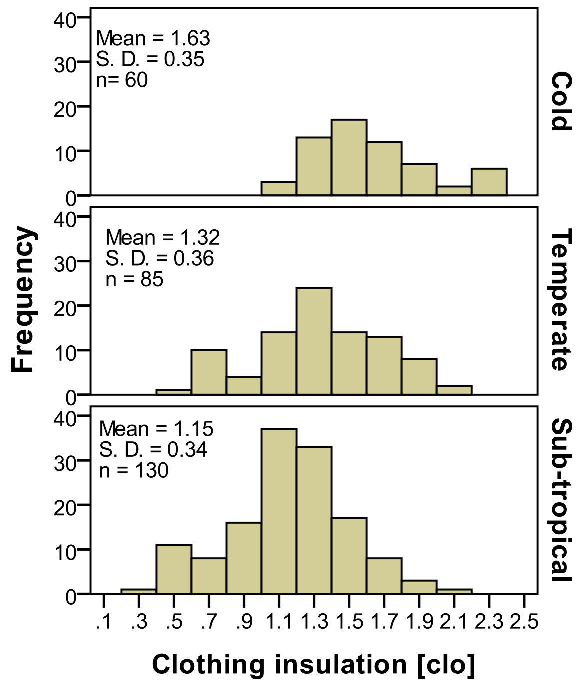


Figure 4.13 Distribution of the clothing insulation in three climatic regions in winter.

4.6.2 Relationship between preferred temperature and clothing insulation

Figure 4.14 shows the relationship between the estimated preferred temperature and clothing insulation for raw data and binned data at 0.2 clo intervals. We have obtained the following equations from the regression analysis. We applied weighted linear regression analysis for those binned data.

Raw data: $T_p = -3.41 I_{cl} + 24.1$ (n = 275, $R^2 = 0.11$, S.E. = 0.58, $p<0.001$) (4.8)

Binned data: $T_p = -3.28 I_{cl} + 24.0$ (n = 275, $R^2 = 0.73$, S.E. = 0.66, $p<0.001$) (4.9)

where, I_{cl} denotes the clothing insulation [clo].

As it is given in Figure 4.14, the preferred temperature is negatively correlated with clothing insulation. The coefficient of determination of the binned data is much higher than the raw data. However, the slopes of the raw data and binned data are very similar to each other. There is a tendency for the preferred temperature to be lower as the clothing insulation increases. For clothing insulation of 1.63 clo in the cold region, 1.32 clo in the temperate region and 1.15 clo in the sub-tropical region (Figure 4.13), the preferred temperature is 18.7 ºC, 19.7 ºC, and 20.3 ºC, respectively. We can say that the low indoor globe temperature in the cold region requires the people to wear more clothes and thereby results in their preferred temperature remaining at a lower value. From these results it can be seen that the residents were adapting to their respective regions by clothing adjustment. Clothing insulation can therefore be said to be a major factor in "adaptive thermal comfort".

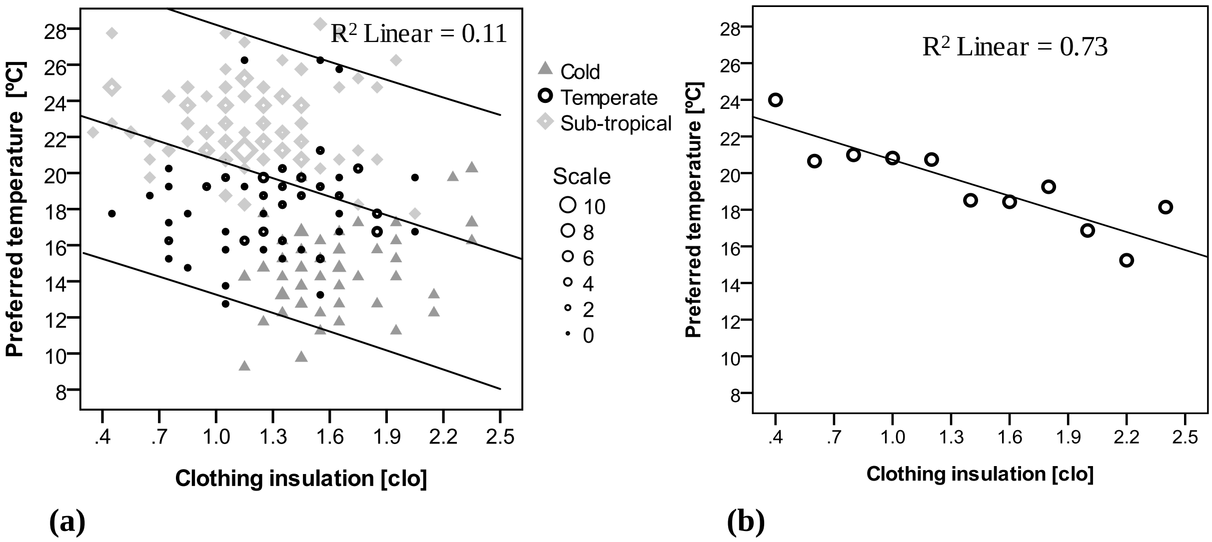


Figure 4.14 Relationship between estimated preferred temperature and clothing insulation: (a) raw data (95% of the data points are within the band) and (b) binned data.

4.7 Summer thermal comfort

We first present the indoor thermal environment measured during the voting time in summer and the perception of the people as well as comfort temperature and preferred temperature estimated from the votes given by them in respective regions. Then, we discuss the clothing insulation value and its relation to preferred temperature in three different regions in this section.

4.7.1 Indoor thermal environment during voting

Figure 4.15 shows the measured indoor air temperature (T_i), indoor globe temperature (T_g), estimated mean radiant temperature (T_{mrt}), and operative temperature (T_{op}) with measure outdoor air temperature (T_o) during the voting time in summer by using the method of box-plotting folowing the same path used in previous section. The dailly mean indoor air temperature ranged from 12 to 21 ºC in cold region, 22 to 30 ºC in temperate region and 27 to 37 ºC in sub-tropical region, and this was similar to the value observed by Rijal (2018) in Nepalese traditional houses in summer and also those obsered in the central part of China by Han et al. (2007), and differente climatic regions in India by Thapa et al. (2018). The mean indoor air temperature is close to the indoor globe temperature, mean radiant temperature, and operative temperature in cold, temperate, and sub-tropical region's houses. The measured indoor air temperature at 25% and 75% within the ascending order from the lowest value in the houses corresponded to 14.5 ºC and 19.1 ºC in cold region, and 24.6 ºC and 27.0 ºC in temperate region, respectively; and those in the houses corresponded to 29.5 ºC and 33.2 ºC in the sub-tropical region, respectively. There is a circle point in the sub-tropical region in the figure is outlier. The fluctuating range of indoor air temperature in cold region's houses exceeds than the houses in temperate and sub-tropical's regions. The difference can be due to the size of the windows, walls thickness, and heat capacity of the materials used in the houses.

The indoor relative humidity was recommended as 40 ~ 70% by Ogawa (1999). Table 4.2 shows the range of the measured indoor and outdoor air temperature, indoor and outdoor relative humidity, and indoor air movement of the respective regions during the voting time. Due to naturally ventilated rooms, the indoor relative humidity was similar to that of outdoors, and thus all regions the people were considered as exposed to similar humidity conditions. The maximum indoor air movement was 0.41, 0.25, and 2.56 m/s in cold, temperate, and sub-tropical regions, respectively during the voting time.

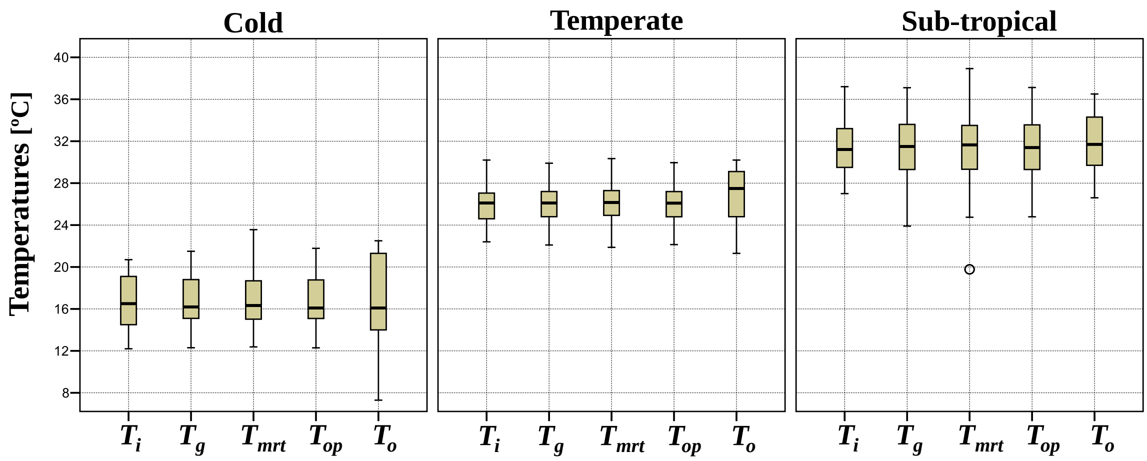


Figure 4.15 Temperature measured in investigated houses in cold, temperate and sub-tropical regions (lower range of box denotes 25% from the lowest temperature and upper edge denotes 75% from the lowest temperature).

Table 4.2 Descriptive statistics of air temperatures, relative humidity, and air movement

Climate	Items	T_i [°C]	RH_i [%]	T_o [°C]	RH_o [%]	V_i [m/s]
Cold (n = 254)	Mean	16.6	45	16.7	46	0.2
	S.D.	2.5	10	4.1	15	0.1
Temperate (n = 256)	Mean	26.0	51	27.0	46	0.1
	S.D.	1.7	7	2.6	9	0.0
Sub-tropical (n = 295)	Mean	31.4	50	31.9	51	0.3
	S.D.	2.4	10	2.7	10	0.5

n: Number of people, S.D.: Standard deviation, T_i: Indoor air temperature, RH_i: Indoor relative humidity, RH_o: Outdoor relative humidity, V_i: Indoor air movement

The results of this study indicate that in the sub-tropical climatic region, the average indoor and outdoor air temperatures tend to be higher than those in temperate and cold climatic regions. It was 31.9 °C outdoors with 31.4 °C indoors as it is seen in Table 4.2. The result is similar to the study of Rijal et al. (2010). It can be said that if indoor environment is extremely hot, it directly affects human health. The mortality rate rises evidently with increasing hot stress (Regmi et al., 2008). The study of Julio et al. (2006) showed that the 45 ~ 64 years age-group is a risk group to be taken into account when it comes to considering the health-related effects of temperature extremes. The elderly and infants are more at risk from exposure to low temperature which is presented by the study of David and Veronique (2016). Exposure to high temperatures can increase the risk of heat stroke (Bouchama and Knochel, 2002), and health problems such as respiratory and cardiovascular hospitalizations and deaths (Anderson et al., 2013). In Nepal, under a high emissions scenario heat-related death in the elderly (65 + years) are approximately 4 deaths per 100,000 people annually between 1961 and 1990 as it was reported by World Health Organization (2015).

4.7.2 Relationship between indoor globe and outdoor air temperature

Figure 4.16 shows the relationship between the measured indoor globe temperature and outdoor air temperature at the time of voting. There are 1002 plots from all three regions. As expected in general, a higher outdoor air temperature also results in a higher indoor globe temperature. For this relationship, we have found the following equations:

Cold: $T_g = 0.54T_o + 7.7$ (n =254, $R^2 = 0.84$, S.E.= 0.01, $p<0.001$, $7.3 \leq T_o \leq 22.5$) (4.10)

Temperate: $T_g = 0.47T_o + 13.4$ (n =256, $R^2 = 0.48$, S.E.= 0.03, $p<0.001$, $21.3 \leq T_o \leq 30.2$) (4.11)

Sub-tropical: $T_g = 0.80T_o + 5.8$ (n=295, $R^2 = 0.73$, S.E.= 0.03, $p<0.001$, $26.6 \leq T_o \leq 36.5$) (4.12)

where, T_o denotes the outdoor air temperature, n denotes the number of data points, R^2 denotes the coefficient of determination, S.E. denotes the standard error of the regression coefficient, and p denotes the significance level of the regression coefficient.

The indoor globe temperature is moderately correlated (r = 0.69 ~ 0.92) with outdoor air temperature in all three regions. The values of the correlation coefficient are higher than those in the previous studies, for example, in the study of Shing et al. (2017), Ioannou et al. (2018), KC et al. (2019), Toe and Kubota (2013) Imagawa et al. (2016), and Gautam et al. (2019). Many factors affect the field survey data and it is not possible to eliminate all the noise effects (Nicol et al., 2012). Thus, the correlation coefficients obtained from the field survey data are usually lower than those obtained from climate chamber studies (Garcia et al., 2019). The slope of the regression line for the cold and temperate regions are rather flat than in the sub-tropical region. This is likely to be due to the heat-capacity effect of the houses, which have thick walls in the cold and temperate regions. In the cold and temperate regions, the houses are made of stones and mud with thick walls (45 to 60 cm) as it is given in Figures 2.4 (a) and 2.5 (a), but in the sub-tropical region, the houses are made of wood with thin walls (2.5 cm) which is given in Figure 2.6 (a) and Table 2.4. By comparing the results with the previous studies by Rijal et al. (2010), Nicol et al. (1996), and Thapa et al. (2018), the indoor air temperature in this study is the lowest at high altitude.

Within the range of outdoor air temperature between 21 ºC and 22.5 ºC, there are data points for both cold and temperate regions. According to the regression lines shown above, T_g is 19.6 ºC for the cold region and 23.7 ºC for the temperate region, when assuming the outdoor air temperature is 22 ºC; that is, the regional difference of the indoor globe temperate (ΔT_g), is 4.1 ºC. Similarly, within the range of outdoor air temperatures between 26 ºC and 30 ºC, there are data points for both temperate and sub-tropical regions. According to the regression lines, T_g is 27.0 ºC for the temperate region and 29.0 ºC for the sub-tropical region, when assuming the outdoor air temperature is 29 ºC. Thus, the regional difference of the indoor globe temperature (ΔT_g), is 2.0 ºC. These tendencies are similar to the findings of previous study by de Dear et al. (1997). Similarly, Rijal et al. (2010) found that the indoor temperature has large seasonal and regional differences, and Nicol and Roaf (1996) also found that the temperature is different depending on the climate.

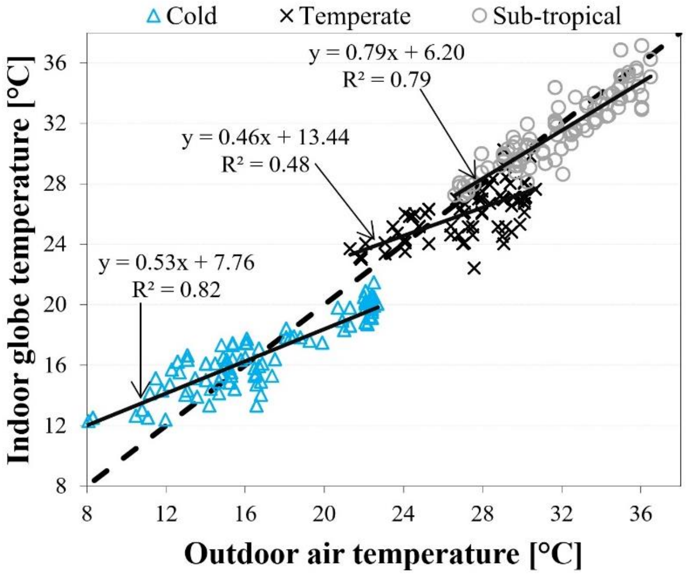


Figure 4.16 Relationship between indoor globe temperature and outdoor air temperature.

4.8 Thermal sensation vote and thermal preference

Figure 4.17 shows the frequency distribution of the thermal sensation votes obtained in the cold, temperate and sub-tropical regions. We received the largest number of votes for "4. Neutral" in cold region. If the thermal sensation votes 3, 4 and 5 are grouped as "comfort zone" then 99.2% of the votes are in the "comfort zone" in the cold region, 79% in temperate and 45.8% in sub-tropical regions. The people seem to adapt to the given indoor environment in cold and temperate regions and vice versa in sub-tropical region. If we focus on the thermal sensation votes for "4. Neutral" alone, they comprise 76% of all votes in the cold region. This percentage is higher in the other two regions: 43.8% in temperate and 28.8% in sub-tropical regions. The number of votes from 2, 6 and 7 are most numerous (54.4%) in sub-tropical region; this number is 53.6% and 33.5% more than in the cold and temperate regions. This is probably due to indoor globe temperature of higher than 30 °C occurring in the sub-tropical region, and such high values of globe temperature will never be occurring in cold and temperate regions.

We separated thermal sensation votes into votes acquired in morning time (7:00 to 10:59, n = 390), afternoon time (11:00 to 15:59, n = 253), and evening time (16:00 to 19:30, n = 162). Figure 4.18 shows the thermal sensation votes of the people in the cold, temperate, and sub-tropical regions with respect to the time of the day. There is no difference in the mean thermal sensation votes in cold region with respect to time. However, there are differences in the thermal sensation votes in temperate and sub-tropical regions with respect to the data indicated by the range of standard error. The results indicate that the thermal sensation vote in respective regions were related to the time of the day, which in turn affected the indoor and outdoor temperatures.

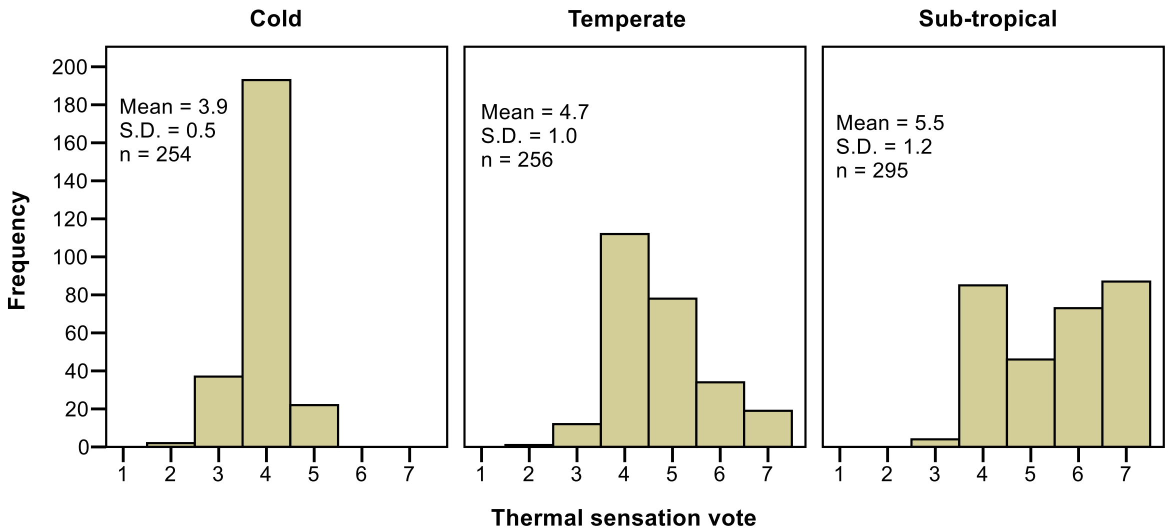


Figure 4.17 Frequency distribution of the thermal sensation votes.

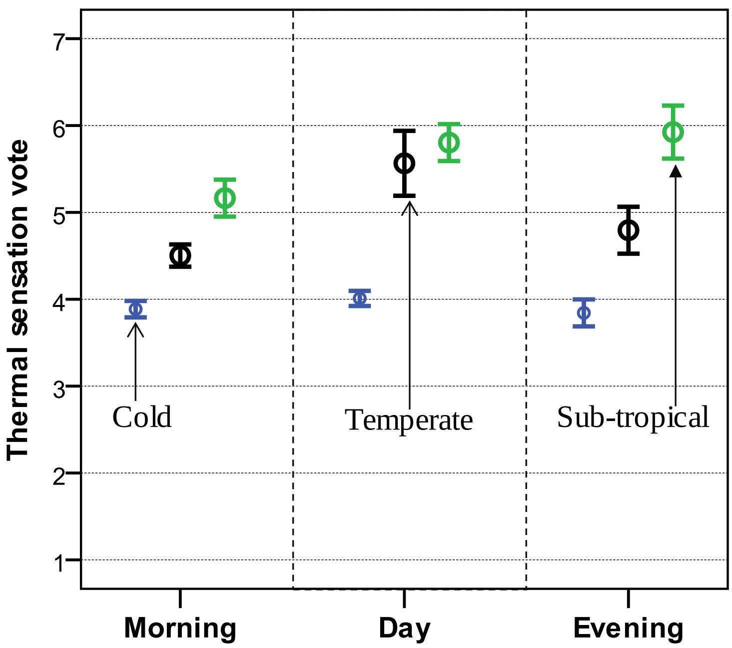


Figure 4.18 Thermal sensation vote of peoples in cold, temperate and sub-tropical regions; in morning, day and evening times (Mean ±2 S.D.).

We also separated thermal sensation votes into three acquired age group (15 ~ 29, 30 ~ 49, and 50 ~ 70 years). Table 4.3 shows the numbers and percentile of thermal sensation votes by age group in respective regions. We received the largest number of votes for “4 Neutral” in all age group of people in cold and temperate regions. Conversely in sub-tropical region, 10.2% of votes for “6. Hot” of 15 ~ 29 years age group of the people, 13.2% and 7.8% of votes for “7. Very hot” were observed in both 30 ~ 59 and 50 ~ 70 years age group of people. This indicates that the individuals (all age group of people) had difficulty in adapting to the given indoor environment in the sub-tropical region. The frequency distribution of the thermal sensation vote was separated for male and female which is seen in Figure 4.19. We received similar voting trend of both male and female in all investigated regions.

Figure 4.20 shows the frequency distribution of the thermal preference votes. We received 22.8% of the preference votes “2. A bit warmer” in the cold climatic region only, this is the cause of low indoor globe temperature. We received the largest number of preferred votes “3. No change” in cold and temperate regions, which indicates that the occupants are satisfied with their given indoor thermal environment. However, in the sub-tropical region, we received the largest number of preferred votes for “4. A bit cooler”, indicating that the occupants prefer to change their indoor environment to be perceived to be a little cooler. The relative numbers of votes corresponding to the two categories (vote “4. A bit cooler” and “5. Much cooler”) were 6.7% in the cold region, 57.8% in the temperate region and 70.5% in the sub-tropical region, respectively. Although, the smallest number of mTSV votes are in the “4. Neutral” in sub-tropical climatic region as it has been in Figure 4.18, most of the respondents prefer a bit cooler in sub-tropical and temperate climatic regions. It can be concluded that the occupants experience hot indoor environments in their everyday life in summer in sub-tropical and temperate regions.

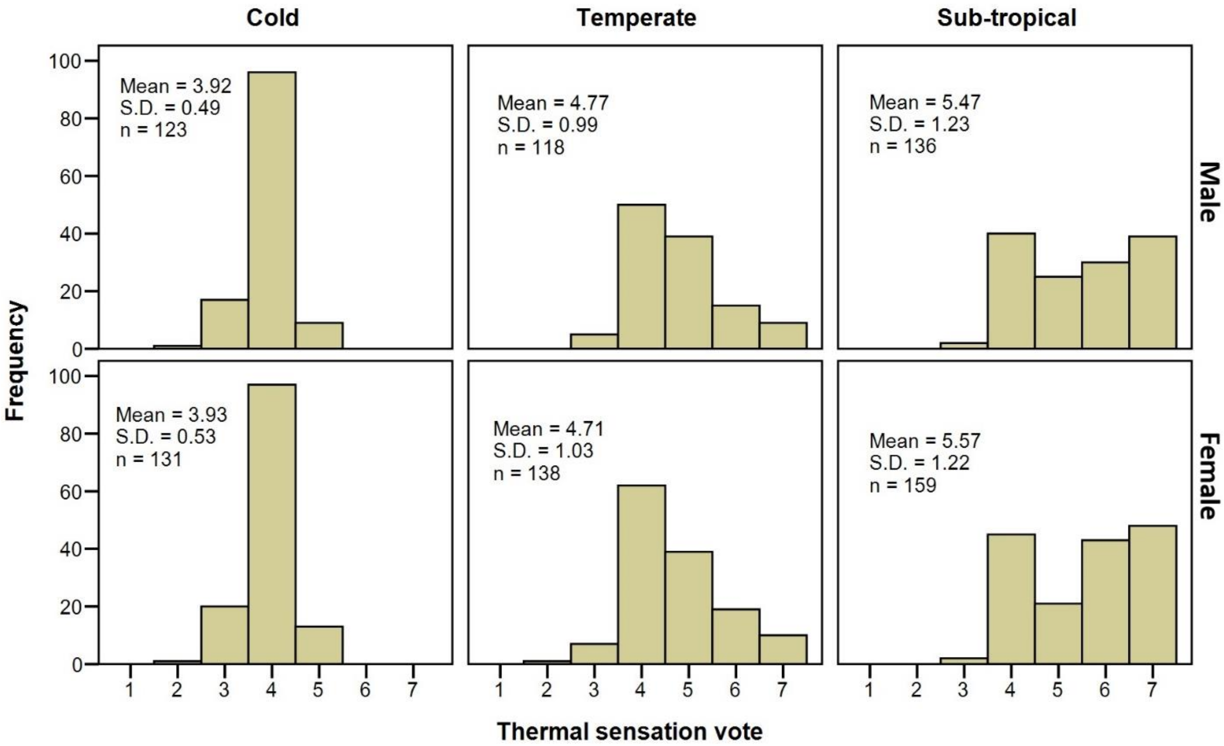


Figure 4.19 Frequency distribution of the thermal sensation votes for male and female.

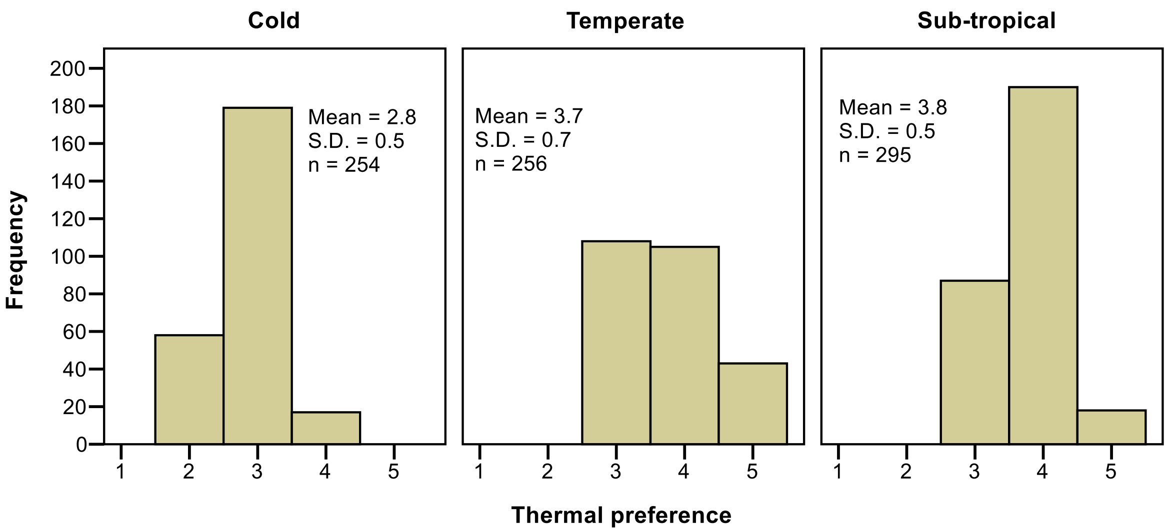


Figure 4.20 Frequency distribution of the thermal preference.

Table 4.3 Subjective evaluation of thermal sensation votes by age group

Climate	Scale	mTSV (Age group)					
		15 ~ 29 years	Percentage [%]	30 ~ 49 years	Percentage [%]	50 ~70 years	Percentage [%]
Cold	1	0	0	0	0	0	0
	2	0	0	0	0	2	0.8
	3	13	5.1	17	6.7	7	2.8
	4	55	21.7	85	33.5	53	20.9
	5	6	2.4	10	3.9	6	2.4
	6	0	0	0	0	0	0
	7	0	0	0	0	0	0
Total		74	29.1	112	44.1	68	26.8
Temperate	1	0	0.0	0	0.0	0	0.0
	2	1	0.4	0	0.0	0	0.0
	3	9	3.5	2	0.8	1	0.4
	4	37	14.5	43	16.8	32	12.5
	5	19	7.4	41	16.0	18	7.0
	6	6	2.3	18	7.0	10	3.9
	7	7	2.7	11	4.3	1	0.4
Total		79	30.9	115	44.9	62	24.2
Sub-tropical	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	1	0.3	1	0.3	2	0.7
	4	22	7.5	50	17.0	13	4.4
	5	10	3.4	26	8.8	10	3.4
	6	30	10.2	29	9.8	14	4.8
	7	25	8.5	39	13.2	23	7.8
Total		88	29.8	145	49.2	62	21.0

4.9 Humidity feeling and humidity preference

Humidity affects our comfort directly and indirectly. It is a factor to relate thermal sensation, skin moisture, and discomfort, choice of cloths, health and observation of air quality. It is difficult to understand the level of thermal environment by observing the relative humidity (Ogawa, 1999). Another researcher Tanabe et al. (1987) concluded that the thermal sensation alone is not a reliable predictor of thermal comfort. The harshly dry and humid natural environment in summer season required people weak perception. We asked humidity feeling and humidity preferences of the respondents during the voting time. Figure 4.21 shows the frequency distribution of the humidity sensation votes obtained in the cold, temperate and sub-tropical regions. We received the largest number of votes for “4. Neither humid nor dry” in cold region, "3. Slightly dry" in temperate and sub-tropical regions. The humidity sensation votes 1, 2, and 3 are grouped as "dry zone" then 62.6% of the votes are in the "dry zone" in the cold region, 55.9% in temperate and 62.0% in sub-tropical regions. The people seem to feel dry humidity to the given indoor environment in all study areas. If we focus on the humidity sensation votes for "4. Neither humid nor dry" alone, they comprise 34.6% of all votes in the cold region. This percentage is bigger in the other two regions: 30.5% in temperate and 18.0% in sub-tropical regions. This is probably due to indoor air temperatures of higher than 30 °C occurring in the sub-tropical region, and such high values of air temperature will never be occurring in cold region.

Figure 4.22 shows the frequency distribution of the humidity preference votes. We received the largest number of preferred votes for "2. A bit more humid" in all investigated areas. This indicates that the respondents prefer making their indoor environment a bit more humid. However, in the cold region, we received 45.7% of preferred votes for "3. No change", indicating that the respondents are satisfied with their given indoor humidity environment. The relative number of votes corresponding to the two categories (vote "1. Much more humid" and "2. A bit more humid") were 53.9% in the cold region, 61.7% in the temperate region and 73.2% in the sub-tropical region, respectively. Although, the smallest number of humidity sensation votes are in the "4. Neither humid nor dry" in sub-tropical climatic region as shown in Figure 4.20, most of the respondents prefer a bit more humid in sub-tropical climatic region. It is concluded that the occupants experience dry indoor environments in their everyday life in summer in sub-tropical region.

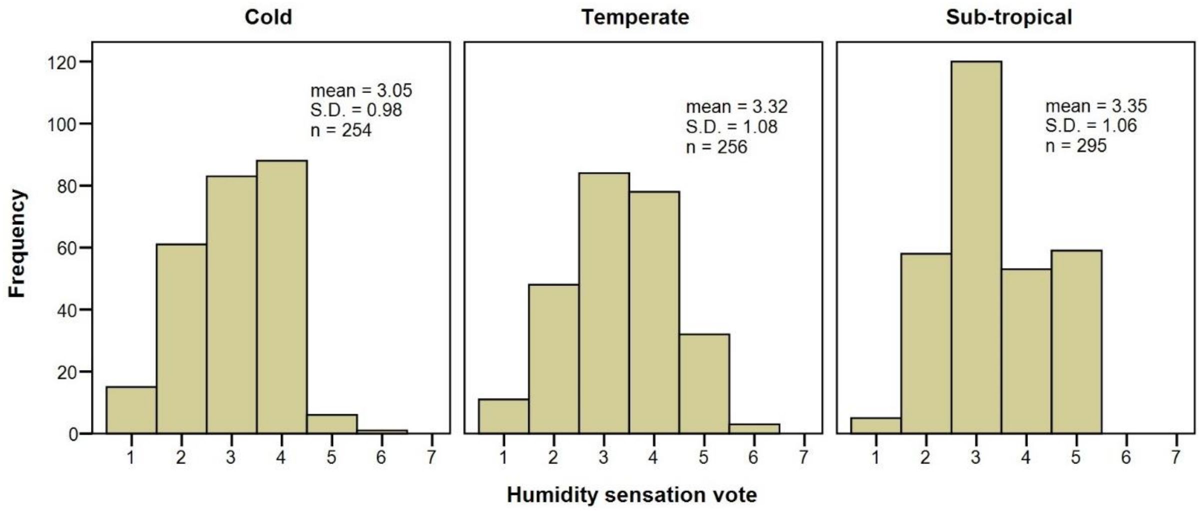


Figure 4.21 Frequency distribution of the thermal sensation votes.

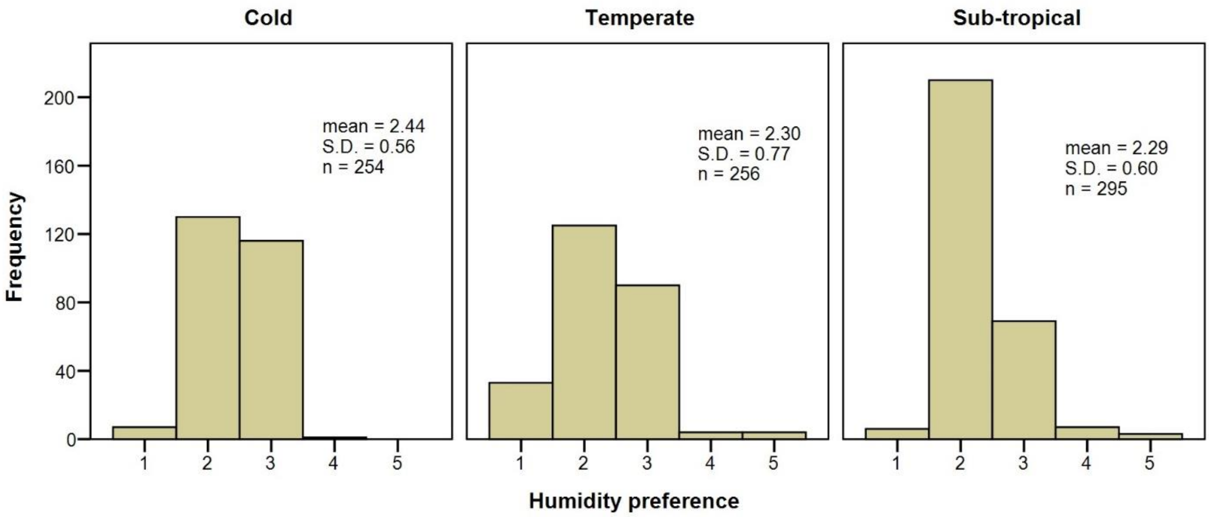


Figure 4.22 Frequency distribution of the humidity preference.

4.10 Comfort and preferred temperature

The regression analysis of thermal sensation and indoor globe temperature was conducted to estimate the comfort temperature in three climatic regions. However, the regression equations for all regions are not statistically significant. This means that a reliable estimate of the comfort temperature is not possible using regression analysis as indicated in previous researches, for example, in the study by Rijal et al. (2010, 2017, 2019), Gautam et al. (2019), Griffiths (1990), Nicol et al. (1999), and Xu et al. (2018). Based on the votes on the thermal sensation and thermal preference with the corresponding values of indoor globe temperature, we estimated the comfort temperature and preferred temperature values based on the equations (2.4) and (2.5).

Figure 4.23 (a) shows the frequency distribution of the estimated comfort temperature in each climatic region. In the three investigated regions, the estimated mean comfort temperature is the lowest in the cold region, middle in the temperate region and highest in the sub-tropical region. The mean value of the comfort temperature is 16.8 ºC, 24.8 ºC, and 28.4 ºC as indicated in the graphs. The comfort temperature ranges from 12 ºC to 23 ºC in the cold region, from 19 ºC to 32 ºC in the temperate region and from 20 ºC to 34 ºC in the sub-tropical region. The regional difference in the summer comfort temperature (ΔT_c) is 8.0 ºC between the temperate and cold regions, 3.6 ºC between the sub-tropical and temperate regions and 11.6 ºC between the sub-tropical and cold regions. Nicol and Roaf (1996) found that the comfort temperature was lower at high altitude and higher at low altitude. In the same way, Rijal (2010) found that the indoor neutral temperature is the highest in sub-tropical climate, moderate in temperate climate, and lowest in cold climate areas and also found a large seasonal difference in comfort temperature, from 3.5 °C to 13.8 ºC. These differences may be attributed to the difference in clothing insulation, which we will discuss later. The values of comfort temperature obtained here are found to be similar to those obtained in previous study of Humphreys et al. (2013).

As it is seen in Figure 4. 23 (b), the estimated mean preferred temperature is also the lowest in the cold region (17.2 ºC), middle in the temperate region (23.8 ºC) and the highest in the sub-tropical region (29.1 ºC). Considering the mean value of the comfort temperature and preferred temperature and their corresponding values of standard deviation (S.D.), the preferred temperature is quite close to the comfort temperature. This tendency is similar to that of the observed in a previous study of Griffiths (1990) and Hwang (2018). The preferred temperature is higher than the comfort temperature in the cold and sub-tropical regions and vice versa in temperate region.

There are 254 plots in cold, 256 plots in temperate, and 295 plots in sub-tropical regions, respectively. As expected, the increases in comfort temperature result in the increases of preferred temperature. We found the following equations from the regression analysis.

$T_p = 0.95T_c+1.3$ (n = 805, $R^2 = 0.89$, S.E. = 0.01, $p<0.001$) (4.13)

Figure 4.24 shows the relationship between the estimated preferred temperature and comfort temperature described above. The cross points of the regression lines to the diagonal in figure is 26 ºC. Such tendency suggests that the respondents of the cold region in particular want to shift the indoor environment condition to be warmer in such a case that the comfort temperature is low. Similar tendencies can be seen for the indoor temperature and cognitive temperature, which is the temperature value imagined by the respondents based on their respective indoor environmental conditions (Nagai et al., 2014). For indoor thermal environments with high temperatures during summer, there is a tendency for the cognitive temperature to be lower than the measured values of indoor temperature.

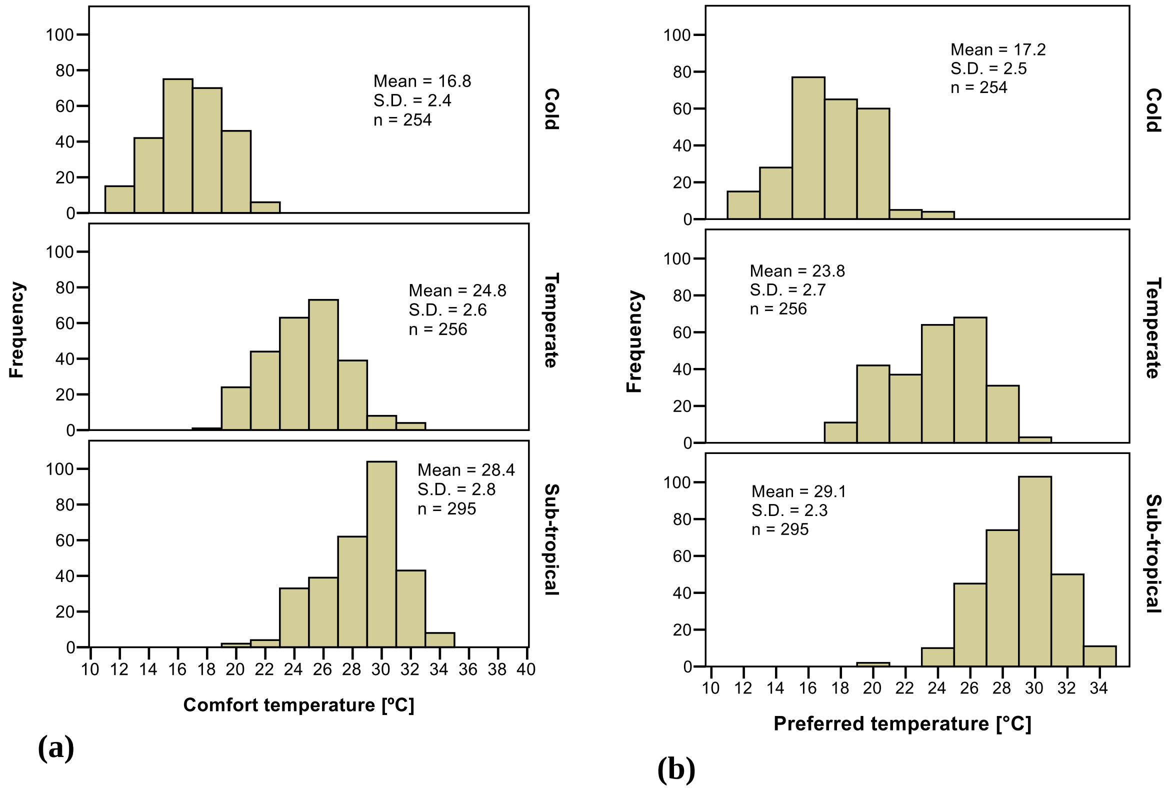


Fig 4.23 Frequency distribution of estimated comfort and preferred temperatures: (a) comfort temperature and (b) preferred temperature.

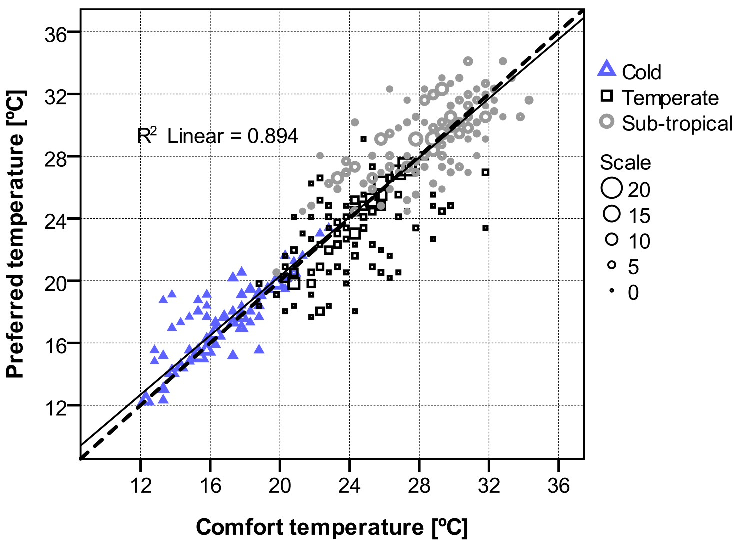


Figure 4.24 Relationship between preferred temperature and comfort temperature.

4.11 Overall comfort and thermal satisfaction

Overall comfort due to the prevailing conditions was noted in a six-point scale, 1 very comfortable, 2 moderately comfortable, 3 slightly comfortable, 4 slightly uncomfortable, 5 moderately uncomfortable, 6 very uncomfortable. Table 4.4 shows the subjective evaluation of overall comfort and thermal satisfaction votes obtained from the summer survey. The total votes from cold, temperate and sub-tropical regions are 254, 256, and 295, respectively. Specifically, 9.0% votes from cold region and 4.3% votes from temperate region corresponded to very comfortable. Assuming that the overall comfort votes of either "Very comfortable", "Comfortable" or "Slightly comfortable" corresponded to "Comfortable", 85.0%, 49.2% and 31.9% "Comfortable" levels were observed in cold, temperate and sub-tropical regions, respectively. Conversely, 15.0%, 50.8% and 68.1% uncomfortable level were observed in cold, temperate and sub-tropical regions, respectively. This indicates that more than half of the respondents in temperate region and more than 68% respondents in sub-tropical region had difficulty in adapting the given indoor environment in the study areas.

Table 4.4 Subjective evaluation of overall comfort and thermal satisfaction

Climate	Scale	Overall comfort			Thermal satisfaction		
		No of sample	Percentage [%]		No of sample	Percentage [%]	
Cold	1	23	9.0		36	14.2	
	2	95	37.4	85.0	90	35.5	87.5
	3	98	38.6		96	37.8	
	4	28	11.0		24	9.4	
	5	10	3.9	15.0	8	3.1	12.5
	6	0	0.0		0	0.0	
Total		254	100.0		254	100.0	
Temperate	1	11	4.3		1	0.4	
	2	43	16.8	49.2	80	31.3	55.1
	3	72	28.1		60	23.4	
	4	87	34.0		68	26.6	
	5	39	15.2	50.8	40	15.6	44.9
	6	4	1.6		7	2.7	
Total		256	100.0		256	100.0	
Sub-tropical	1	0	0.0		0	0.0	
	2	28	9.5	31.9	31	10.5	30.5
	3	66	22.4		59	20.0	
	4	95	32.2		112	38.0	
	5	100	33.9	68.1	79	26.8	69.5
	6	6	2.0		14	4.7	
Total		295	100		295	100	

The thermal satisfaction in this research has been defined as feeling of people regarding the temperature. We observed thermal satisfaction level of the respondents, as shown in appendix 2, during the survey time (e.g., very satisfy, moderately satisfy, slightly satisfy, slightly un-satisfy, moderately un-satisfy and very un-satisfy). Table 4.4 shows the subjective evaluation of overall comfort and thermal satisfaction votes obtained in the respective regions. We received the largest number of votes for "2. Moderately satisfy" in cold and temperate region and "4. Slightly un-satisfy" in sub-tropical region. If thermal satisfaction votes 1, 2, and 3 are grouped as "satisfy zone", then 87.5% of the votes are in the "satisfy zone" in the cold, 55.1% in temperate and 30.5% in sub-tropical region. The people feel difficulty to adapt to the given indoor environment in the sub-tropical region.

4.12 Comfort temperature and outdoor temperature

The relationship between comfort temperature and outdoor air temperature is called an adaptive model (Humphreys et al., 2016), which has been standardized as ASHRAE 55 (2013) and CEN 15251 (2007) by compiling the data sets provided for various seasons in various countries. There are all together 805 plots from all three regions. The estimated comfort temperature is again lowest in the cold region, middle in the temperate region and high in the sub-tropical region. We found the following equations from the regression analysis.

$T_c = 0.51T_o + 8.9$ (n = 805, $R^2 = 0.46$, S.E.= 0.02, $p<0.001$) (4.14)

Figure 4.25 shows the relationship between the estimated comfort temperature and the measured outdoor air temperature described above. The cross points of the regression lines to the diagonal in figure is 19 ºC. In the cold region, most of the data points are above the diagonal line which is vice versa in temperate and sub-tropical regions. This implies that the comfort temperature in cold region is higher than that of the outdoor air temperature. However, the comfort temperature in temperate and sub-tropical regions is lower than that of the outdoor air temperature. Such tendency suggests that the respondents of the cold region in particular want to high comfort temperature which is vice versa in temperate and sub-tropical regions.

The results of this study indicate that in the sub-tropical climatic region, the average indoor and outdoor air temperature tend to be higher than those in temperate and cold climatic regions. It was 31.9 °C outdoors with 31.4 °C indoors as it has been in sub-section 4.7.1. The result is similar to the study by Rijal et al. (2010). It can be said that if indoor environment is extremely hot, it directly affects human health. The mortality rate rises evidently with increasing hot stress (Regmi et al., 2008). Similarly, Julio et al. (2006) pointed that the 45 ~ 64 years age-group is a risk group to be taken into account when it comes to considering the health-related effects of temperature extremes. The elderly and infants are more at the risk from exposure to low temperature as it is presented by David and Veronique (2016). Exposure to high temperatures can increase the risk of heat stroke (Bouchama & Knochel, 2002), and health problems such as respiratory and cardiovascular hospitalizations and deaths (Anderson et al., 2013).

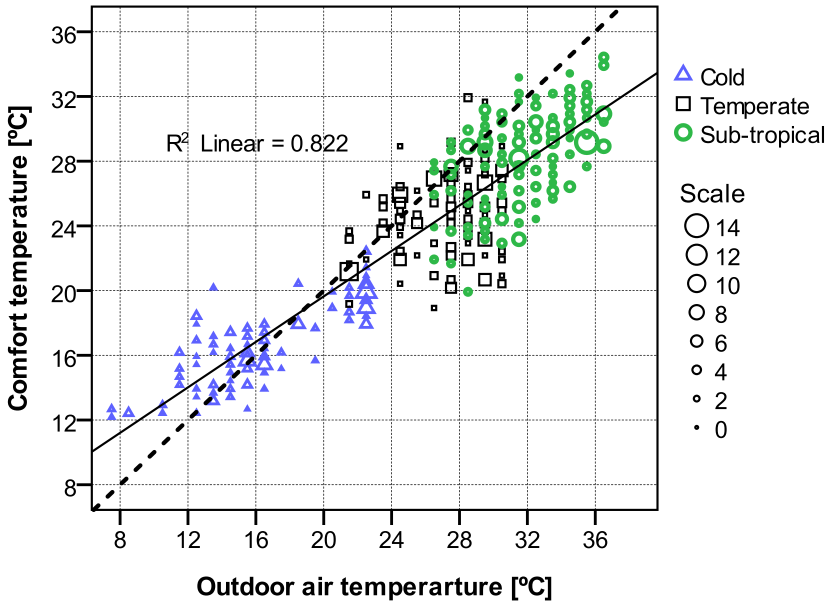


Figure 4.25 Relationship between comfort temperature and outdoor air temperature.

4.13 Summer behaviors taken to adjust thermal environment

Typically, people adopt two types of adaptive behaviours: one is to change their indoor environmental condition (e.g., opening windows) and the other is to change themselves (e.g., wearing less clothes) as discussed by Nicol (2004) on his study, adaptive thermal comfort standard in the hot humid tropics. The natural tendency to adapt for varying circumstances in our environment. The natural tendency is expressed in the adaptive approach to thermal comfort. The comfort temperature is a result of the collaboration between the people and the buildings or other environment they are inhabiting (Nicol and Humphreys, 2002). Due to the climatic variations, differences in socio-culture life style in different regions and seasons in Nepal, people not only wear different types of clothing but also adopt a verity of behaviours to restore their thermal comfort. In the cold region, temperature is very low in almost all the time of year, people wear thick and warm clothes for their thermal comfort. In the sub-tropical region, temperature is extreme hot or very high, wear thin and light clothes for their thermal comfort. In general, Nepalese women often wore traditional clothing such as saris, blouses, and Kurta-shawls, while Nepalese men especially young generation wore western-style clothing such as T-shirts, shirts, jackets, and trousers. According to the finding of the study of Rijal et al. (2010), in the cool climate, people wore layers of thick clothing and, until they went to bed, shoes indoors in winter. In the sub-tropical climate, people wore light clothing and men often wore only shorts in summer. Nepalese people not only wear different types of clothing but also adopt a verity of behaviours to restore their thermal comfort according to climate and culture. We observed certain behaviours adopted by the respondents as it is seen in Table 2.9, during the survey time (e. g., using fan, use light clothes, take a shower, sit under the shade, change posture, and nothing in particular).

Figure 4.26 shows the percentage of behaviours adopted by people in the respective regions to adjust thermal environment. We received 53% and 24% votes of sub-tropical and temperate regions for “Use fan” for coolness. Nicol et al. (2004) suggested that the comfort temperature can be increased by 2 °C, over a wide range of outdoor air temperature when fan usage is increased. In sub-tropical region, people tend to use light clothes and tend to shower more frequently than temperate region. Measures corresponding to “Nothing in particular” is more adopted by temperate than that of sub-tropical region’s people. However, 97% of people voted in “Nothing in particular” in cold region. This is potentially because the level of adaptation of the people in cold region than that of in temperate and sub-tropical regions.

Clothing insulation directly affects the heat exchange between the human body and the surrounding environment. It plays a key role in obtaining personal thermal comfort of the respondents in different thermal environment. Therefore, clothing adjustment is an important behaviour in studied areas in Nepal. We took clothing value from ISC, 2003, as already discussed respective regions in summer. Figure 4.27 shows high clothing values in the cold region, intermediate values in the temperate region and low values in the sub-tropical region, as expected. The mean clothing insulation is 1.4 clo in cold region, which is 0.7 clo and 0.9 clo higher than the temperate and sub-tropical regions, respectively. It is higher than the 1.38 clo which is pointed by Jiao et al. (2017) in Shanghai, 0.90 clo in northeast India, and observed by Thapa et al. (2018) and 0.77 clo in Korea by Yang et al. (2016). As discussed in the previous section, the indoor globe temperature in the cold region was lower than the temperate and sub-tropical regions. Thus, it is reasonable that the respondents in the cold region have higher clothing insulation than in temperate and sub-tropical respondents. The people do not wear less than 0.7 clo in cold region or more than 1.3 clo in the sub-tropical, and 1.5 clo in temperate regions. This trend is similar to the results of Rijal et al. (2010) in Nepal, Watanabe et al. (2013) in Japan, and Jiao et al. (2017) in China.

We discussed that in cold region, the comfort and preferred temperature is lower than that is compared to other two regions. As expected, the increases in clothing insulation result in the decreases the preferred temperature. Figure 4.28 shows the relationship between the estimated preferred temperature and clothing insulation. We have obtained the following equation for regression analysis.

$T_p = -8.66I_{cl} + 31.0$ (n = 805, $R^2 = 0.49$, S.E. = 0.31, $p < 0.001$) (4.15)

where, I_{cl} denotes clothing insulation [clo].

As it is given in Figure 4.28, the preferred temperature is negatively correlated with clothing insulation. There is a tendency for the preferred temperature to be lower as the clothing insulation increases. Referring to the clothing insulation of 1.4 clo in cold region, 0.7 clo in temperate region, and 0.5 clo in sub-tropical region presented in Figure 2.24, the preferred temperature becomes 18.9 ºC, 24.9 ºC, and 26.7 ºC, respectively. We can say that the lower indoor globe temperature in the cold region requires to people to wear more clothes and thereby results in their preferred temperature remaining at a lower value. However, in temperate and sub-tropical regions; people wear less clothes and there by results in their preferred temperature remaining at a higher value.

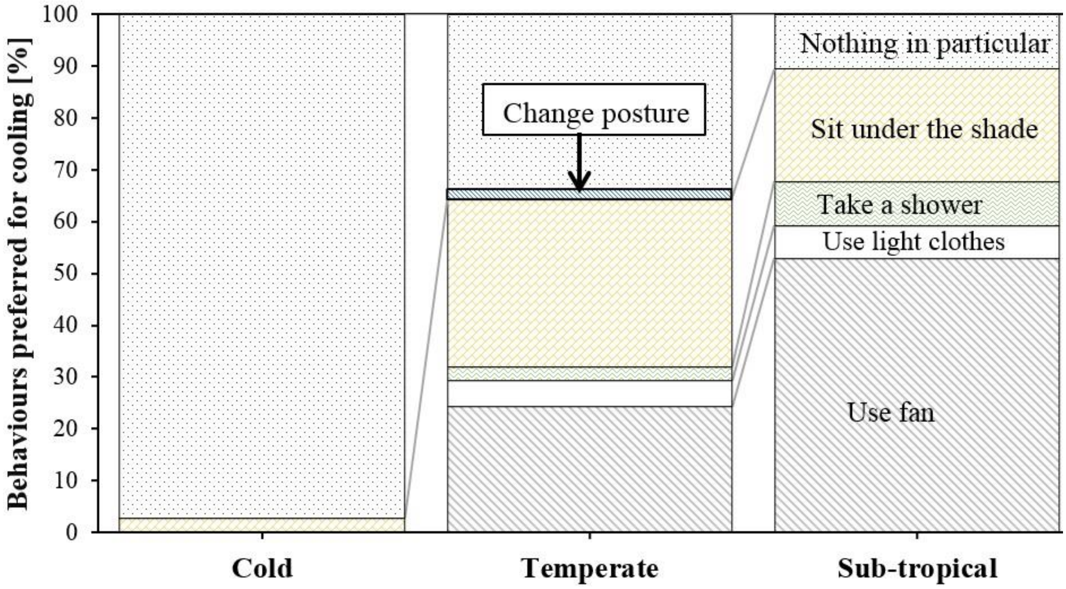


Figure 4.26 Various behaviors adopted to restore thermal comfort in respective regions.

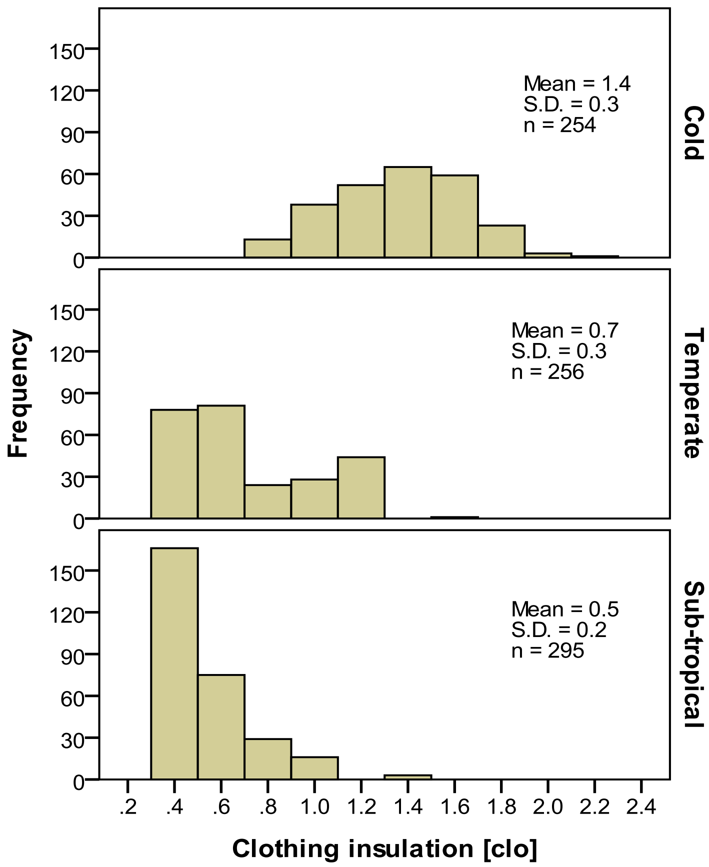


Figure 4.27 Frequency distribution of the clothing insulation in summer.

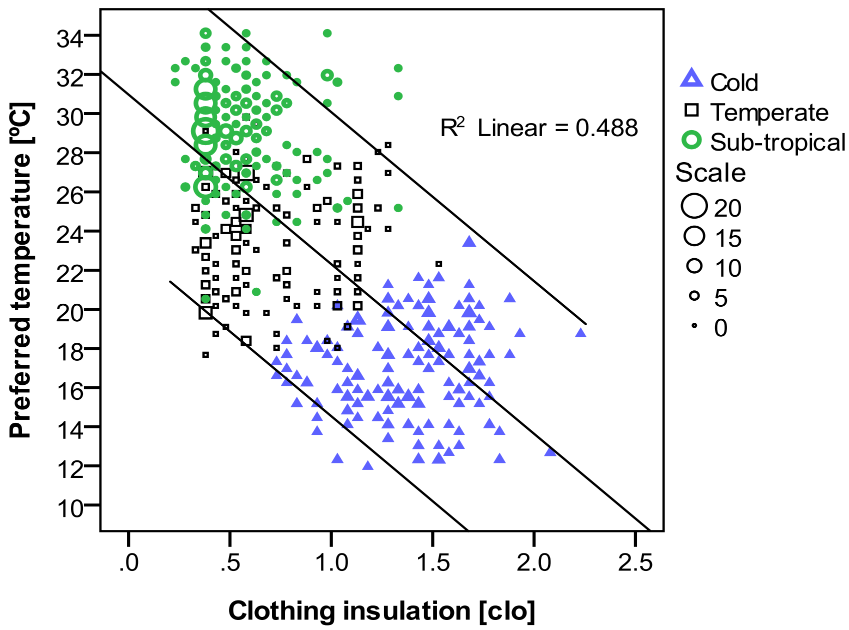


Figure 4.28 Relationship between estimated preferred temperature and clothing insulations.

4.14 Conclusions

This research has been conducted to investigate how people living in different climatic regions of Nepal achieve thermal comfort in their respective traditional houses by undertaking various adaptive behaviours such as clothing adjustment in winter and other adaptive behaviours in summer. For this purpose, we measured the indoor thermal environment in 427 traditional houses and conducted thermal comfort survey with 1287 respondents present at home during the daytime between 7:00 to 19:30, in cold, temperate and sub-tropical regions in winter and summer. From the study, we have derived following findings:

1. The percentage of people reporting their environments to be in the "comfort zone", which is assumed to correspond to the central 3 categories of thermal sensation vote, is 76.8%, 82.6% and 84.7% in winter and 99.2%, 79.0%, and 45.8% in summer in the cold, temperate, and sub-tropical regions, respectively. The people seem to adapt to the given indoor thermal environment in the respective climatic regions in winter. However, the people of sub-tropical region feel difficult to adapt to the given indoor thermal environment in summer.
2. The mean comfort temperature in the cold region was 13.8 °C, which is 4.1 °C and 9.3 °C lower than that in temperate and subtropical regions in winter.
3. Similarly, the mean comfort temperature is lower (16.8 °C) in the cold region, middle

(24.8 °C) in temperate region, and high (28.4 °C) in sub-tropical region in summer. The comfort temperature in cold region is similar to the one found in previous studies, but significantly lower than that given in ASHRAE and CEN standards. It indicates that we may need to propose an adaptive standard which is suitable for extremely cold regions.

4. The seasonal differences of comfort temperature are 3.0 °C, 6.9 °C, and 5.3 °C in cold, temperate, and sub-tropical regions, respectively.
5. The regional difference of comfort temperature for temperate and cold region is 4.1 °C and 6.6 °C in winter and summer, respectively. Similarly, the regional difference of comfort temperature for sub-tropical and temperate region is 5.2 °C and 4.6 °C in winter and summer. The regional difference of comfort temperature for sub-tropical and cold region is 9.3 °C and 11.9 °C in winter and summer. However, the regional difference of comfort temperature for these regions is higher than that of compared to other regions.
6. The mean preferred temperature in the cold region is 14.7 °C, which is 3.8 °C and 8.1 °C lower than in the temperate and subtropical regions in winter. The preferred temperature is 0.9 °C higher than the comfort temperature in the cold region.
7. As it is expected, in summer, the preferred temperature is low in cold, middle in temperate and high in sub-tropical regions, respectively. The mean preferred temperature in the cold region is 17.2 °C, which is 6.6 °C and 11.9 °C lower than that of in the temperate and subtropical regions in summer. The results indicate that people desire a warmer thermal environment in cold region in both seasons, which is considered to be a natural physio-psychological tendency of human beings.
8. The mean clothing insulation in the cold region was 1.63 clo, which is 0.31 clo and 0.48 clo higher than in the temperate and sub-tropical regions in winter.
9. As it is expected, in summer, the clothing insulation value is high in cold, middle in temperate and high in sub-tropical regions, respectively. The mean clothing insulation in the cold region was 1.4 clo, which is 0.7 clo and 0.9 clo higher than that in the temperate and sub-tropical regions in summer. The clothing insulation is negatively correlated with outdoor air temperature. This result indicates that people increase the level of clothing insulation as their major adaptive behaviour in the cold regions in order to survive under low temperature indoor

conditions.

Overall, we noted that there exists a significant regional difference in the indoor air temperature, comfort temperature, preferred temperature and clothing insulation in winter and summer, and also that the people living in Nepalese traditional houses tend to achieve thermally comfortable conditions by adjusting their clothing as much as possible, depending on their respective local climate and building conditions. The context clarified in this analysis is, we believe, applicable to similar climates, building types and lifestyles in other regions.

Chapter 5: Thermal history of local and migrant peoples

5.1 Introduction

Nepal has diverse climatic and geographical variations. It is broadly classified into three ecological regions: Mountain, Hilly, and Terai regions, all of which extend from east to west. The climatic features of the three regions can be observed within a short distance from south to north. Northern mountain, central hilly, and southern terai regions are dominated by cold, temperate, and sub-tropical climates, respectively. Each region has its distinctive housing patterns, cultural differences including the so-called adaptive behaviours to avoid thermal discomfort from the local outdoor environmental conditions. Each year, Nepalese people living in the sub-tropical region face extreme heat in summer, which causes various problems ranging from discomfort to illness and death (Rijal et al., 2010). To avoid the discomforts due to hot environmental conditions, people adopt a variety of actions, such as staying on the roof, in semi-open spaces or front yards during the evening time, drinking cold drinks, taking showers, using fans, and wearing less clothing for the ease of releasing heat from their bodies.

The sub-tropical region has fertile land, plain topography, easy access to various infrastructures such as educational and health facilities (CBS, 2011). Thus, people living in cold and temperate regions migrate to the sub-tropical regions (Government of Nepal, 2013/14). The number of migrants migrated from cold and temperate regions to sub-tropical regions was 410,064 in 1971 and it increased by 3.1 times over a 40-year period and reached 1,273,599 in 2011 (CBS, 2011; and Government of Nepal (2013, 2014). This indicates that migration towards sub-tropical region is one of the major movements of human activities in Nepal.

Migrant people living in new climatic conditions can differ from local people with respect to physio-psychological expectation of indoor thermal environmental conditions that they are exposed. The basic characteristics of skin tissues and sweat glands of people are determined on the basis of the climate of their place of birth (Derbyshire et al., 2012). The study of Nakayama (1981) indicated that humans acquire active sweat glands if they grow in hot climate for the first

2.5 years from birth, and they do not acquire many active glands if they start living in hot climate only after 2.5 years since birth. Liu et al. (2017) examined a tracked field study of thermal adaptation during a short-term migration between cold and hot-summer and warm-winter areas of China and expressed that the previous thermal experience of migrants can affect their ways of thermal response, their behavioural adjustment in particular. In the same way, Luo et al. (1998) studied indoor climate experience, migration, and thermal comfort expectation in buildings and concluded that long-term comfortable thermal experiences may increase people's expectation of thermal environment, and thermal comfort perception is closely related to long-term thermal history. We also focused on the long-term thermal history of the migrant people. Based on Wohlwill (1998), the adaptation of people is based on past environmental exposure. People can exhibit different responses to thermal expectation and thus comfortable temperatures can vary on the basis of seasons and past environmental information accumulated within the minds of people according to their respective experiences (Shukuya (2019). Matsumoto et al. (1999) also described that a short-period adaptation by the migrant people leads to increased sweating and that longer period adaptation by local people leads to more efficient non-transpiration heat dissipation. The short period adaptation (such as more sweating) was observed in Japanese students by Tsujita et al. (1978). Likewise, Hori et al. (1976) suggested that local Thai people possess higher conductive–convective coefficient of heat transfer from body core to skin than that of the Japanese migrant people. Additionally, physiological adaptation based on thermal history is observed in humans and other animals. In this regard, Inagaki (1992) indicated that the hair density of Japanese monkey in cold climate exceeds in other climates; this corresponds to a long thermal history. Thus, long-term thermal history affects thermal physiological adaptation and thermal comfort (Shukuya, 2019).

Many field studies examined thermal comfort and adaptive behaviour in buildings around the world. For example, Nicol and Roaf (1996) observed in Pakistan, de Dear and Brager revisions to ASHREA standard 55 (2002), Wang (2006) studied in Harbin, China, Indraghanti (2010) studied in Hyderabad, India, Nicol et al. (2012), Thapa et al. (2018) studied in north east India, Damiati et al. (2016) studied in office buildings in Malaysia, Indonesia, Singapore, and Japan, Zaki et al. (2017) studied in university classroom in Malaysia and Japan, Khalid et al. (2019)

investigated comfort temperature and adaptation for patients and visitors in Malaysia hospitals. Similarly, Singh et al. (2011) performed a study on the adaptive model of comfort for different climatic zones in India and concluded that the occupants adopt different manners of adaptation based on the types of climatic zones. Following the same intent, Ning et al. (2016) conducted a study on thermal history and adaptation in Harbin, China and suggested that a thermally comfortable zone with a higher indoor temperature was formed in the case of people exposed to warmer climatic conditions. They also observed that the neutral temperature for people with warm exposure was 1.9 °C higher than that for people with cold exposure. Based on the conceptualization of adaptive thermal comfort introduced by Humphreys and Nicol (1998) and, then by Barger and de Dear (1998), Nicol et al. (2012), and Rijal et al. (2018, 2019), people adapt to their thermal environments by adopting various actions such as opening/closing windows, adjusting blinds and by using mechanical heating or cooling. People use the aforementioned adaptive actions to maintain their state of dynamic equilibrium under their surrounding environmental conditions (Humphreys et al., 2013). In this regard, Liu et al. (2017) conducted a study on thermal adaptation during a short-term migration in different climatic areas of China and observed a significant difference in thermal response between migrants and natives. The study suggests that migrant people require a period of time before they can adapt to the thermal environment. The thermal perception of migrant people can gradually increase if they learn techniques for improving their living condition, and this is similar to those adopted by local people.

As we discussed earlier in chapter 1; section 1.1, Figure 1.4, schematic relationship between building environment technology and types of human physical behaviour, horizontal axis, vertical axis, conventional path, proposed path for developing country, proposed path for developed country in the beginning of chapter 1, Figure 5.1 also shows the relationship between types of human physical behaviour and the types of the building environment technology for local and migrant peoples in sub-tropical regions. The horizontal axis represents the types of building technology and the vertical axis represents the types of human physical behaviour. The left side of the horizontal axis indicates that only basic passive technology is used, while the right side indicates that only active technology is used. The former suggests that when occupants are required to restore their thermal comfort, they do everything manually using muscular power; thus, they have a very active behaviour. The latter requires no manual activity or muscular power; it means that people rely on active technology for thermal comfort. In this diagram, the current conditions of local people and migrant people's life style in sub-tropical region is positioned in the area "T". This is due to the difficulty in regulating and sustaining the indoor environmental conditions in old and poor buildings; thus, people need to take more thermal activity to avoid thermal discomfort. The area "T" has two circles with two dots points in the centre representing the condition of traditional houses, of both group of people in sub-tropical region. The traditional houses of migrant people are in active building envelopment system and people are required to restore their thermal comfort with active behaviour. But the result is opposite for the case of local people. This mean that, people can exhibit different responses to thermal expectation and thus comfortable temperatures can vary based on seasons and past environmental information accumulated within the mind of people according to their respective experiences, and active systems may provide the occupants with not much opportunities for adjusting the thermal environment; while on the other hand, the passive systems do require too many actions, in order to achieve comfort (Shukuya, 2019).

Many studies focused on exploring thermal comfort under different environmental conditions. However, there is a paucity of studies regarding the changes of thermal comfort in the adaptability process of migrant people. There are no studies that have yet explored how people adapt to local climate, which differs significantly from their original local climate in the past. With respect to Nepal, a few studies examined the thermal comfort based on field investigations. Although, Rijal et al. (2010, 2018, 2019, and 2020), Gautam et al. (2019), and Thapa et al. (2018) conducted field investigations, they did not focus on the differences between local and migrant peoples in the sub-tropical regions of Nepal. Therefore, it is important to examine the differences in the indoor thermal environment of local and migrant peoples and evaluate the differences or similarities in comfort temperature, preferred temperature, the upper limit of acceptable temperature, and behavioural responses to the thermal environment in summer. In this study, we focused on how the thermal history of people that affects their thermal adaptability. Hence, we investigated the following indicators for local and migrant peoples:

- Thermal acceptability

- Adaptive thermal comfort
- Thermal adjustments

A series of field measurements with a questionnaire survey in the sub-tropical climatic region of Nepal were conducted during the summer of 2019.

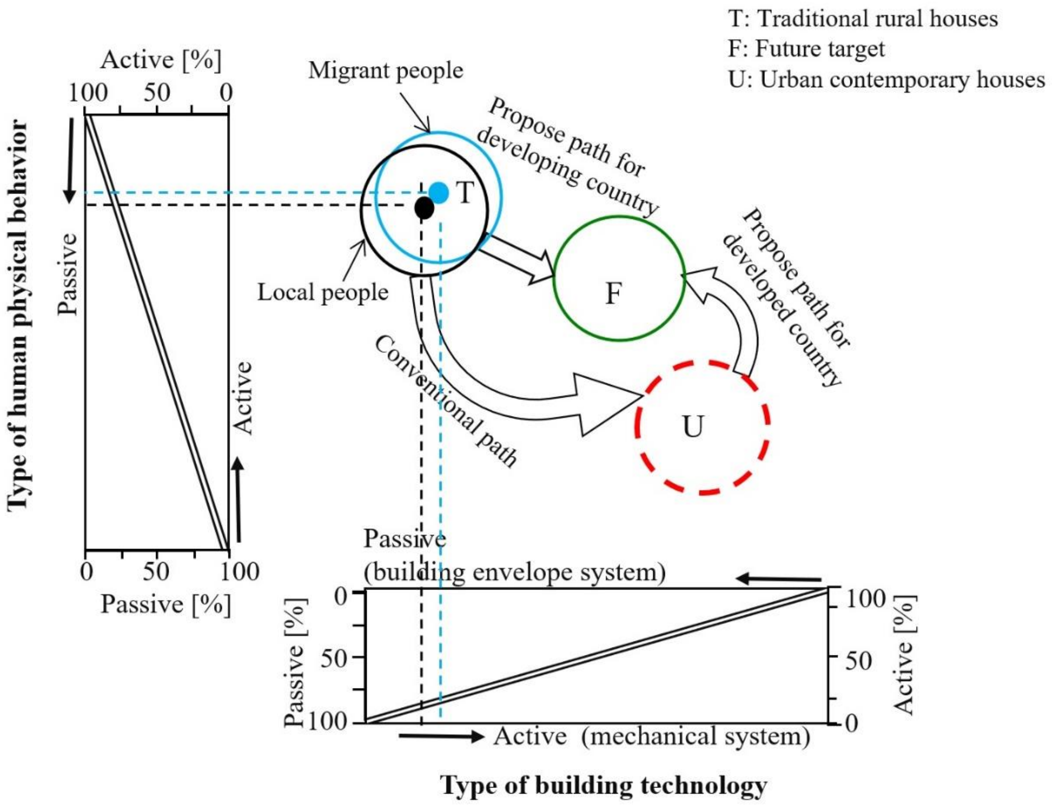


Figure 5.1 Schematic diagram of human physical behaviour and types of the building technology.

5.2 Methodology

5.2.1 Research area and climate

Hariwon was selected as the study area. It is at an altitude 157 m. which is just in the range of terai region from 60 to 600 m. It is located in Sarlahi district, as given in Figure 5.2 (a). Figure 5.2 (b) shows its monthly mean outdoor air temperature and relative humidity by His Majesty's Government of Nepal (1995 ~ 1996). In this area, the climate is dry in March, April, and May and rainy (hot-humid) in June, July, and August. The summer season starts from March to August. The mean outdoor air temperature is high from April to August and relative humidity is high from June to September.

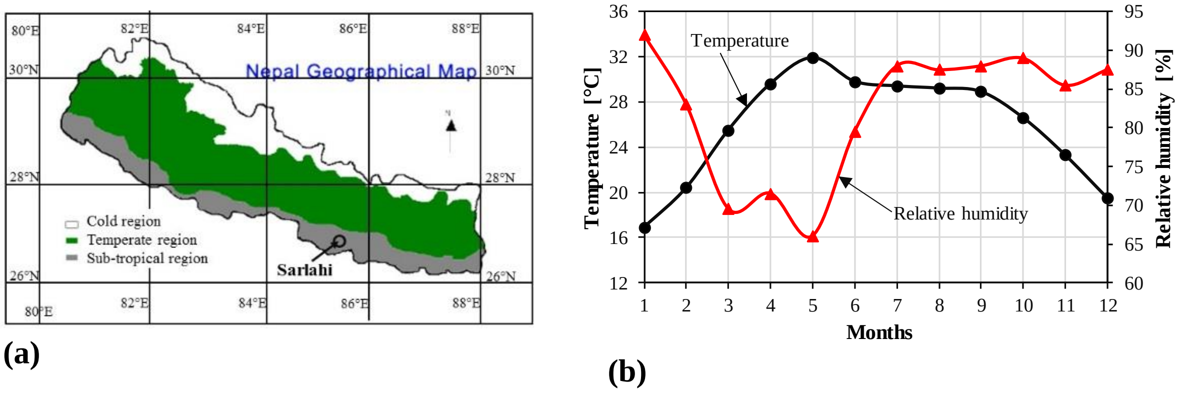
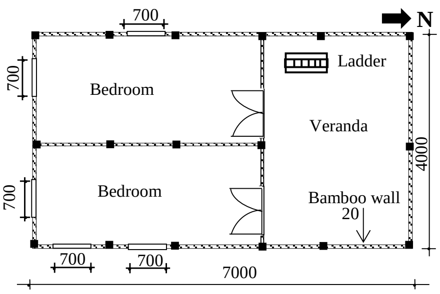
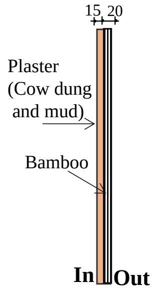


Figure 5.2 General climatic characteristics of the area investigated in the study: (a) Map of Nepal; (b) Monthly mean outdoor air temperature and relative humidity [HMG].

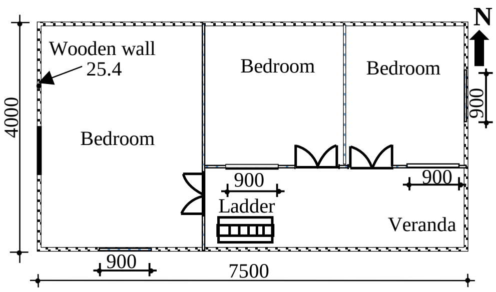
5.2.2 Investigation of houses

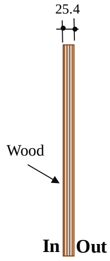
After reaching to the study area, we visited many wooden and brick houses to the maximum possible extent and contacted the people dwelling the village. The sample size for the survey was based on the availability of the people in the village for the interview. Hence, a total of 122 houses (96 wooden and 26 brick) were selected for the investigation. The number of houses of local and migrant peoples corresponded to 61 and 61, respectively. Most of the wooden houses were composed of bamboo walls and tile roof for local people (Figure 5.3 (a)) and wooden walls with tile roofs for migrant people (Figure 5.3 (b)). A few houses were also composed of brick walls and concrete roof for both people (Figure 5.3 (c)). The houses of the local people were connected with each other, while the houses of the migrant people were significantly separated from each other. Generally, the house size of local people was smaller than those of the migrant people. These houses were designed and constructed by local people with locally available materials such as wood, sun dried bricks, and cement. Figure 5.3 shows three examples of wooden and brick houses with cross-sectional views of typical external walls. The brick houses include 230-mm thick brick walls, while the wooden houses include relatively thin walls. Table 5.1 shows the dimensions of these houses, their structure and finishing of the walls, and the size of each window. Generally, the kitchen, storeroom, and living room are on the ground floor, and the bedrooms are on the first floor. These types of houses are widely observed in the study area.



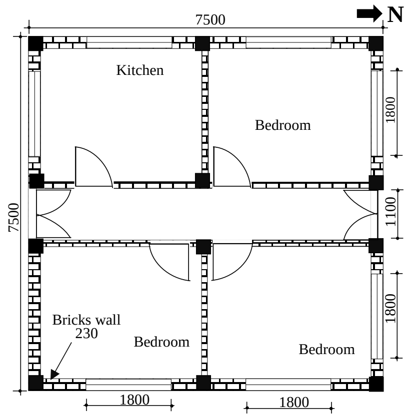


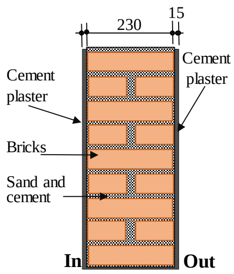
(a) Wooden house used by local people





(b) Wooden house used by migrant people





(c) Brick house used by both peoples

Figure 5.3 Three examples of houses that are investigated in the study: external view, floor plan, and cross section of typical external walls (the units are in mm).

5.2.3 Respondents

Human migration includes the movement of people from one place to another with the intents of settling, permanently or temporarily, at a new location which is different than their original place. The National Living Standards Survey (NLSS-III) defined that: ‘A person who has changed his/her residence from previous place (another VDC or municipality or another country) to the present place (VDC or municipality) is considered a migrant’. All respondents in the present survey live in similar type of houses, as shown in Figure 5.3. We found two types of people in the study area. We defined them by asking their place of origin, caste, religion, language, culture, and festivals as given in Table 5.2. The first type corresponded to local people who were born in Hariwon and were living in the area. The second type corresponded to migrant people who moved to the area from hilly or mountain regions 3 to 20 years before. The interview confirmed as to when they moved. Table 5.3 lists the basic information of local and migrant peoples and their profiles including body height and body mass. Among the 395 respondents, 192 corresponded to local people and 203 corresponded to the migrants. The respondents were 46% males and 54% females for local people and 45% males and 55% females for migrant people. The ages of the respondents ranged from 15 to 70 years. The average age corresponded to 36 years for local people and 38 years for migrant people. All the local and migrant peoples who participated in the survey had been living within the area of 2-km diameter.

Table 5. 1 Description of the three types of houses surveyed

Dimension [m]				No. of floors	Walls			Height and width of a window [m]	No. of windows
Houses	Depth	Width	Height		Structure	Finish	Thickness [mm]		
a	7.0	4.0	5.0	2	Bamboo	Cow dung and mud	20	0.7×1.0	7
b	7.5	4.0	5.0	2	Wood	None	25	1.2×1.2	9
c	7.5	7.5	2.2	1	Bricks	Cement	230	1.8×1.8	7

Table 5. 2 General characteristics of local and migrant peoples

People	Living	Castes	Religions	Languages	Festivals	Clothing	Occupations
Local	Since the birth	Danuhar, Yadab, Koiri, Shaha	Hinduism and Islam	Danuhar, Maithili, Bhojpuri	Kulpuja, Deepawali, Chhath, Holi	Blouse, sari, kurta, salwar, dhoti-kachad	Agriculture, business, services
Migrant	Moved 3–20 years before	Brahmins, Chhetri, Tamang	Hinduism, Buddhism	Nepali, Newari, Tamang,	Dashain, Tihar, Teej, Shivaratri	Blouse, kurta-salwar, sari, pants shirt, t-shirt,	Business, services, agriculture

Table 5. 3 Number of votes and basic information of the respondents

Respondents	Number of votes	Male	Female	Age (Years)		Body height (cm)		Body weight (kg)	
				Mean	S.D.	Mean	S.D.	Mean	S.D.
Local	192	89	103	36	14	157.8	6.2	56.8	8.6
Migrant	203	91	112	38	15	158.5	6.6	58.7	9.1
Total	395	180	215						

S.D.: Standard deviation

5.2.4 Thermal environment measurement and thermal comfort survey

The measurement of thermal environment and thermal comfort survey were conducted for a one-month period from 18th April to 19th May 2019. We measured indoor and outdoor air temperatures and relative humidity and indoor globe temperature and air movement by using a set of instruments as it is presented in Figure 2.10 (a). Table 2.5 shows the details of the measuring instruments. As soon as we arrived in the houses that were surveyed, we first set the instruments outdoors and then indoors. The measurements were performed only once in each house during the daytime from 7:00 to 19:30. The indoor sensors were placed approximately 1.1 m above the floor surface and 1 m. away from the occupants. The outdoor sensors were placed 1.5 m. above the ground surface and approximately 3 m. away from the houses and were protected from the incidence of direct solar radiation. We also measured the indoor air velocity with a hot-wired sensor and with a digital recorder. Given the limited survey period and budget, we were unable to perform continuous measurements in the 122 houses that we visited. Therefore, we conducted a series of spot measurements in those 122 similar types of houses. The measured data was recorded for 15 ~ 20 minutes after the instruments were set to ensure stabilised measurements. We assumed that the measured indoor thermal environmental data can be used for the analysis of the votes given by the respondents. This type of methodology is widely used in adaptive thermal comfort field surveys as it was used by Nicol and Roaf (1996), Nicol et al. (2012), and Humphreys et al. (2013).

All voting was performed in living rooms (n = 188), bedrooms (n = 130) or kitchens (n = 77) where residents used them for sitting, resting and working. To capture their daily lifestyle and minimize the activity level before voting, we did not fix specific room for voting. However, all the rooms were naturally ventilated to a good extent, and thus the temperature difference between the rooms was considered as very low. Additionally, some residents also used the kitchen room for living and sleeping purposes. Figure 2.10 (d) shows one of the interview scenes of data collection in the sub-tropical region. We used the modified scale of thermal sensation (mTSV), thermal preference (TP), and thermal acceptance, as given in Table 2.9. The scales were presented in local language which was also performed in previous studies by Rijal et al. (2010), Thapa et al. (2018), Khatri and Gadi (2019), Humphreys et al. (2016). We prepared a checklist of clothing insulation and recorded the clothing worn by the respondents during the time of survey as given in Table 2.10. Given the absence of data on the thermal insulation level of Nepalese traditional clothing, we applied the closest clothing insulation values available from ISO 2003 and referred to the data reported by Indraganti et al. (2015). We also asked questions on behaviours adopted for thermal comfort. The respondents were asked to choose only one of the behaviours and activity level (the activity of the respondents performed in the last 15 min) from the list that was prepared which is shown in Table 2.9. The metabolic rate was estimated as per ASHRAE Standard 55 (2017).

5.3 Thermal conditions of the investigated houses during the survey

Despite the differences in languages, cultures, religions, and festivals between local and migrant peoples, they live in similar types of houses. Figure 5.4 shows the range of measured indoor air temperature (T_i), globe temperature (T_g), estimated mean radiant temperature (T_{mrt}), and operative temperature (T_{op}) with measured outdoor air temperatures during the voting time (T_o) by using the method of box-plotting. The daily mean indoor air temperature ranged from 27 to 37.2 °C, and this was similar to the values observed in Nepalese traditional houses in summer by Rijal (2018) and also those observed in the central southern part of China by Han et al. (2007). The mean indoor air temperature is closer to the indoor globe temperature, operative temperature, and mean radiant temperature in local and migrant peoples' houses, and thus we used globe temperature for further analysis. The measured indoor globe temperatures at 25% and 75% within the ascending order from the lowest value in the houses of local people corresponded 29.2 °C and 34.2 °C, respectively; and those in the houses of migrant people corresponded 30 °C and 33.1 °C, respectively. A few circles point in the figure are outliers. The fluctuating range of indoor globe temperature in the houses of local people exceeds in the houses of migrant people. The difference can be due to the size of the windows, wall thickness, and heat capacity of the materials used in the houses. The indoor relative humidity was recommended as 40 –70% by Ogawa (1999). Table 5.4 shows the range of measured indoor and outdoor relative humidities, air movement, and metabolic rates of the people during the voting time. Due to naturally ventilated rooms, the indoor relative humidity was similar to that of outdoors, and thus both groups of people were considered as exposed to similar humidity conditions. The maximum indoor air movement was 2.6 m/s during the voting time. More than 84% votes were collected below 0.2 m/s of air movement. The mean activity level of local and migrant peoples was similar (Table 5.4).

Table 5.4 Descriptive statistics of relative humidity, air movement, and metabolic rate

People	Item	RH_i (%)	RH_o (%)	V_i (m/s)	Metabolic rate (Met)
Local (n = 192)	Mean	47	50	0.1	1.4
	S.D.	9	11	0.1	0.5
Migrant (n = 203)	Mean	52	56	0.4	1.5
	S.D.	9	12	0.6	0.7

n: Number of people, S.D.: Standard deviation, RH_i: Indoor relative humidity, RH_o: Outdoor relative humidity, V_i: Indoor air movement

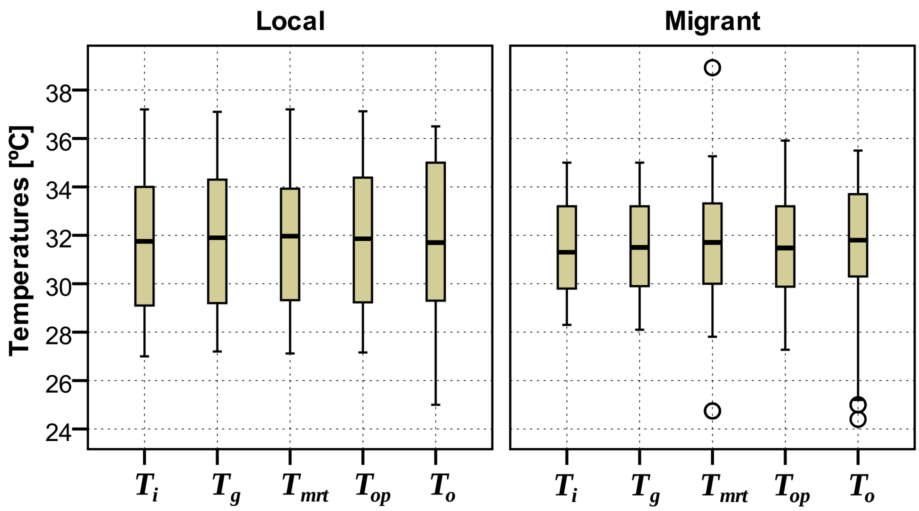


Figure 5.4 Temperature measured in the houses of local and migrant peoples (lower edge denotes 25% from the lowest temperature and upper edge denotes 75% from the lowest temperature).

5.4 Thermal acceptability

5.4.1 Perception of hotness

Local and migrant peoples perceive hotness differently based on their past experiences, and thus it was first analysed. Figure 5.5 shows the frequency distribution of thermal sensation votes obtained from the survey. As it is presented in Table 5.4, the total votes from local people and migrant people are 192 and 203, respectively. Several votes corresponded to “Hot” and “Very hot" for local and migrant peoples. Specifically, 32% votes from local people and 27% votes from migrant people corresponded to "Very hot". Assuming that the thermal sensation votes of either "Hot" or "Very hot" corresponded to "discomfort", 59% discomfort and 56% discomfort levels were observed for local people and migrant people, respectively. Conversely, 41% and 44% comfort levels were observed in local and migrant peoples, respectively. This indicates that more than 50% individuals (irrespective of local or migrant peoples) had difficulty in adapting to the given indoor environment in the study area. With respect to the thermal sensation of "Neutral" alone, 24% votes were obtained from local people and 23% votes were obtained from migrant people. The responses were mainly during morning time, and thus they could have been due to low indoor temperature.

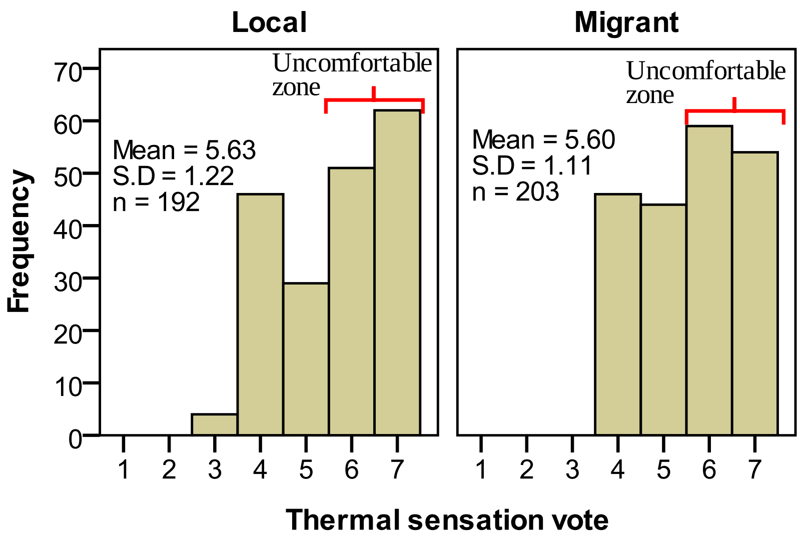


Figure 5.5 Frequency distribution of thermal sensation votes as provided by local and migrant peoples.

We separated thermal sensation votes into votes acquired in morning time (7:00 to 11:00, n = 158), afternoon time (11:00 to 16:00, n = 166), and evening time (16:00 to 19:30, n = 71). Figure 5.6 shows the thermal sensation vote of local and migrant peoples with respect to the time of the day. There is no difference in the mean thermal sensation votes of both groups of people with respect to time. However, there are differences in the votes of local people with respect to time as indicated by the range of standard error. The results indicate that the thermal sensation votes of local people were related to the time of day, which in turn affected the indoor and outdoor temperatures.

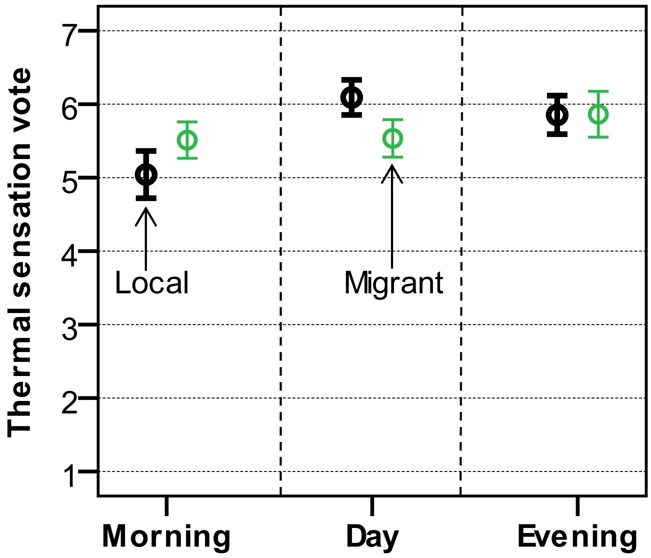


Figure 5.6 Thermal sensation vote of local and migrant peoples in morning, day, and evening times (Mean ± 2 S.E.).

All the thermal sensation votes were sorted into the bins of indoor globe temperature (e.g., "$27.5 \le T_g < 28.5$", "$28.5 \le T_g < 29.5$", . . .). Subsequently, the proportion of the number of hot-side votes, namely "Slightly hot", "Hot", and "Very hot", to the number of all votes within the corresponding bins was calculated. The calculation was separately performed for local and migrant peoples. The results are shown in Figure 5.7. The vertical axis represents the proportion of hot-side votes and the horizontal axis represents indoor globe temperature. The circular plots indicate local people and triangular plots represent migrant people. Although the number of votes from both sets of individuals were similar, we binned the data, and thus higher number of points were obtained for local people. As expected, the proportion of hot-side votes increased gradually when the indoor globe temperature got increased. Given that the plots resemble logistic curves; the following equations are obtained:

Local people, $\ln\left(\frac{P_t}{1-P_t}\right) = 0.472T_g - 13.6$ ($n = 192$, $R^2 = 0.213$, S.E. = 0.083, $p<0.001$) (5.1)

Migrant people, $\ln\left(\frac{P_t}{1-P_t}\right) = 0.334T_g - 9.2$ ($n = 203$, $R^2 = 0.016$, S.E. = 0.098, $p = 0.001$) (5.2)

where P_t denotes the proportion of hot-side votes, n denotes the total number of votes used, R^2 denotes the coefficient of determination, S.E. denotes the standard error of the regression coefficient, and p denotes the significance level of the regression coefficient.

The thermal condition based on the indoor globe temperature of 31 °C or above indicated that more than 70% of people felt hot (local or migrant people). This indicates that the indoor globe temperature adequately reflects the thermal perceptions of hotness. In the case of indoor globe temperature below 30 °C, the proportion of local people is lower than that of migrant people. Luo et al. (2018) presented that thermal experiences can increase the thermal expectation, and thermal comfort perception is closely related to long term thermal history. Similarly, Shukuya (2019) suggested that new pieces of information obtained from external and internal environment is always compared with the old pieces of information that are piled up as memory within brain to ensure that life can be sustained to the maximum possible extent. Hence, local people are potentially more accustomed to the resulting indoor thermal environment in hot and humid climatic region than migrant people. The result is consistent with that of obtained from the study of Xu et al. (2018) in Nanjing, China. The present result suggests that the differences in the climatic background and thereby differences in thermal history affects the thermal perception of people.

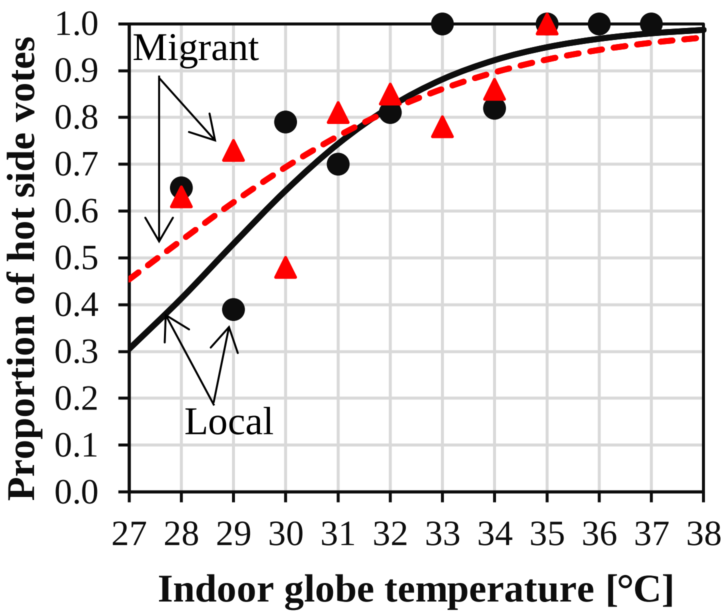


Figure 5.7 Relationship between the proportion of hot-side votes and indoor globe temperature for local and migrant peoples.

5.4.2 Preferences for cooling

Differences in the desires of local and migrant peoples to perform cooling can arise due to their past experiences and thermal history. Therefore, this has been analysed as the second step. Figure 5.8 shows the frequency distribution of thermal preference votes. Most votes correspond to “A bit cooler” for local and migrant peoples. This indicates that the respondents prefer making their indoor environments cooler. The votes for “No change” correspond to 28% for local people and 17% for migrant people. As noted in section 5.4.1, more than 61% votes of local people are associated with the comfort zone. Although, both sets of people are observed as performing similar activities and live-in similar types of houses, local people appear as more satisfied with their indoor thermal environment in comparison to migrant people. The relative number of votes corresponding to either of “A bit cooler” or “Much cooler” are 72% for local people and 84% for migrant people. This is consistent with the results presented in Figure 5.3, especially in terms of the difference in “Slightly hot” votes of mTSV. The values of thermal preference obtained in this study are similar to those obtained in Nigeria by Akande (2010). It is concluded that migrant people are less tolerant of their indoor thermal environment in summer when compared to local people.

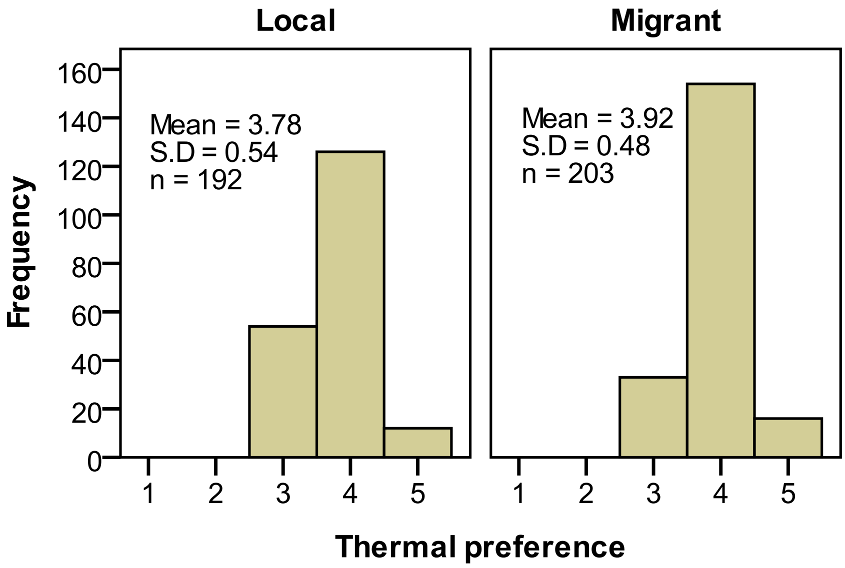


Figure 5.8 Frequency distribution of thermal preference votes as provided by local and migrant peoples.

As noted in the case of thermal sensation votes, we performed a logistic regression analysis. All the thermal preference votes are first sorted into the bins of indoor globe temperature, such as “$27.5 \le T_g < 28.5$”, “$28.5 \le T_g < 29.5$”, . . ., and then the proportion of the number corresponding to either "Much cooler" or "A bit cooler" to all vote numbers within the corresponding bins are calculated. The calculation is performed separately again for local and migrant peoples. Figure 5.9 shows the results. Here, the circular plots correspond to local people and the triangular plots correspond to migrant people. Thus, the following logistic regression equations were obtained.

Local people, $\ln\left(\frac{P_r}{1-P_r}\right) = 0.795T_g\text{-}23.4$ (n = 192, R^2 = 0.375, S.E. = 0.122, p<0.001) (5.3)

Migrant people, $\ln\left(\frac{P_r}{1-P_r}\right) = 0.490T_g\text{-}13.6$ (n = 203, R^2 = 0.090, S.E. = 0.123, p<0.001) (5.4)

where P_r denotes the proportion of people that prefer cooler temperature, and all the other variables are the same as those in equation (5.2).

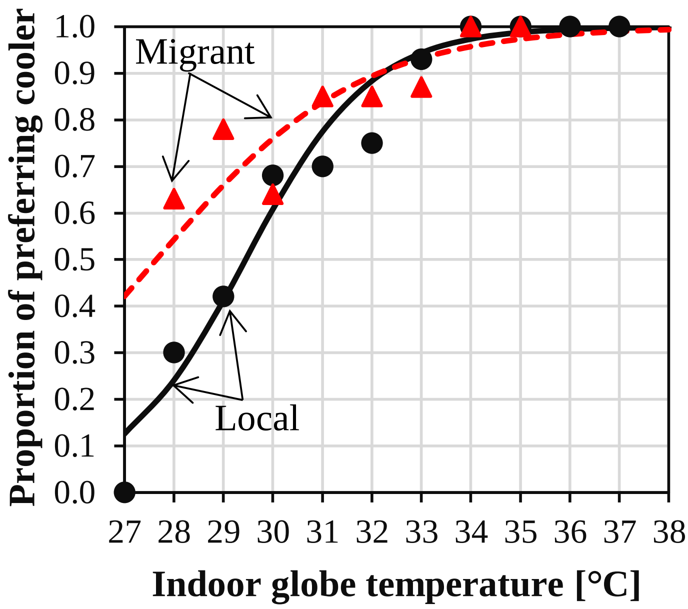


Figure 5.9 Relationship between the proportion of people preferring cooler temperature and the indoor globe temperature for local and migrant people.

When the indoor globe temperature increases, the proportion of people preferring cooler temperature also increases. When the indoor globe temperature is below 31 ºC, the proportion of local people preferring cooler temperature is significantly lower than that of the migrant people. As expected, local people are more satisfied with higher indoor globe temperature than the migrant people. Differences can be observed with respect to age, clothing insulation, activity changes, thermal perceptions, and preferences of people as it was found by Gao et al. (2018). The clothing insulation of people is discussed later. The age group can affect the preferences of people (Schellen et al., 2010). The proportion of local people preferring cooler temperature and that of migrant people indicates a significant difference prior to when the indoor globe temperature reaches 31 ºC. The difference appears to exceed as it is given in Figure 5.5. When indoor globe temperature corresponds to or exceeds 32.5 ºC, more than 90% of local and migrant peoples prefer cooler temperature.

5.4.3 Unacceptability

To confirm the observations in Figures 5.7 and 5.9, we also examined the proportion of unacceptability. The acceptability votes (as to whether the current thermal environment is "Acceptable" or "Unacceptable") are used to calculate the proportion of unacceptability. The votes are again sorted into the bins of indoor globe temperature, such as "$27.5 \leq T_g < 28.5$", "$28.5 \leq T_g < 29.5$", . . ., and the proportion of the number of unacceptable votes to that of all votes within the corresponding bins are calculated. Figure 5.10 shows the proportion of unacceptability and the indoor globe temperature. The circular plots denote local people and triangular plots denote migrant people. The logistic regression fitting leads to the following equations.

Local people, $\ln\left(\frac{P_u}{1-P_u}\right) = 0.212T_g - 9.0$ (n = 192, R^2 = 0.03, S.E. = 0.090, p = 0.018) (5.5)

Migrant people, $\ln\left(\frac{P_u}{1-P_u}\right) = 0.311T_g - 11.2$ (n = 203, R^2 = 0.05, S.E. = 0.098, p = 0.002) (5.6)

where P_u denotes the proportion of unacceptable votes, and all the other variables are the same as those in equation (5.2).

The proportion of thermal unacceptability increases as the indoor globe temperature increases for local and migrant peoples. This indicates that the indoor globe temperature is associated with the respondents' thermal acceptability. Nakaya et al. (2005) reported that the proportion of thermal unacceptability increases as effective temperature increases. The trends obtained here are similar to the findings in Japanese dwellings by Nakaya et al. (2005). The upper limit of acceptable temperature (assuming unacceptability of 10%) is 32 ºC for local people and 29 °C for migrant people, and the latter is 3 °C lower than the former. This is attributed to the differences in thermal environmental information within their brains and bodies that they accumulated through their respective experiences. This conclusion appears considerably reasonable because all migrant people and their family members came from temperate and cold regions and experience the indoor thermal environment with significantly lower temperature in the past than those of local people. Based on ASHRAE standard-55 (2013) Atlanta, the upper limit of indoor air temperature is 30.5 ºC, as accepted by 90% of people, which corresponds to an unacceptability of 10%. The present results corresponding to 32 °C for local people and 29 °C for migrant people are 1.5 °C higher and 1.5 ºC lower than the upper limit value (30.5 °C) as per ASHRAE standard 55-2013. This is potentially because the local people in this study are more tolerant than the people surveyed in the previous studies for creating the ASHRAE standard. It is also reasonable to conclude that the migrant people in the study are originated from cold and temperate regions, and thus they are less tolerant.

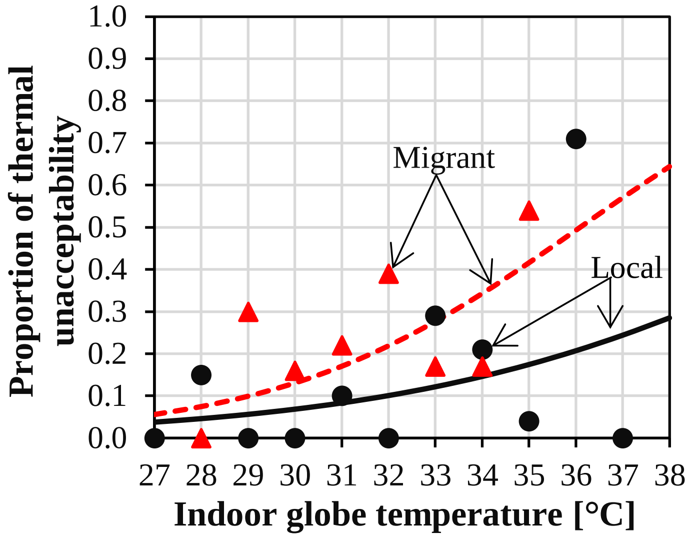


Figure 5.10 Relationship between the proportion of thermal unacceptability and indoor globe temperature of local and migrant peoples.

5.5 Adaptive thermal comfort

5.5.1 Comfort temperature and preferred temperature

People can exhibit different psychological and physiological characteristics inherited from their ancestors and also due to their respective thermal environmental experiences. In the study, we examined whether they reflect the values of comfort temperature and preferred temperature. First, the regression analysis of thermal sensation and indoor globe temperature was made to estimate the comfort temperature. The following regression equations are obtained:

Local people $TSV = 0.20T_g - 0.87$ (n = 192, R^2 = 0.223, S.E. = 0.88, $p < 0.001$) (5.7)

Migrant people $TSV = 0.05T_g + 4.00$ (n = 203, R^2 = 0.007, S.E. = 1.30, $p = 0.219$) (5.8)

where *TSV* denotes the thermal sensation vote, T_g denotes the indoor globe temperature [°C], n denotes the number of people, R^2 denotes the coefficient of determination, S.E. denotes the standard error of the regression coefficient, and *p* denotes the significance level of the regression coefficient.

The regression coefficient of the migrant people is considerably low. When the comfort temperature was estimated by substituting '4 Neutral' in the equations 5.7 and 5.8, it was 24.4 ºC for local people and 0° C for migrant people. The unreliable comfort temperature for migrant people is potentially due to the problem in the application of the regression method which was also indicated in previous studies by Rijal et al. (2010, 2019), Gautam et al. (2019), Griffiths (1990), Rijal et al. (2017), Xu et al. (2018). Based on the votes of the thermal sensation and thermal preference with the corresponding values of indoor globe temperature, we estimated the comfort temperature and preferred temperature values based on equations (2.4) and (2.5). Figure 5.11 shows the frequency distribution of the estimated comfort temperature of local and migrant peoples. The mean values of comfort temperature are 28.5 ºC for local people and 28.3 ºC for migrant people. Therefore, there is no difference between local and migrant peoples in terms of comfort temperature. The values of comfort temperature obtained in this study are very similar to those obtained in previous studies, as listed in Table 5.5. Furthermore, comfort temperature that is lower than those obtained in the present study are from two Japanese cases and partly from Iranian cases and those that are higher from China, Singapore, Malaysia, Indonesia, and India. The range of comfort temperature in Pakistan is wider than thatof the present study. In summer, the comfort temperature obtained in this study does not differ from those in previous studies. As shown in Figure 5.12, the estimated mean preferred temperature of local and migrant peoples are 29.4 ºC and 28.8 °C, respectively, and the latter is 0.6 °C lower than the former. The preferred temperature is significantly close to the comfort temperature, and this is similar to the findings of Hwang (2018).

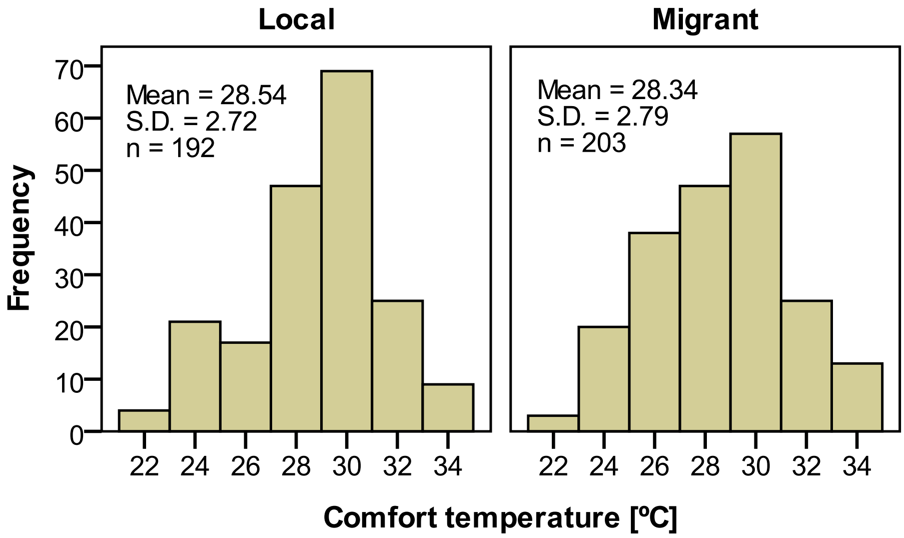


Figure 5.11 Frequency distribution of estimated comfort temperature for local people and migrant people.

Figure 5.13 shows the relationship between the estimated preferred temperature and comfort temperature described above. There are 192 plots for local and 203 plots for migrant peoples. As expected, decreases in the comfort temperature decreases the preferred temperature. The linear regression equations for local and migrant peoples are as follows.

Local people, $T_p = 0.609T_c + 12.1$ (n = 192, $R^2 = 0.51$, S.E. = 0.04, $p < 0.001$) (5.9)

Migrant people, $T_p = 0.502T_c + 14.5$ (n = 203, $R^2 = 0.54$, S.E. = 0.03, $p < 0.001$) (5.10)

where T_p denotes the preferred temperature, T_c denotes the comfort temperature, and all the other variables are the same as those in equation (5.2).

The points at which the comfort temperature and preferred temperature are equal to each other are 31 °C for local people and 29 °C for migrant people. This tendency is again consistent with the results obtained in the previous section. Hence, migrant people are less tolerant of indoor thermal environment than those of the local people. This is similar to the trends obtained in a previous study conducted in Japan, Norway, and in the UK by Shahzad and Rijal (2019).

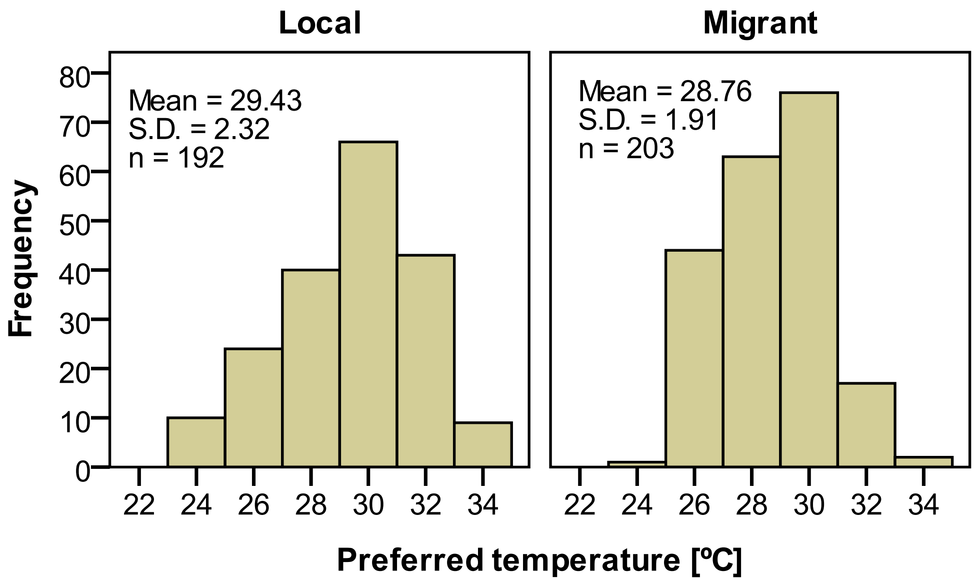


Figure 5.12 Frequency distribution of estimated preferred temperature for local and migrant peoples.

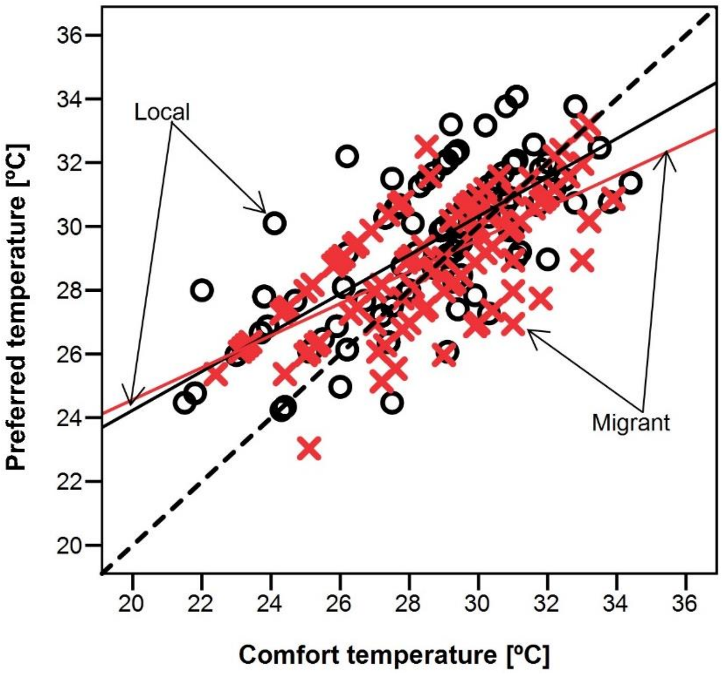


Figure 5.13 Comparison of the estimated preferred temperature and comfort temperature.

Table 5.5 Comparison of estimated comfort temperature obtained in the study with those reported in the previous studies

Countries	Buildings types	Reference	Types of temp.	T_c [ºC]
Nepal (Sarlahi)	Dwelling	This research	Globe	28.3~28.5
Pakistan	Natural ventilated	Nicol and Roaf [1996]	Globe	26.7~29.9
India	Apartment	Indraganti [2010]	Globe	29.2
Japan (Kanto)	Detached & condominium	Rijal et al. [2013]	Air	27.0
China	Chinese dwelling	Han et al. [2007]	Operative	28.6
Japan (Kansai)	Detached houses	Nakaya et al. [2005]	Operative	27.6
Japan (Kanto)	Condominium	Rijal et al. [2020]	Air	25.6
Singapore	Natural ventilated	de Dear et al. [1991]	Operative	28.5
Malaysia	Residential building	Djamila et al. [2013]	Air	30.2
Indonesia	Residential building	Feriadi and Wong [2004]	Operative	29.2
Iran	Dwelling and office	Heidari and Sharples [2002]	Air	28.4

5.5.2 Relationship between the comfort temperature and outdoor temperature

Figure 5.14 (a) shows the estimated comfort temperature values (whose distribution is given in Figure 5.11 that are plotted with respect to the measured outdoor air temperature. The linear regression equations for local and migrant peoples are obtained as follows.

Local people, $T_c = 0.46T_o + 14.1$ (n = 192, $R^2 = 0.33$, S.E. = 0.05, $p < 0.001$) (5.11)

Migrant people, $T_c = 0.66T_o + 7.5$ (n = 203, $R^2 = 0.33$, S.E. = 0.07, $p < 0.001$) (5.12)

where, T_o denotes the measured outdoor air temperature during voting and other variables are the same as those in equations (5.2).

The regression coefficient of local people is lower than that of the migrant people, and thus local people are less sensitive to the given outdoor air temperature (Figure 5.14 (a)). Two regression lines cross at outdoor air temperature of 33 °C, and the corresponding comfort temperature is 29.3 °C. This implies that the comfort temperature for local and migrant peoples is the same at the outdoor air temperature of 33 °C. As discussed in the last paragraph of previous section, the upper limit of acceptable indoor globe temperature is 32 °C for local people and 29 °C for migrant people. The comfort temperature of 29.3 °C at the outdoor air temperature of 33 °C is significantly lower than the acceptable limit temperature for local people. However, it is almost identical to those of the migrant people. The result again suggests that local people are more tolerant than migrant people.

The relationship between comfort temperature and outdoor air temperature is termed as the adaptive model in the study undertaken by Humphreys et al. (2016), which is standardised as per ASHRAE 55 (2013) and CEN 15251 (2007) by compiling the data sets provided for various seasons in various countries. To evaluate the comfort temperature via the adaptive models from existing standards, comfort temperatures of both groups of people are plotted relative to the running mean outdoor air temperature shown in Figure 5.14 (b) and (c). The equations for adaptive standards are given below:

ASHRAE 55 (2004) $T_c = 0.31T_{om}+17.8$ (5.13)

ASHRAE 55 (2013) $T_c = 0.31T_{rm}+17.8$ (5.14)

CEN (2013) $T_c = 0.33T_{rm}+18.8$ (5.15)

where, T_{od} denotes the monthly mean outdoor air temperature and T_{rm} denotes the daily running mean outdoor temperature (°C). The slope and constant are identical for 2004 and 2013 versions of ASHRAE standard.

As shown in Figures 5.14 (b) and (c), we compared the comfort temperature with that of ASHRAE 55 (2013) and CEN (2007) standard because the thermal comfort survey was conducted only for five days, and thus daily running mean temperature is more appropriate for comparison purposes. The same method is also used in previous studies to evaluate the comfort temperature by Damianti et al. (2016), Zaki et al. (2017), Shing et al. (2019), Indraganti et al. (2013 and 2014). Each data point in the figure represents the comfort temperature for each occupant. More than 75% of the comfort temperatures of local and migrant peoples are within the 80% comfort zone of the ASHRAE standard (Figure 5.13 (b)). With respect to the CEN standard, more than 82% of the comfort temperature is within categories III±4K (Figure 5.14 (c)). The results indicate that the comfort limit of local and migrant peoples exceed adaptive thermal comfort standards.

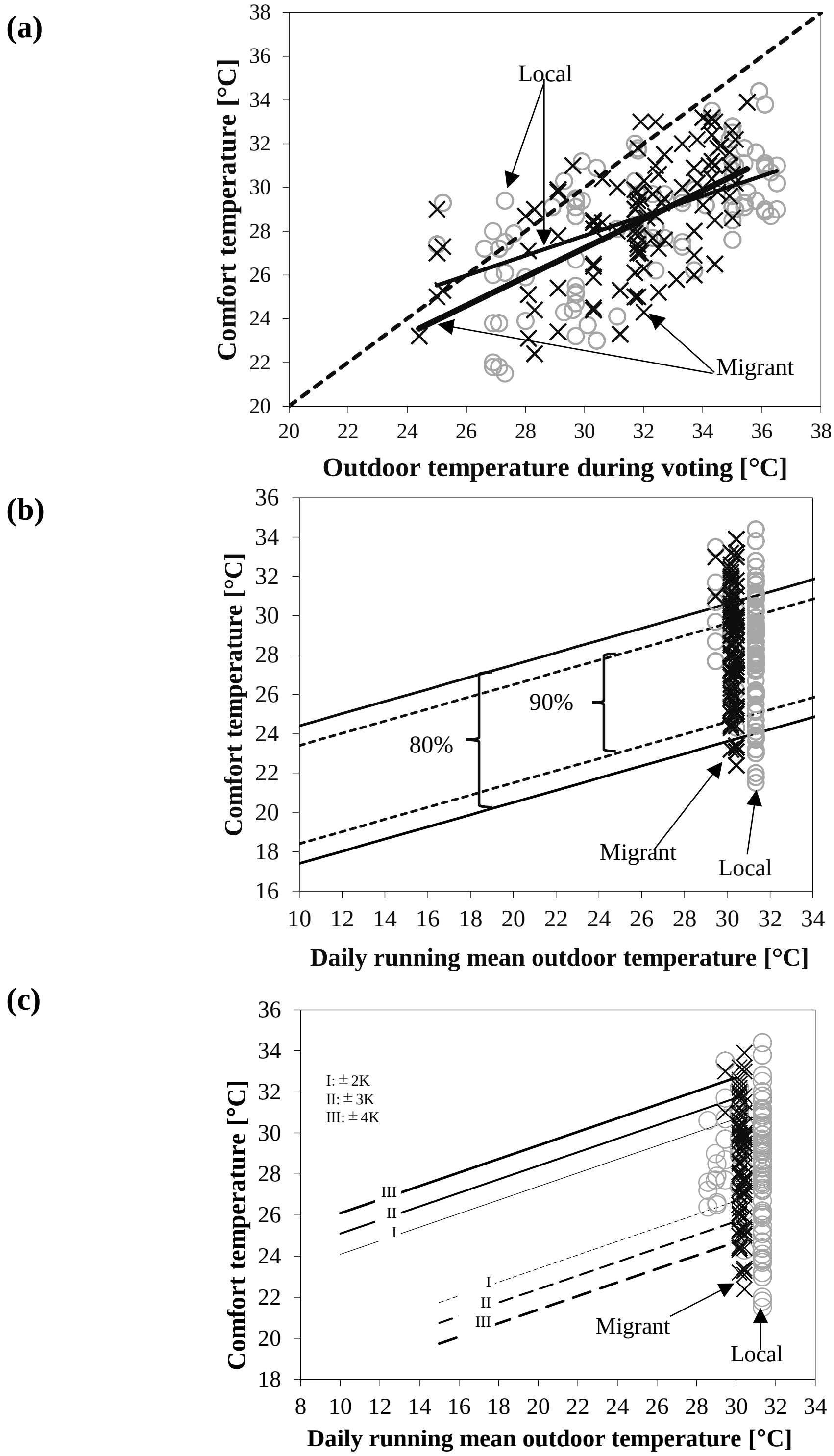


Figure 5.14 Relationship between the comfort temperature and outdoor temperature: (a) present study, (b) ASHRAE standard (2013), and (c) CEN standard. The weighting factor to calculate the running mean temperature is assumed as 0.8, which is identical to that used in the CEN standard.

5.6 Thermal adjustments

5.6.1 Perception of sweating

The perception of sweating is physiological response of human body and involves measurement of sweat that is perspired. However, it is not easy to directly measure the sweating rate of people. Thus, we asked the perceived level of sweating. Sweating is a bodily function that aids in regulating body-core and skin-layer temperatures. Green et al. (2001) studied entitled lactate sweat relationship in young and middle-aged men and concluded that sweating is also dependent on skin layer and body core temperatures and the activity level of people. Figure 5.15 shows the perception of sweating for local and migrant peoples. The percentage of “None” for local people is 42%, which exceeds than those of migrant people by 26% (= 42%-16%). With respect to “Slightly” and “Moderately” votes, it is significantly higher for the migrant people. The results indicate that it is difficult for migrant people to adapt to the given indoor thermal environment.

All the perceived sweating votes are sorted into the bins of indoor globe temperature (e.g., “$27.5 \le T_g < 28.5$”, “$28.5 \le T_g < 29.5$, . . .,) and then the proportion of the number of sweating votes (either “Slightly”, “Moderately” or “Largely”) to that of all votes within the corresponding bins are calculated. This calculation is performed for local and migrant peoples. Figure 5.16 shows the relationship between the proportion of sweating and measured indoor globe temperature. The symbols in the figure are identical to those used in the previous figures. Based on the same procedure as before, the following logistic regression equations for local and migrant peoples are obtained:

Local people, $\ln\left(\frac{P_s}{1-P_s}\right) = 0.547T_g - 16.9$ (n = 192, $R^2 = 0.32$, S.E. = 0.077, $p < 0.001$) (5.16)

Migrant people, $\ln\left(\frac{P_s}{1-P_s}\right) = 0.478T_g - 13.1$ (n = 203, $R^2 = 0.09$, S.E. = 0.124, $p < 0.001$) (5.17)

where, P_s denotes the proportion of sweating votes and all the other variables are the same as those in equation (5.2).

The proportion of sweating increases when the indoor globe temperature gets increased. The difference between local and migrant peoples is significant. In the case of indoor globe temperature at 29 ºC, only 26% of the local people perceived sweating while 66% of migrant people perceived sweating. When the indoor globe temperature gradually increases, the difference in the proportion of perceived sweating between local and migrant peoples decreases and the difference between them is less than 10% when the indoor globe temperature is 35 °C.

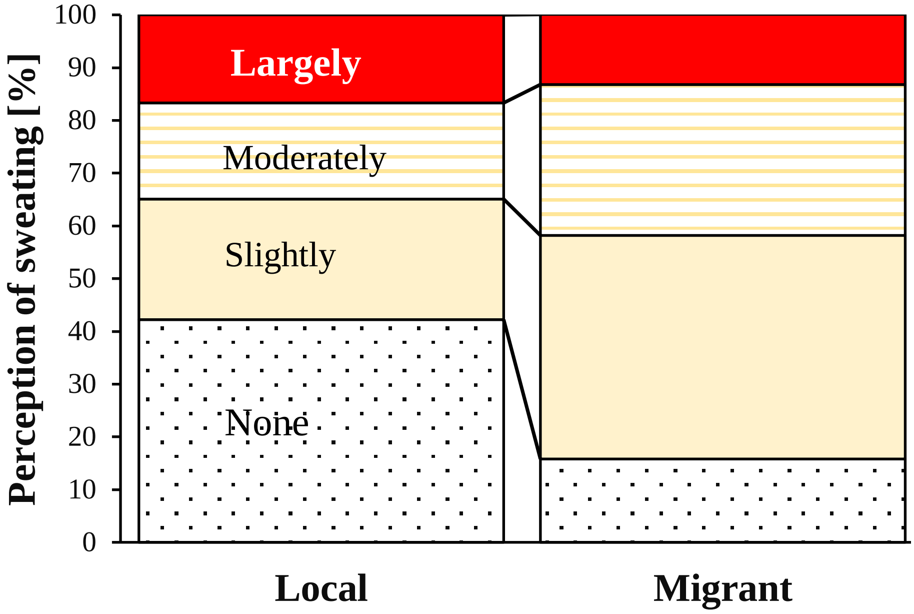


Figure 5.15 Perception of sweating for local and migrant peoples.

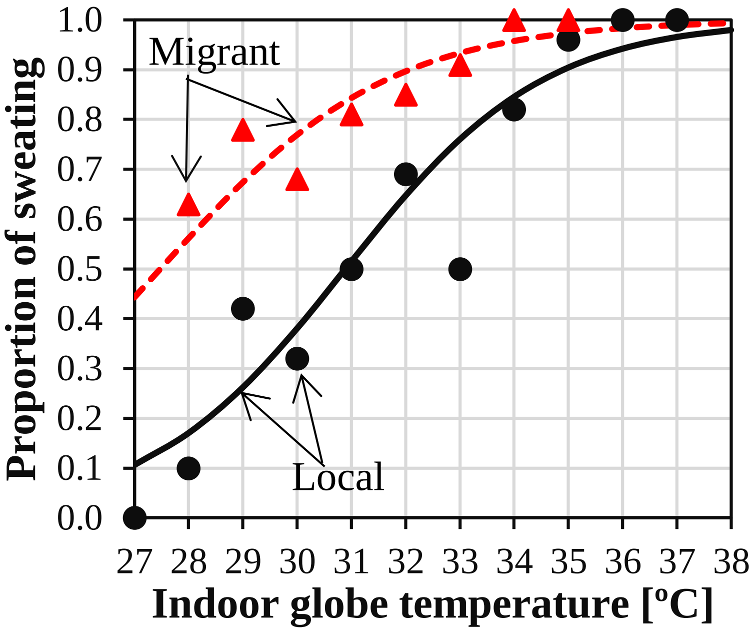


Figure 5.16 Relationship between the proportion of sweating and indoor globe temperature for local and migrant peoples.

5.6.2 Behaviors taken to adjust thermal environment

Typically, people adopt two types of adaptive behaviours: one is to change their indoor environmental condition (e.g., opening windows) and the other is to change themselves (e.g., wearing less clothes) as it is discussed by Nicol (2004) in his study on adaptive thermal comfort standard in the hot humid tropics. The harshly hot and humid natural environment in summer season require people to adopt a variety of behaviours to restore thermal comfort (Rijal et al., 2010). We observed certain behaviours adopted by the respondents, which is given in Table 2.9, during the survey time (e.g., using fan, light clothes, taking showers, sitting under a shade, and nothing in particular).

Figure 5.17 shows the percentage of behaviours adopted to adjust thermal environment for local and migrant peoples. We received most votes for “Use fan” by 48% of local people and by 66% of migrant people. This indicates that the respondents prefer using fans for coolness. It is known that the comfort temperature can be increased by 2 ºC, over a wide range of outdoor air temperature when fan usage is increased (Nicol et al., 2004). Local people tend to use light clothes more when compared to the migrant people. However, the difference between local and migrant peoples is not significant. Local people also tend to shower more frequently than the migrant people. However, migrant people tend to sit in the shade more often. Besides, measures corresponding to “Nothing in particular” is more adopted by local people than by the migrant people. This is potentially because the level of adaptation in local people exceeds that of migrant people.

Figure 5.18 shows the frequency distribution of clothing insulation of local and migrant peoples. The arithmetic mean clothing insulation of local and migrant peoples is approximately 0.52 clo. However, the most clothes voted corresponds to 0.40 clo for local and migrant peoples. Nepalese people wear different clothing based on seasons, and thus the clothing is lighter in summer and heavier in winter (Rijal et al., 2010). The mean clothing insulation obtained in the study is similar to other studies given in Table 5.6. This is probably due to the limitation of clothing in summer and because Nepalese people mostly follow the cultural tradition.

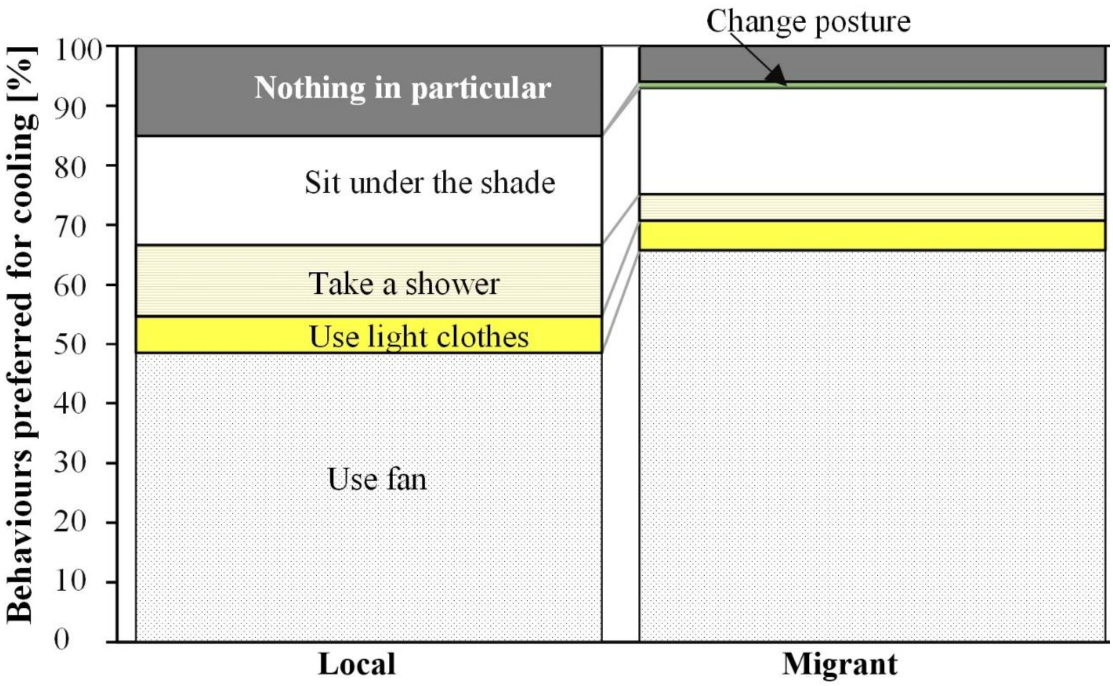


Figure 5.17 Various behaviors adopted to restore thermal comfort.

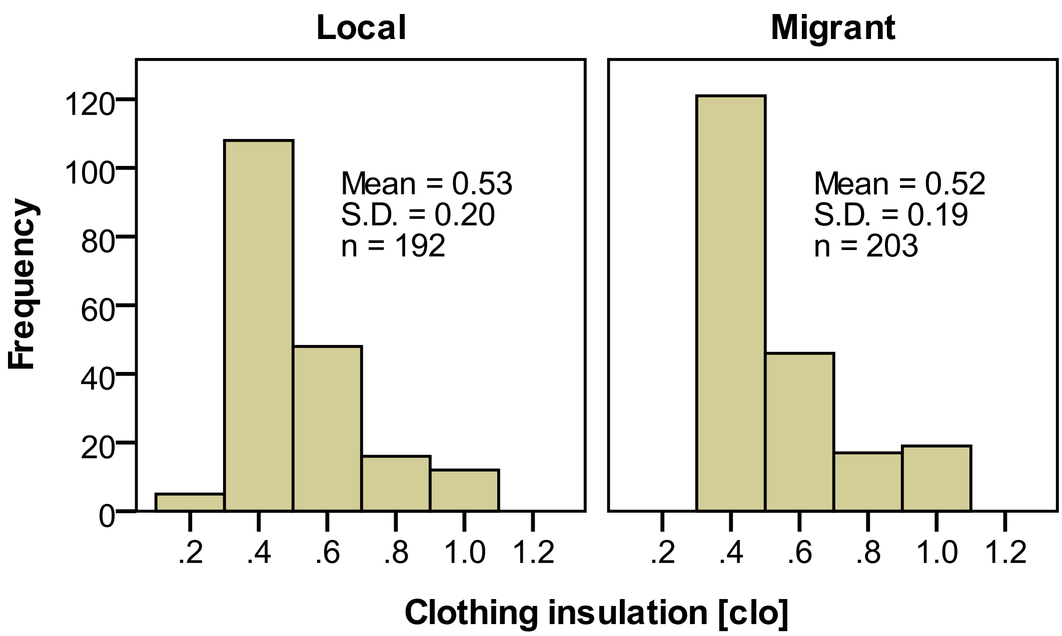


Figure 5.18 Frequency distribution of the clothing insulation for local and migrant peoples.

Table 5.6 Comparison of clothing insulation in summer with previous studies

Country	Reference	Climate	Number of vote	Mean I_{ci} [clo]
Nepal	Present study	Sub-tropical	395	0.50
Nepal	Rijal [2018]	Sub-tropical	6*	0.47
India	Thapa et al. [2018]	Sub-tropical and humid	436	0.50
Brazil	Vecchi et al. [2017]	Temperate and humid	466	0.42
China	Xu et al. [2018]	Sub-tropical	161	0.46
China	Jiao et al. [2074]	Sub-tropical	1161	0.44

*: Number of people, I_{ci} : Clothing insulations

5.7 Conclusions

In the study, a thermal comfort survey with thermal environmental measurements was conducted in the sub-tropical region of Nepal in order to investigate the effect of thermal history on thermal comfort of local and migrant peoples. The thermal acceptability, adaptive thermal comfort, and thermal adjustments were selected as the key indicators. The results obtained are as follows:

1. The upper limit of acceptable indoor globe temperature for local people was 32 °C, which is 3 °C higher than those of the migrant people. This difference was due to the difference in the thermal history embedded within the body and brain between local and migrant peoples. This is probably the reason as to why migrant people cannot easily accept the high indoor temperature in sub-tropical regions in the summer season.
2. There is a significant difference in the preferred temperature between local and migrant peoples under the condition of indoor globe temperature lower than 31 ºC. This indicates that it is more difficult for the migrant people to maintain thermal comfort than those of local people. At globe temperature above 31 °C, the difference gradually decreases, and the difference ceases as the indoor globe temperature reaches 35 °C.
3. The proportion of the sweating votes was 26% within all votes of local people, while it was 66% within those of migrant people. Migrant people voted “sweating” more than local people.

4. Among various adaptive behaviours that should be considered for restoring thermal comfort, fan usage was dominant for both the local and migrant peoples.
5. Local people appeared more tolerant than migrant people because the percentage of people who adopted "Nothing in particular" behaviour was higher in local people than to the case of migrant people.

In conclusion, all three indicators used in the study suggest that it is highly probable that the thermal history developed through past experiences affects the thermal adaptability of people in summer. Therefore, it is necessary to recommend a solution for providing people with sufficiently comfortable built environment based on their thermal history. The finding of the study indicates that a single standard or guideline for a uniform thermal environment and comfort may not be appropriate. However, it should be established with respect to each region. The study was limited for summer cases, and thus a similar investigation for winter is necessary. Indoor acceptable temperature, comfort temperature, and thermal adjustments with respect to migration period, season, age, gender, and economic background should be examined further in the future to confirm the thermal adaptation of local and migrant peoples. This will deepen our understanding on the short- and long-term thermal history of migrant people. The knowledge will consequently aid in providing a better indoor thermal environment.

Chapter 6: Conclusions and recommendations

This chapter is all about the summary, conclusions, and implications of the research. In this chapter, I have briefly summarized the entire thesis from Chapter three to Chapter five with all topics and sub-topics as much as possible. Finally, a summary of this particular chapter is outlined.

6.1 Conclusions of chapter 3

In the third chapter, we discussed a series of surveys on the indoor thermal environment in three climatic regions; cold, temperate, and sub-tropical regions in winter and summer. Continuous measurement of the thermal environment was performed for a month from December 3rd 2016 to January 3rd 2017 for winter and April 18th to May 17th, 2019 for summer. Indoor air temperature, outdoor air temperature, indoor globe temperature, indoor relative humidity, and outdoor relative humidity were measured at respective regions and sensors with digital data loggers at the interval of 10 minutes. The indoor air temperature for all investigated houses is highly affected by the outdoor air temperature. Among all three climatic regions; the range of outdoor air temperature is narrower in the cold region than that of temperate and sub-tropical regions in both seasons.

The mean indoor air temperature in winter is 10.9 °C, 15.4 °C, and 18.4 °C in cold, temperate, and sub-tropical regions, respectively. However, the mean indoor air temperature in summer is 15.6 °C, 25.7 °C, and 29.9 °C in cold, temperate, and sub-tropical regions, respectively. The cause of this in indoor air temperature may be due to the size of the windows, wall thickness, and heat capacity of the materials used. The seasonal differences of mean indoor air temperature are 4.7 °C, 10.3 °C, and 11.5 °C in cold, temperate, and sub-tropical regions, respectively. The regional differences between indoor air temperature (ΔT_i) for temperate and cold regions are 8.8 °C in summer. Similarly, the regional differences between indoor air temperature (ΔT_i) for temperate climate is 3.1 °C in summer. However, the regional differences between indoor air temperature (ΔT_i) for sub-tropical and cold regions are 11.5 °C in summer, which is wider than that of the other two regions. This is caused by the difference in elevations.

In the winter, 80% cumulative frequency of indoor air temperature is 11 °C, 16 °C, and 22 °C in cold, temperate, and sub-tropical regions respectively. In the temperate climatic region, it has been found that in 80% of the time, temperature is below 16.5 °C and 18.2 °C in H1 (traditional house) and H4 (modern house). However, 80% of the time temperature is below 22.8 °C and 21.0 °C in H13 and H16. It is concluded that the indoor air temperature does not only depend on the outdoor air temperature but also depends on the thickness of the walls, materials used in houses, and size of the windows. Compared to modern houses, the traditional houses were 3.8 °C, and 2.5 °C cooler in temperate and sub-tropical regions in summer but the result is opposite in the cold region. Still, the cold region has low indoor air temperature which means the traditional house is better than modern house in cold regions.

The indoor water vapor concentration looks quite similar to outdoor water vapor concentrations in all investigated areas. The mean indoor water vapor concentration is low in cold (7.4 g/m^3), middle in temperate (11.9 g/m^3), and high in sub-tropical (17.5 g/m^3) regions, respectively. The regional difference in the summer mean indoor water vapor concentration is 4.5 g/m^3 between temperate and cold regions, 5.6 g/m^3 between sub-tropical and temperate regions, and 10.1 g/m^3 between sub-tropical and cold regions. These differences might be the effect of the lower indoor air temperature in the cold region and higher indoor air temperature in the sub-tropical region.

6.2 Conclusions of chapter 4

In the fourth chapter, we discussed how people living in different climatic regions of Nepal achieve thermal comfort in their respective traditional houses by undertaking various adaptive behaviours such as clothing adjustment in winter and other adaptive behaviours in summer. For this purpose, we measured the indoor thermal environment in 427 traditional houses and conducted thermal comfort survey with 1008 respondents present at home during the daytime between 7:00 to 19:30, in cold, temperate and sub-tropical regions in winter and summer.

The percentage of people reporting their environments to be in the “comfort zone”, which is assumed to correspond to the central 3 categories of thermal sensation vote, is 76.8%, 82.6%, and 84.7% in winter and 99.2%, 79.0%, and 45.8% in summer in the cold, temperate, and sub-tropical regions, respectively. The people seem to adapt the given indoor thermal environment in the respective climatic regions in winter. However, the people of the sub-tropical region feel difficult to adapt to the given indoor thermal environment in summer.

The mean comfort temperature in the cold region was 13.8 °C, which is 4.1 °C and 9.3 °C lower than that of in temperate and subtropical regions in winter. Similarly, the mean comfort temperature is lower (16.8 °C) in the cold region, middle (24.8 °C) in temperate region, and high (28.4 °C) in sub-tropical region in summer. The comfort temperature in cold region is similar to the one observed in previous studies, but significantly lower than that given in ASHRAE and CEN standards. It indicates that we may need to propose an adaptive standard which is suitable for extremely cold regions.

The seasonal differences of comfort temperature are 3.0 °C, 6.9 °C, and 5.3 °C in cold, temperate, and sub-tropical regions, respectively. The regional difference of comfort temperature for temperate and cold region are 4.1 °C and 6.6 °C in winter and summer. Similarly, the regional difference of comfort temperature for sub-tropical and temperate region are 5.2 °C and 4.6 °C in winter and summer. The regional difference of comfort temperatures for the sub-tropical and cold region are 9.3 °C and 11.9 °C in winter and summer. However, the regional difference of comfort temperature for these regions is higher in comparison to other regions.

The mean preferred temperature in the cold region is 14.7 °C, which is 3.8 °C and 8.1 °C lower than in the temperate and subtropical regions in winter. The preferred temperature is 0.9 °C higher than the comfortable temperature in the cold region. As expected, in summer, the preferred temperature is low in the cold, middle in temperate, and high in sub-tropical regions, respectively. The mean preferred temperature in the cold region is 17.2 °C, which is 6.6 °C and 11.9 °C lower than that of the temperate and subtropical regions in summer. The results indicate that people desire a warmer thermal environment in the cold regions in both seasons, which is considered to be a natural physio-psychological tendency of human beings.

The mean clothing insulation in the cold region was 1.63 clo, which is 0.31 clo and 0.48 clo higher than in the temperate and sub-tropical regions in winter. As expected, in summer, the clothing insulation value is high in cold, moderate in a temperate region, and high in sub-tropical regions, respectively. The mean clothing insulation in the cold region was 1.4 clo, which is 0.7 clo and 0.9 clo higher than that in the temperate and sub-tropical regions in summer. The clothing insulation is negatively correlated with outdoor air temperature. This result indicates that people increase the level of clothing insulation as their major adaptive behaviour in the cold regions in order to survive under low-temperature indoor conditions.

Overall, we have concluded that there exists a significant regional difference in the indoor air temperature, comfort temperature, preferred temperature and clothing insulation in winter and summer, and also that the people living in Nepalese traditional houses tend to achieve thermally comfortable conditions by adjusting their clothing as much as possible, depending on their respective local climate and building conditions. The context clarified in this analysis is, we believe, applicable to similar climates, building types and lifestyles in other regions.

6.3 Conclusions of chapter 5

In the fifth chapter, we discussed adaptive thermal comfort considering the thermal history of local and migrant peoples living in the sub-tropical climatic region of Nepal. The thermal comfort survey with thermal environmental measurements was conducted in the sub-tropical region of Nepal to investigate the effect of thermal history on the thermal comfort of local and migrant peoples. The thermal acceptability, adaptive thermal comfort, and thermal adjustments were selected as the key indicators. The sample size for the survey was based on the availability of the people in the village for the interview. Hence, a total of 122 houses (96 wooden and 26 brick) were selected for the investigation. Among the 395 respondents, 192 corresponded to local people and 203 corresponded to the migrants. The respondents were 46% males and 54% females for local people and 45% males and 55% females for migrant people.

The upper limit of acceptable indoor globe temperature for local people was 32 °C, which is 3 °C higher than that of the migrant people. This difference was due to the difference in the thermal history embedded within the body and brain between local and migrant peoples. This is probably the reason why migrant people cannot easily accept the high indoor temperature in sub-tropical regions in the summer season. There is a significant difference in the preferred temperature between local and migrant peoples under the condition of indoor globe temperature lower than 31 ºC. This indicates that it is more difficult for migrant people to maintain thermal comfort than those of the local people. At globe temperature above 31 °C, the difference gradually decreases, and the difference ceases as the indoor globe temperature reaches 35 °C.

The proportion of the sweating votes was 26% within all votes of local people, while it was 66% within those of migrant people. Migrant people voted "sweating" more than the local people. Among various adaptive behaviours that should be considered for restoring thermal comfort, fan usage was dominant for local and migrant peoples. Local people appeared more tolerant than migrant people because the percentage of people who adopt "Nothing in particular" behaviour was higher in local people than those of migrant people.

6.4 Recommendations

The traditional houses are well adapted to the local climate with the use of the local building materials. However, traditional practice has been diminished by the more introduction of the artificial building materials, modern design, and new technology. Under this circumstance, some strong policies based on a field research to sustain the traditional architecture with some rational modern metamorphosis is necessary. To sustain traditional constructing technology, we have to make policies to improve traditional technology using modern skills without deteriorating the cultural norms by keeping an eye on positive aspects of traditional houses that should be preserved and inherited in the future. All over the world, 40% of the energy supplied is used in buildings. Most of the people in Nepal are living with passive means of heating and cooling; that is, without mechanical heating and cooling. Therefore, their indoor thermal environment depends much on natural climatic patterns. The traditional construction skill of building systems has been replaced with modern technologies and contemporary houses. We have to control such encroachment of modern housing technology on traditional houses.

The people living in Nepalese traditional houses tend to achieve thermally comfortable conditions by adjusting their clothing as much as possible, depending on their active physical behaviours in respective local climate and building conditions. The context clarified in this analysis is, we believe, applicable to similar climates, building types, and lifestyles in other regions. The findings seem to be useful for the improvement of traditional houses and to control such encroachment of modern housing technology on traditional houses in cold, temperate, and sub-tropical climatic regions in the future.

The three indicators; thermal acceptability, adaptive thermal comfort, and thermal adjustment used in the study suggest that the thermal history that is developed through past experiences affects the thermal adaptability of people in summer. Therefore, it is necessary to recommend a solution for providing people with a sufficiently comfortable built environment based on the thermal history of people.

The findings of the study indicate that a single standard or guideline for a uniform thermal environment and comfort may not be appropriate. However, it should be established with respect to each region. The study is limited for summer cases, and thus a similar investigation for winter is necessary. Indoor acceptable temperature, comfortable temperature, and thermal adjustments with respect to migration period, season, age, gender, and economic background should be examined further in the future to confirm the thermal adaptation of local and migrant peoples. This will deepen our understanding of the short-term and long-term thermal history of migrant people. The knowledge will consequently aid in providing a better indoor thermal environment.

6.4 Further work

People in Nepal are living with passive means of heating and cooling; that is, without mechanical heating and cooling. Therefore, their indoor thermal environment depends much on natural climatic patterns. When people are required to restore their thermal comfort, they do everything manually using muscular power; thus, a very active behaviour. The later requires no manual activity or muscular power. It means that people rely on active technology for thermal comfort. In the current conditions of traditional houses in Nepal, people get thermal comfort only manually active using muscular power. This is due to the difficulty in regulating and sustaining the indoor environmental conditions in old and poor buildings; thus, people need to take more thermal activity to avoid thermal discomfort. People are required to restore their thermal comfort, representing contemporary houses, in which mechanical systems for heating and cooling, particularly in the urban areas of developed countries, are used. People can be more passive in their behaviour as the active systems take over most regulation of the indoor thermal environment.

In both situations, people may lack optimal overall health and comfort. On the one hand, the active systems may provide the occupants with less opportunities for adjusting the thermal environment; while on the other hand, the passive systems do require too many actions, in order to achieve comfort (Shukuya, 20109). Our future target includes various occupants' behaviours together with the rational use of various passive and active technologies in buildings.

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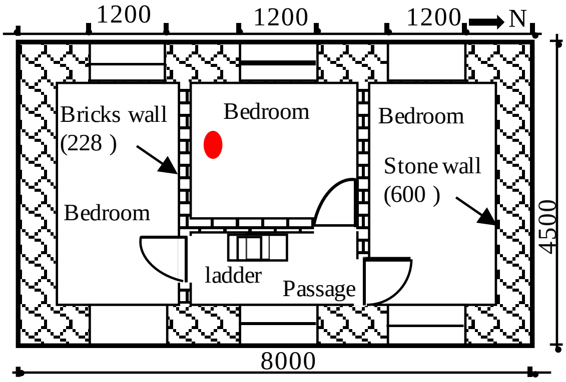
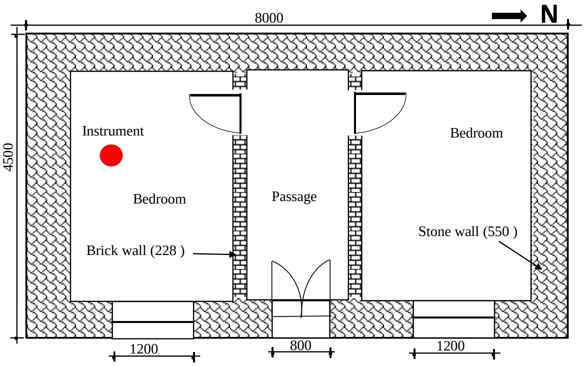
Appendix-1

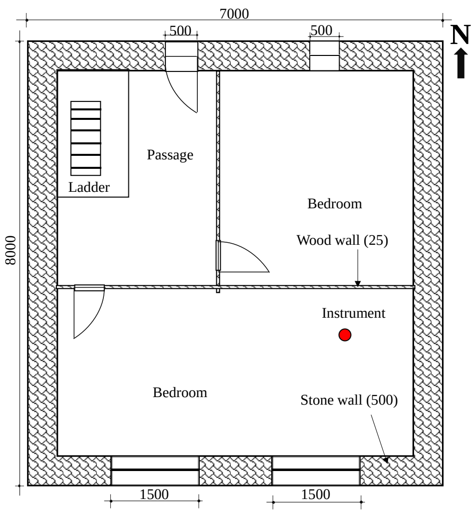
Traditional and modern houses their plan view that were continous measured indoor thermal environment in the cold, temperate, and sub-tropical regions.



H1

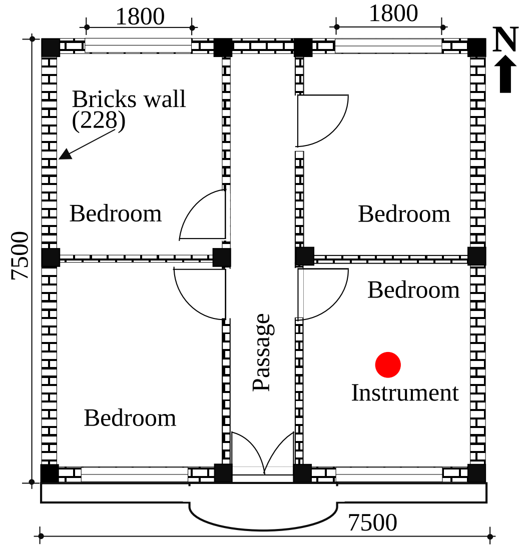


H2

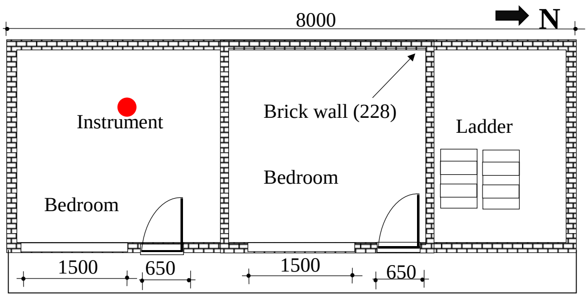


H3


HOTEL AMMONITE
2019

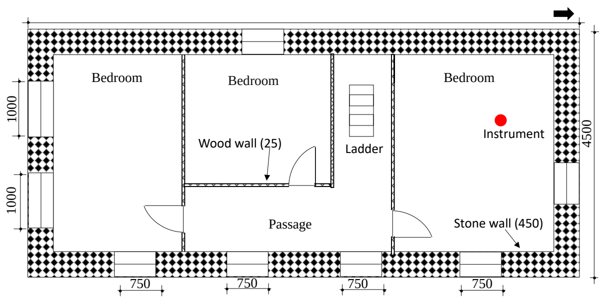

1800
1800
N
Bricks wall
(228)
Bedroom
Bedroom
Bedroom
Passage
Instrument
Bedroom
7500
7500

H4

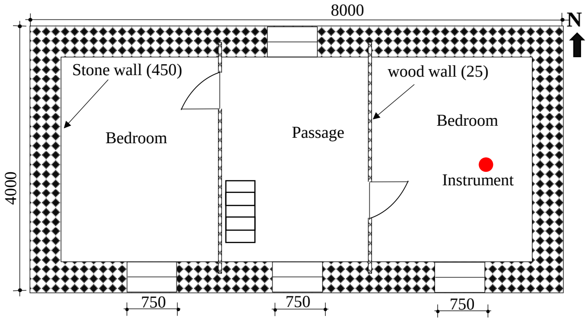

8000
N
Instrument
Brick wall (228)
Ladder
Bedroom
Bedroom
1500
650
1500
650

H5

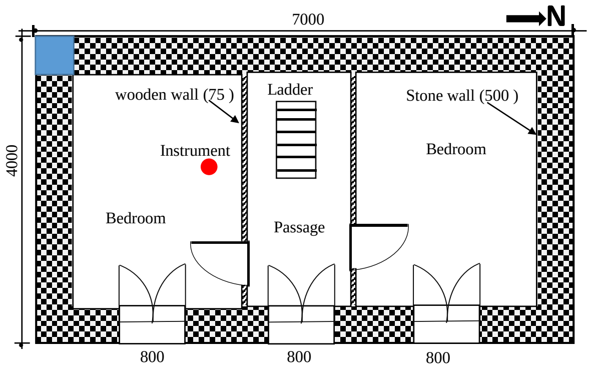

2019/11/04


Bedroom
Bedroom
Bedroom
1000
Wood wall (25)
Ladder
Instrument
4500
1000
Passage
Stone wall (450)
750
750
750
750

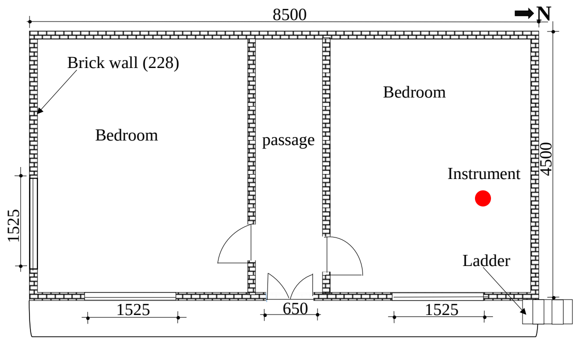
H7


8000
N
Stone wall (450)
wood wall (25)
Bedroom
Passage
Bedroom
Instrument
4000
750
750
750

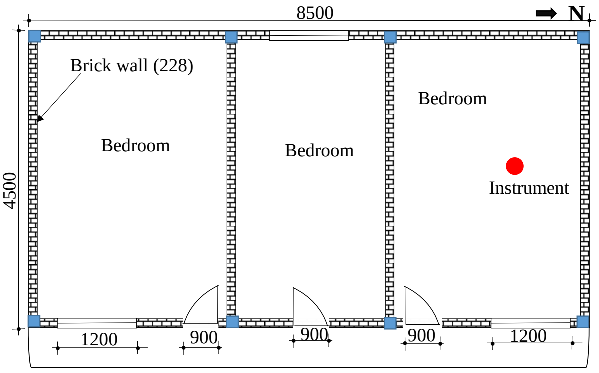
H8


7000
N
wooden wall (75)
Ladder
Stone wall (500)
Instrument
Bedroom
4000
Bedroom
Passage
800
800
800

H9


8500
N
Brick wall (228)
Bedroom
Bedroom
passage
Instrument
4500
1525
Ladder
1525
650
1525

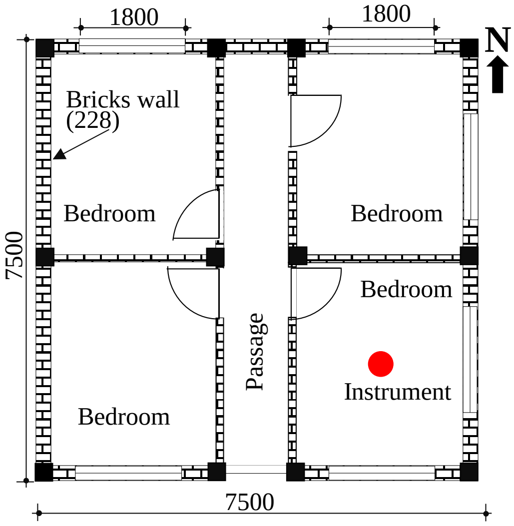
H10



8500
N
Brick wall (228)
Bedroom
Bedroom
Bedroom
Instrument
4500
1200
900
900
900
1200

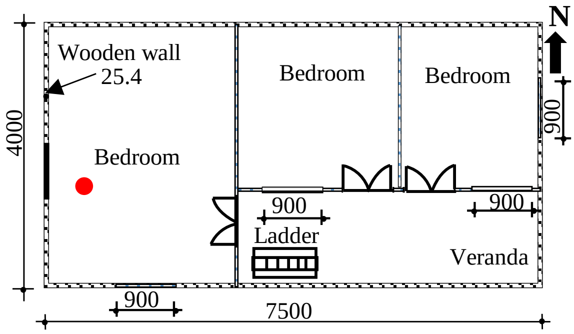
H11

SHOT ON OPPO



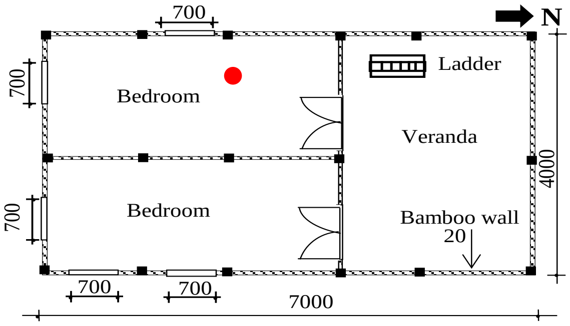
1800
1800
N
Bricks wall
(228)
Bedroom
Bedroom
Bedroom
Passage
Instrument
Bedroom
7500
7500

H12



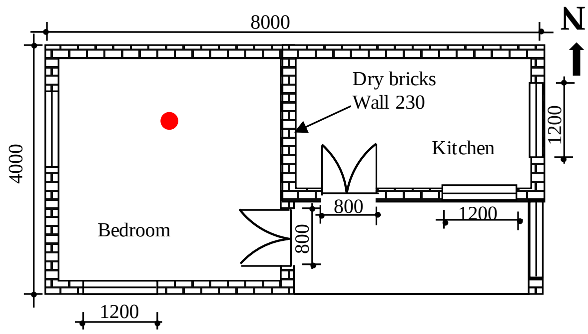
N
Wooden wall
25.4
Bedroom
Bedroom
Bedroom
4000
900
900
900
Ladder
Veranda
900
7500

H13



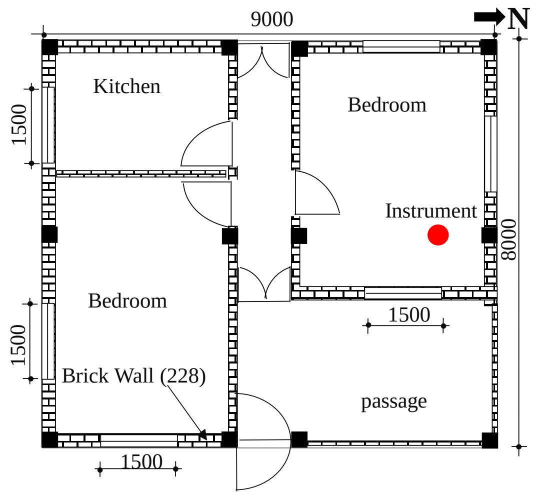
700
N
Ladder
700
Bedroom
Veranda
4000
700
Bedroom
Bamboo wall
20
700
700
7000

H14



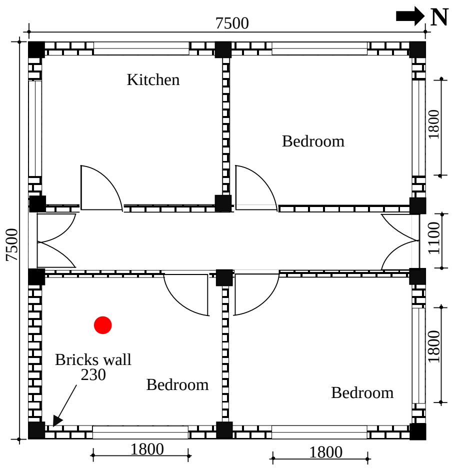
8000
N
Dry bricks
Wall 230
1200
Kitchen
4000
800
1200
Bedroom
800
1200

H15



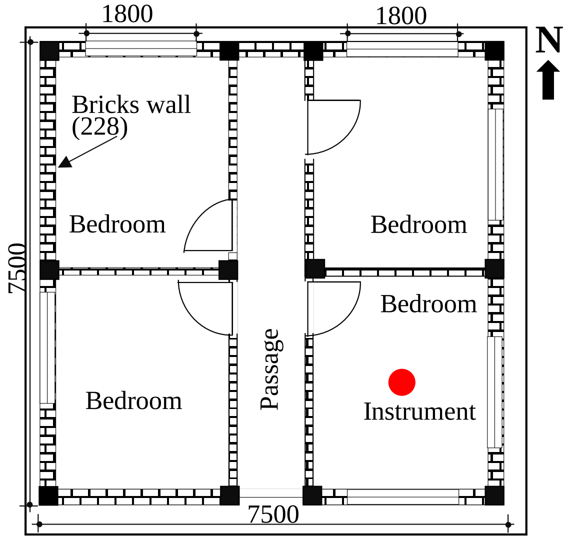
9000
N
Kitchen
1500
Bedroom
Instrument
8000
Bedroom
1500
1500
Brick Wall (228)
passage
1500

H16


N
7500
Kitchen
Bedroom
1800
1100
7500
Bricks wall
230
Bedroom
Bedroom
1800
1800
1800

H17


2019/04/17


1800
1800
N
Bricks wall
(228)
Bedroom
Bedroom
7500
Bedroom
Bedroom
Passage
Instrument
7500

H18

Appendix-2

Questionnaire used in the field survey in 2016 and 2019.

1) Now, how do you feel the air temperature?	**2) Now, how do you prefer the air temperature?**	**(१) चिसो तातोको अनुभव:** **अहिले, वायुको तापक्रम कस्तो अनुभव गर्नु भएको छ ?**	**(२) तापक्रम को चाहना:** **अहिले, वायुको तापक्रमको कस्तो चाहना गर्नु भएको छ ?**
1. Very cold 2. Cold 3. Slightly cool 4. Neutral (Neither cold nor hot) 5. Slightly warm 6. Hot 7. Very hot	1. Much warmer 2. A bit warmer 3. No change 4. A bit cooler 5. Much cooler	१ जाडो, २ चिसो ३ अलिकति चिसो ४ ठिक्क (चिसो पनि तातो पनि छैन), ५ अलिकति तातो ६ तातो, ७ गर्मी	१ धेरै न्यानो चाहिन्छ । २ अलिकति न्यानो चाहिन्छ । ३ एतिकै ठिक्क छ । ४ अलिकति शितल चाहिन्छ । ५ धेरै शितल चाहिन्छ ।
3) Now, do you feel <u>overheating</u>?	**4) Can you <u>accept</u> the present thermal environment?**	**(३) धेरै गर्मीको अनुभव:** **अहिले, धेरै गर्मीको अनुभव गर्नू हुन्छ कि हुदैन ?**	**(४) अहिले जाडो/गर्मी वातावरण खप्न सक्नु हुन्छ कि हुदैन ?**
0. Not feeling 1. Feeling	1. Acceptable 2. Unacceptable	० अनुभव गरिरहेको छैन १ अनुभव गरिरहेको छु	० खप्न सक्छु । १ खप्न सक्दिन
5) Now, how do you feel the humidity of the air?	**6) Now, how do you prefer the humidity of the air?**	**(५) हावाको ओसिलोको अनुभव:** **अहिलेको, हावाको ओसिलोको कस्तो अनुभव गर्नुभएको छ ?**	**(६) ओसिलोको चाहना:** **अहिले, हावाको ओसिलोको कस्तो चाहना गर्नु भएको छ ?**
1. Very dry 2. Dry 3. Slightly dry 4. Neither humid nor dry 5. Slightly humid 6. Humid 7. Very humid	1. Much more humid 2. A bit more humid 3. No change 4. A bit drier 5. Much drier	१ धेरै सुख्खा २ सुख्खा ३ अलिकति सुख्खा ४ ठिक्क (सुख्खा पनि ओसिलो पनि छैन) ५ अलिकति ओसिलो ६ ओसिलो ७ धेरै ओसिलो	१ धेरै ओसिलो चाहिन्छ । २ अलिकति ओसिलो चाहिन्छ । ३ एतिकै ठिक्क छ । ४ अलिकति सुख्खा चाहिन्छ । ५ धेरै सुख्खा चाहिन्छ ।
7) Now, how would you rate the <u>overall comfort</u>? (Please consider the air temperature, humidity and air movement.)	**8) Now, how would you rate the thermal Satisfaction? (Please consider the air temperature, humidity and air movement.)**	**(७) आन्नदपन:** **अहिले, तापक्रम, वाफ, हावा सबै सोच्दा, तपाईको आनन्दपन कस्तो छ ?**	**(८) सन्तोसजनक:** **अहिले, तापक्रम, वाफ, हावाहरु सबै सोच्दा, तपाई कत्तीको सन्तुस्ट हुनुहुन्छ ?**
1. Very comfortable 2. Moderately comfortable 3. Slightly comfortable 4. Slightly uncomfortable 5. Moderately uncomfortable 6. Very uncomfortable	1) Very satisfy 2) Moderately satisfy 3) Slightly satisfy 4) Slightly un-satisfy 5) Moderately un-satisfy 6) Very un-satisfy	१ धेरै आन्नद २ आन्नद ३ अलिकति आन्नद ४ अलिकति असुविधा ५ असुविधा ६ धेरै असुविधा	१ धेरै सन्तुस्ट २ सन्तुस्ट ३ अलिकति सन्तुस्ट ४ अलिकति असन्तुस्ट ५ असन्तुस्ट ६ धेरै असन्तुस्ट

9 Now, do you have any <u>skin moisture</u>?	**10 What have you been doing in the last <u>15 minutes</u>? Please select one main <u>activity</u>.**	(९) शरिरको पसिना: अहिले, शरिरमा कतिको पसिना आएको छ ?	(१०) शरिरको कार्यशिलता: **१५ मिनेट देखि अहिले सम्म के गरेर बस्नु भएको थियो (मुख्य कार्यशिलता एउटा रोज्नुहोस)**
1. None 2. Slightly 3. Moderately 4. Profuse	1. Lying down 2. Sitting resting 3. Sitting working 4. Standing relaxed 5. Standing working 6. Walking indoors 7. Walking outdoors	० छैन १ अलिकति छ २ केही मात्रामा छ ३ धेरै छ	१ पल्टिरहेको २ बसेर आराम गरिरहेको ३ बसेर काम गरिरहेको ४ उभिएर आराम गरिरहेको ५ उभिएर काम गरिरहेको ६ घरभित्र हिडी रहेको ७ बाहिर हिडी रहेको
11 Now, how do you feel the air movement?	**12 Now, what do you <u>prefer</u> the <u>air movement</u>?**	**(११) हावाको गतिको अनुभव** **अहिले, वायुको गतिको कस्तो अनुभव गर्नु भएको छ ?**	**(१२) हावाको गतिको चाहाना** **अहिले, वायुको गतिको कस्तो चाहना गर्नु भएको छ ?**
1. Strong 2. Slightly strong 3. Neutral (neither strong nor weak) 4. Slightly weak 5. Weak	1. Less 2. No change 3. More	१ धेरै चलेको छ २ अलिअलि चलेको छ ३ ठिक्क छ ४ अलि अलि स्थिर छ ५ चलेको छैन	१ कम चाहिन्छ २ एतिकै ठिक्क छ ३ अलि धेरै चलेको चाहिन्छ
13 Now, how do you feel the dryness of throat?	**14 Now, how do you feel the dryness of nose?**	**(१३) घाँटीको सुख्खापनको अनुभव;** **अहिले घाँटीको सुख्खापनको अनुभव कस्तो गर्नुभएको छ?**	**(१४) नाकको सुख्खापनको अनुभव;** **अहिले नाकको सुख्खापनको अनुभव कस्तो गर्नुभएको छ?**
1. Dry 2. Slightly dry 3. Humid	1. Dry 2. Slightly dry 3. Humid	१ सुख्खा २ अलिअलि सुख्खा ३ ओसिलो	१ सुख्खा २ अलिअलि सुख्खा ३ ओसिलो
15 Now, how do you feel the dryness of hand and face?	**16 Do you prefer opening the window, for better air quality?**	**(१५) हात र अनुहारको सुख्खापनको अनुभव:**	**(१६) तपाईले राम्रो तथा स्वस्थ गुणस्तर हावाको लागि झ्याल खोल्न चाहनु हुन्छ?**
1. Dry 2. Slightly dry 3. Humid	1. Yes 2. No	१ सुख्खा २ अलिअलि सुख्खा ३ ओसिलो	१ चाहान्छु २ चाहान्न
17 Do you prefer opening the window, for having coolness?	**18 Now, what do you want to prefer for your coolness?**	**(१७) के तपाई सितलताकोलागि झ्याल खोल्न चाहनुहुन्छ?**	**१८ अहिले तपाई सितलताको लागि के गर्न चाहानु हुन्छ?**
1. Yes 2. No	1. Use fan 2. Use light clothes 3. Take a shower 4. Sit under the shade 5. Change posture 6. Nothing in particular	१ चाहान्छु २ चाहान्न	१ पंखाको प्रयोग २ पातलो वा हलुंगो कपडाको प्रयोग ३ नुहाउन वा पौडीखेल्नचाहान्छु ४ सीतलमा बस्न चाहान्छु ५ बसाई परिबर्तन ६ यतिकै ठिक छ
19 Last night, what time did you go to bed? **………………………..** **20 Today, what time did you get up in the morning?** **………………………..**	**21 Last night, how many times did you wake up cause by hotness?** 1. Never 2. Once 3. Twice 4. Often	**(१९) गयराती कतीबजे सुत्नुभयो?** **……………………………** **(२०) आज विहान कतिबजे उठ्नु भयो?** ………………………..	**(२१) गयराति गर्मिको कारणले कति पटक ब्यूझनु भयो?** 0 ब्यूंझिन १ एक पटक २ दुईपटक ३ पटकपटक

Answer sheet used in the field survey in 2016 and 2019

Sheet No.: -									**Indoor Thermal Comfort Survey 2016/2019**													**Interviewer: -**								
No	Date	Time	Occupation	Name	Sex (M/F)	Age	Weight	Height	O_2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	/	:																												
2	/	:																												
3	/	:																												
4	/	:																												
5	/	:																												
6	/	:																												
7	/	:																												
8	/	:																												
9	/	:																												
10	/	:																												
11	/	:																												
12	/	:																												
13	/	:																												

Measurement sheet used in field survey 2016 and 2019

Weather: - 1. Sunny, 2. Sunny & cloudy, 3. Cloudy, 4. Raining, and 5. Snow falling																												
House type: - 1) Traditional 2) Modern						**Indoor**																			**Outdoor**			
Condition of occupant behaviour (0 Close or off, 1 Open or on)													**Surface temperature [°C]**						**lx**	**°C**	**%**	**°C**	**ppm**	**m/s**	**°C**	**lx**	**lx**	**w/m2**
No	House	Place	Weather	Floor	Time	Internal door	Window	Curtain	Ceiling	Fan	Heating	Ceiling light	Ceiling	Floor	East	West	South	North	Light	T_i	RH_i	T_g	Co_2	Air velocity	T_o	RH_o	Light	Solar radiation
1																												
2																												
3																												
4																												
5																												
6																												
7																												
8																												
9																												
10																												
11																												
12																												
13																												

Publication list

With review

1. Gautam B., Rijal H.B., Shukuya M., Imagawa H., A field investigation on the wintry thermal comfort and clothing adjustment of residents in traditional Nepalese houses**,** Journal of Building Engineering, 26 (2019) 100886. (Available on: 27th August, 2019)
2. Gautam B., Rijal H.B., Imagawa H., Kayo G., Shukuya M., Investigation on adaptive thermal comfort considering the thermal history of local and migrant peoples living in sub-tropical climate of Nepal**,** Building and Environment, 185 (2020) 107237. (Available on: 19th October, 2020)

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1. Gautam B., Rijal H.B., Study on winter thermal environment and adaptive thermal comfort in houses in different climatic regions of Nepal, 17th Conference of the Science Council of Asia (SCA), Philippine International Convection Centre, Philippines. 14th-16th, June, 2017
2. Gautam B., Rijal H.B., Shukuya M., Study on wintry indoor thermal environment of rural houses in Nepal, Grand Renewable Energy Yokohama, Japan. 17th-22th, June, 2018
3. Gautam B., Rijal H.B., Shukuya M., Investigation on wintry thermal comfort in traditional houses of Nepalese three climatic regions, 4th International conference RETRUD, conference in Nepal, Kathmandu. 29th-31st, October, 2018
4. Gautam B., Rijal H.B., Shukuya M., Regional differences of wintry indoor thermal environment of traditional houses in Nepal, SBE19 Tokyo, Built Environment in an area of climate change, Venue: The University of Tokyo, Komaba Campus. IOP Conf. Series: Earth and Environmental Science 294 (2019) 012034. doi:10.1088/1755-1315/294/1/012034. 6th-8th, August, 2019

Publications (without review)

1. Gautam B., Rijal H.B., Study on latrine usage and its relation to health in Tamang and Non Tamang community in rural area of Nepal, AIJ Kanto Chapter Architectural Research Meeting, Tokyo, pp. 205-206. 2017.2
2. Gautam B., Rijal H.B., Study on blood pressure and outdoor air temperature in winter in rural areas of Nepal, AIJ Summaries of Technical Papers of Annual Meeting, Hiroshima, pp. 297-298. 2017.9

3. Gautam B., Rijal H.B., Shukuya M., Investigation on comfort temperature and clothing insulation in three climatic regions in Nepal, AIJ Kanto Chapter Architectural Research Meeting, Tokyo, pp. 91-92. 2018. 3
4. Gautam B., Rijal H.B., Shukuya M., Study on wintry thermal environment and its impact on human health in traditional and modern houses of Nepal, AIJ Summaries of Technical Papers of Annual Meeting, Sendai, pp. 545-546. 2018.9
5. Gautam B., Rijal H.B., Shukuya M., Comparison of the wintry and autumnal indoor thermal environment in Nepalese rural houses, AIJ Kanto Chapter Architectural Research Meeting, Tokyo, pp. 113-114. 2019.3
6. Gautam B., Rijal H.B., Shukuya M., Study on wintry air temperature and humidity of traditional houses in three regions of Nepal, AIJ Summaries of Technical Papers of Annual Meeting, Kanazawa, pp. 97-98. 2019.9
7. Gautam B., Rijal H.B., Imagawa H. Study on summer thermal environment and its impact on sleeping in wooden and concrete house of Nepal, AIJ Summaries of Technical Papers of Annual Meeting, Chiba, pp. 781-782. 2020.9
8. Gautam B., Rijal H.B., Study on summer air temperature and water vapor concentration of wooden and concrete houses in Nepal, AIJ Kanto Chapter Architectural Research Meeting, Tokyo, pp. 9-10. 2021.3

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CURRICULUM VITAE

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Marital status	:	Married
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To work will full strength in dynamic organization which provides new challenge that help to add value to the organizations and the individuals. Seeking a challenging career to value on time performance, where I can enhance my working skills, strength and experience which helps achieving target.

ACADEMIC QUALIFICATIONS

Education

Proficiency Certificate (Intermediate) Degree 1998-2002

Humanities and Social Sciences (Major of population education)

Patan Multiple Campus, Kathmandu, Tribhuvan University of Nepal

Bachelor's Degree of Education 2003-2007

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Master's Degree in Education 2007-2009

Education (Specialization: Health Education)

Thesis: “Study on latrine and its relation to health in Tamang and Non Tamang community in rural area of Nepal”

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Research **2016-2017**

Master of Environmental and Information Study

Research Theme: Study on thermal environment and human health in rural houses of Nepal

Tokyo City University, Japan

Ph. D. of Environmental and Information Studies **2017-2021**

(Ph. D. Thermal adaptation of people and houses in Nepalese cold, temperate and sub-tropical regions)

Tokyo City University, Japan

ADDITIONAL SKILLS

Languages

Nepalese: Native

English, Hindi, and Japanese

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Statistical operation: SPSS Software

Licenses

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Bike (Non-professional driving license, Nepal)

Work Experiences

Teaching as a social studies and computer subject teacher from Sep. 2002 to Oct. 2004 in Shree Gautam Nath Lower Secondary School, Kavrepalanchok, Nepal.

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From Aug. 2010 to Sep. 2014, taught ***health education*** as a part-time lecturer at Tribhuvan University, Sanjiwani College, and ***social studies and health education*** as a part-time lecturer at Shree Hanuman Higher Education School, Kavrepalanchok, Nepal.