THERMAL MASS REQUIREMENT FOR BUILDING ENVELOPE IN DIFFERENT CLIMATIC CONDITIONS

ANIR KUMAR UPADHYAY

Architect / Urban Planner
4/24, Park Street, Kogarah
NSW 2217, Australia

ABSTRACT

This study investigates the thermal mass requirement at three different places: Mackay, Brisbane and Amberley in Queensland, Australia. These places have been selected considering their proximity to the nearby coast. Mackay is situated along the coast, Brisbane is located near the coast and Amberley lies inland. Climate data of these cities were retrieved from Bureau of Meteorology's data bank and climate analysis tools such as Mahoney tables, Building bioclimatic chart were used to get a clear picture of prevailing climatic conditions. Wind roses for different times in different seasons were prepared to understand the wind direction and speed. This paper concludes that provision of thermal mass in buildings is beneficial in coastal as well as inland locations of Queensland.

THERMAL MASS IN BUILDING

Thermal mass is a major building element in passive solar building design. Passive solar building design understands the local micro-climate and uses natural energies like sun and wind to maintain thermal comfort in buildings. Thermal mass in building fabric will affect the thermal response and performance of spaces. Incorporating thermal mass in buildings helps to balance fluctuating temperatures across the diurnal cycle. A heavy weight building envelope will respond slowly to heat gains from all types of natural or artificial heating sources like sun or mechanical heating systems. Hence, thermal mass assists in the reduction of energy consumed in heating and cooling. Thermal mass together with night ventilation can reduce the maximum indoor temperature in buildings in hot climate conditions (Kammerud R, *et. al* 1984). In summer, thermal mass absorbs the heat from the surroundings, releasing it when cool air passes through it. Thermal mass acts equally well for passively heated buildings by trapping solar radiation in it; and releasing the stored energy slowly when the temperature falls. In this case, thermal mass serves as a radiant heat source which transfers energy from warm objects to cold objects.

METHODOLOGY OF THE STUDY

This paper is a part of a larger study, which aims to develop design guidelines for designers/ builders to help them in selecting design options and building elements that are climatically suitable as well as efficient from energy usage and conservation points of view. The study will cover the major population locations within Australia and hence encompass all the states and major cities which are distinctly different in climatic conditions.

This paper performs a comparative analysis of three cities from Queensland considering their location from the nearby coast. Mackay is situated along the coast, Brisbane is located near the coast and Amberley lies inland. The study is carried out in two steps: firstly, presenting climate data in an easily understandable graphical format and secondly, analyzing climate

data using Building Bioclimatic charts and Mahoney tables. The usefulness of thermal mass in these locations is identified.

CLIMATE STUDIES

The different climate regions of the world are commonly categorized in terms of their thermal and seasonal characteristics (e.g. hot-dry, warm-humid, composite, moderate and cold). Each region requires distinctive design responses, which are frequently reflected in the vernacular building practices and architecture of the region. It is important to note that even within the same climate zone; a wide range of distinct climate characteristics can be found. Mackay, Brisbane and Amberley are in the same climate zone (zone 2) of the Building Code of Australia (BCA).

In order to define local climate more precisely than simply according to the generic typologies, detailed information is required about the local air temperature, humidity and wind patterns. It is possible to obtain detailed information on the weather of a location from weather stations. This information is based on hourly monitoring of weather over several decades, although, not all of that information is relevant for design purposes. The requirements depend upon the potential design implications and the level of environmental analysis that needs to be performed. For example, large diurnal temperature variations in hot dry climates are as important as the average daily temperatures, since they will influence the design strategy to maintain comfort by exploiting the time lag characteristics of thermal mass. Conversely, in warm humid climates, the diurnal swings are much smaller and air movement is essential to define comfort. As a result, it is important to know wind speed and directions at different times in a day (Gonzalo and Habermann, 2006).

Climate data of Mackay, Brisbane and Amberley has been presented in graphical format so that it will be easy to understand while making design decisions.

Mackay

Mackay experiences hot, humid summers and mild, dry winters with annual daily temperature swings around 7 degC. Autumn and spring months are warm and humid during daytime and cool and humid in the nighttime. The average maximum air temperature ranges from 30°C in December and January to 21°C in July. The highest temperature ever recorded is 39.4°C in January. The average minimum temperature ranges from 13°C in July to 23°C in January. The lowest temperature ever recorded is 3.8°C in July.

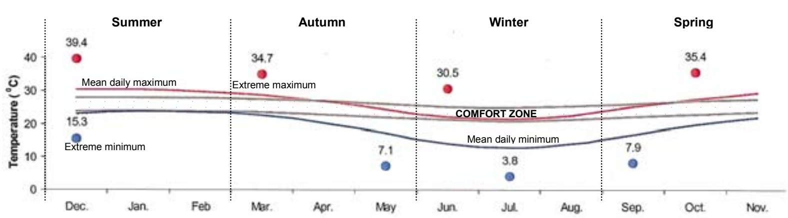

Figure 1. Air temperature across months (Mackay)

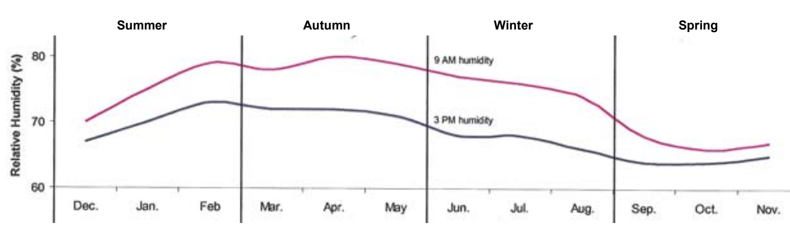

Figure 2. Relative humidity across months (Mackay)

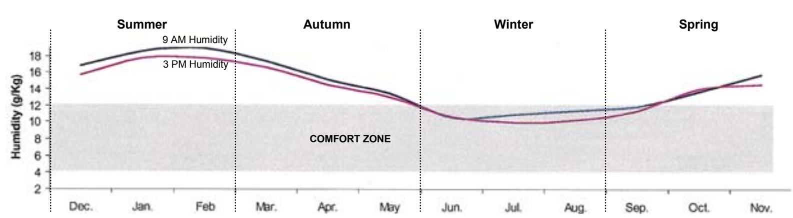

Figure 3. Specific humidity across months (Mackay)

Humidity has been presented in relative humidity (%) and specific humidity (g/Kg). Specific humidity is the ratio of mass of water vapor to the total mass of the moist air sample (ASHRAE, 2001). It gives an idea of vapor content in the air and allows monitoring of the comfort level of humidity. Humidity in Mackay is high for eight months of the year, i.e. October to May. Winter and early spring humidity remains in the comfortable range. The need of heating and cooling can be best described by heating/ cooling degree hours. Cooling threshold

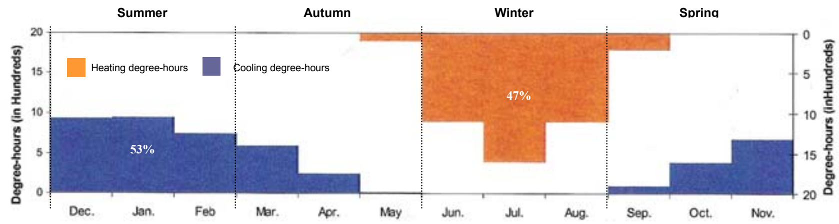

Figure 4. Heating / cooling degree-hours across months (Mackay)

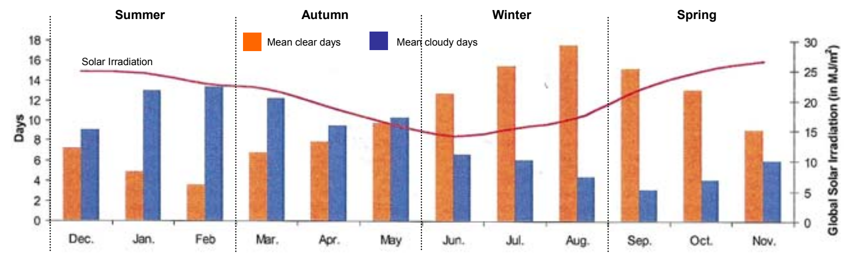

Figure 5. Sky conditions across months (Mackay)

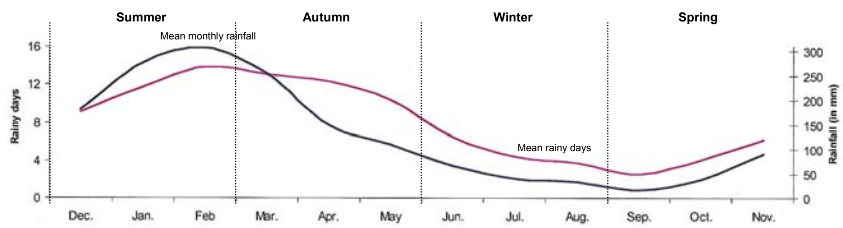

Figure 6. Rainfall across months (Mackay)

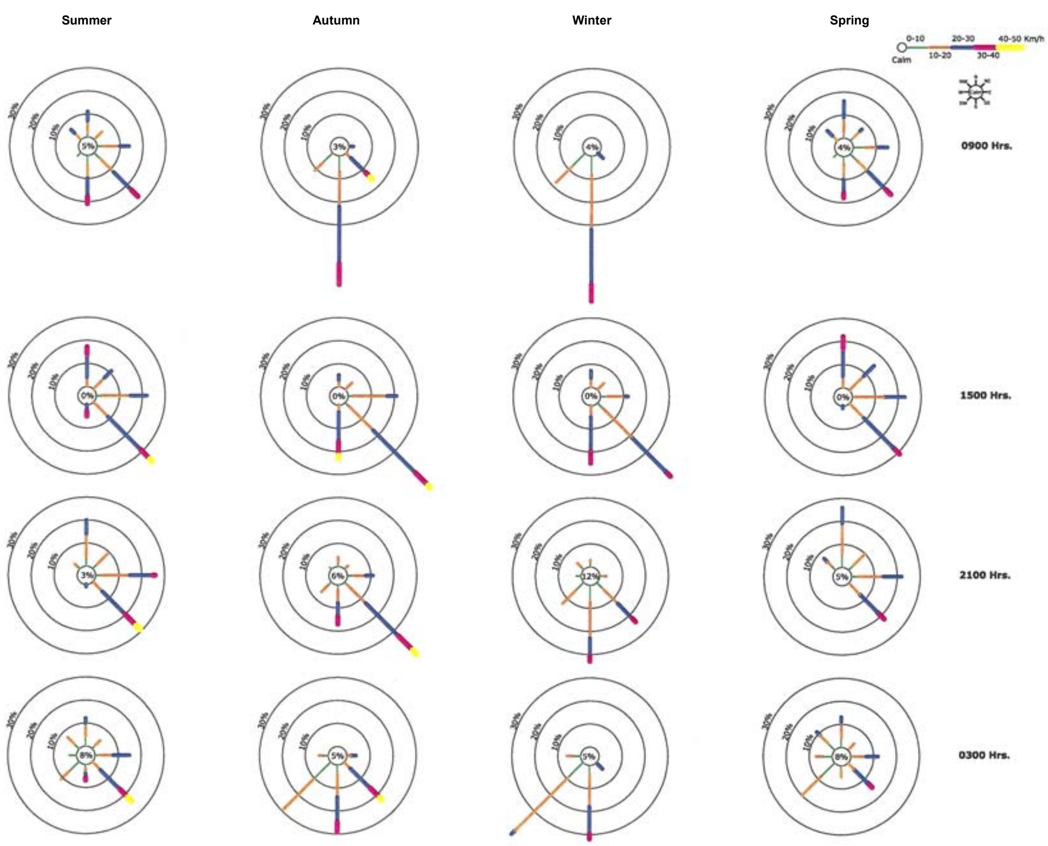

Figure 7. Wind roses across different time and seasons (Mackay)

temperature is determined by the neutral temperature (Szokolay, 1982) for each month. The heating threshold temperature has been taken as 18°C for the year round (Hart and de Dear, 2004). In Mackay, summer, autumn and spring months require cooling but from late autumn to early spring, heating is required. In total, 53% of the time has cooling demand and 47% of time has heating requirements.

Summer months get substantial rain, the sky in summer is overcast for about 12 days in a month. In winter, the sky is clear for almost 15 days per month. Clear sky conditions favor passive solar heating potential in Mackay.

Of the annual mean rainfall of 130 mm, which is approximately 98 days of rainfall, about 50% usually falls between December and February. It rains more frequently during summer and less during winter.

Wind is very strong at all times and is predominantly from the south-east direction. In summer and spring, the wind blows from north to south-east. Afternoon and evening wind blows from the south-east in autumn but the southerly wind is prominent in the morning. In winter, the wind blows from south-east to south-west. Morning wind is very strong from south but afternoon and evening wind comes from south-east and south directions.

Brisbane

Brisbane has a subtropical climate, characterized by hot, humid summers and mild winters. These seasons extend into autumn and spring months, which are transitional periods between the two main seasons. The average maximum air temperature ranges from 29°C in February to 21°C in July. The highest temperature ever recorded is 40.2°C in February. The average minimum temperature ranges from just 9°C in July to 21°C in January and February. The lowest temperature ever recorded is 1.6°C in June. Humidity is high in summer and early autumn months but gradually reduces from April to remain in the comfortable range for the rest of the year.

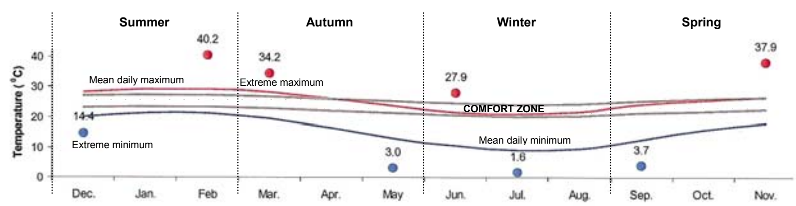

Figure 8. Air temperature across months (Brisbane)

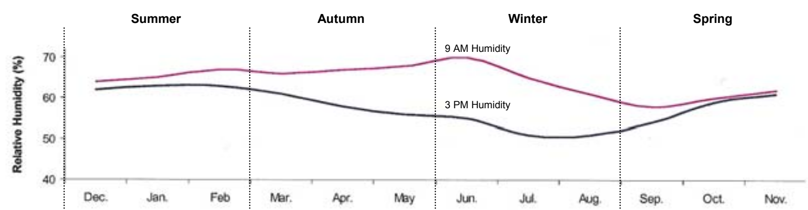

Figure 9. Relative humidity across months (Brisbane)

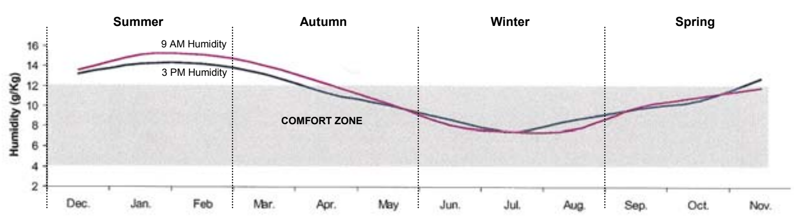

Figure 10. Specific humidity across months (Brisbane)

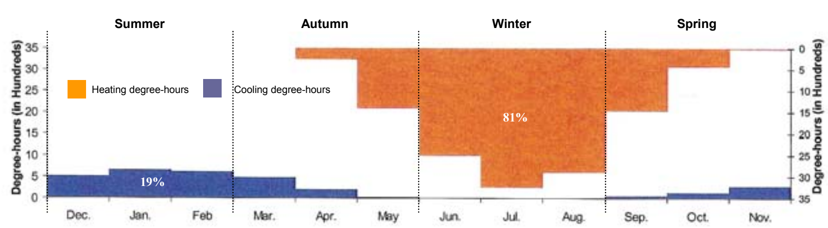

Figure 11. Heating / cooling degree-hours across months (Brisbane)

Summer and early autumn months require cooling; from late autumn to mid spring, heating demand is very high in Brisbane. In total, 81% of the time has heating demand and 19% of time has cooling requirements. Summer months get substantial rain, the sky in summer is cloudy for about 12 days in a month. In winter, the sky is clear for almost 15 days per month. Of the annual mean rainfall of 80 mm, which is approximately 83 days of rainfall, about 50%

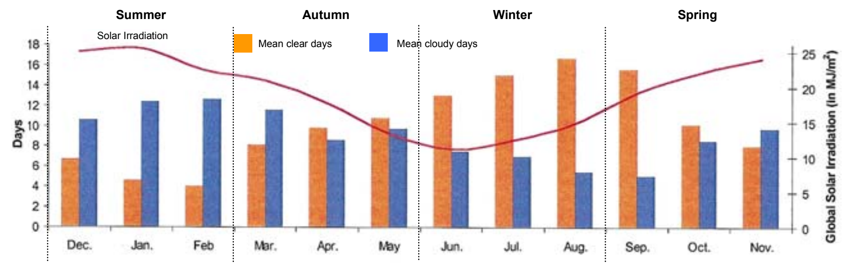

Figure 12. Sky conditions across months (Brisbane)

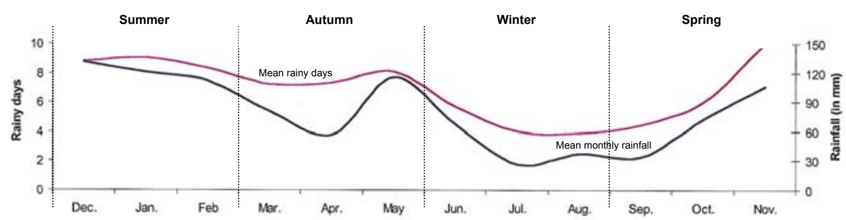

Figure 13. Rainfall across months (Brisbane)

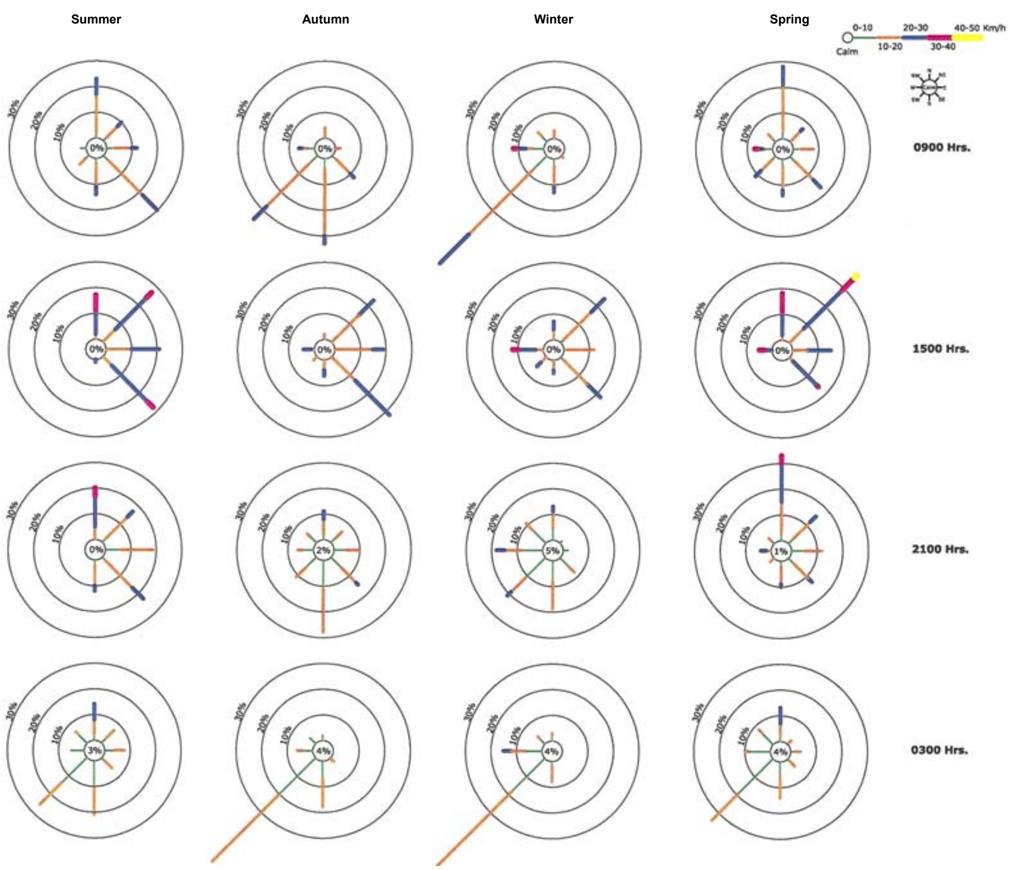

Figure 14. Wind roses across different time and seasons (Brisbane)

usually falls between November and February. Rainfall in summer months is the highest while it is the lowest in winter months.

The wind changes its direction in each season. In summer, the wind comes from north to south-east directions. The autumn wind comes mainly from the south. It ranges from south –

east to south – west. The winter wind pattern is also similar to the autumn. Night and morning wind is strong and comes from the south-west. The afternoon and evening wind is dispersed and weak. The spring wind basically comes from the north. The afternoon wind blows from the north – east and night wind from the south – west.

Amberley

Amberley experiences hot, humid summers and mild winters. Annual daily temperature swings are around 14 degC. Autumn and spring months are warm during daytime but nights are usually pleasant. The average maximum air temperature ranges from 31°C in January to 21°C in July. The highest temperature ever recorded is 44.3°C in January. The average minimum temperature ranges from just 5°C in July to 20°C in January. The lowest temperature ever recorded is -4.9°C in August.

Humidity is high in summer months, remaining so until early autumn and then gradually reducing from April to remain in the comfortable range for the rest of the year.

Summer and early autumn months require cooling, but from late autumn to mid spring, heating demand is very high in Amberley. In total, 77% of the time has heating demand and 23% of time has cooling requirements.

Summer months get substantial rain and the sky is cloudy for about 11 days in a month. In winter, the sky is clear for almost 14 days per month. This availability of clear sky

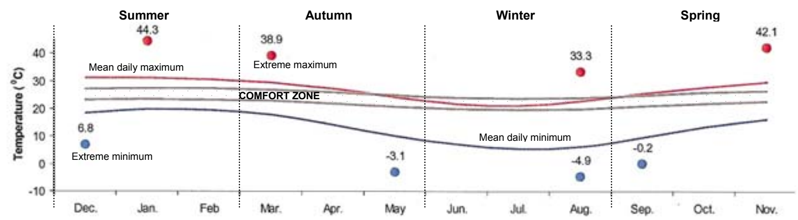

Figure 15. Air temperature across months (Amberley)

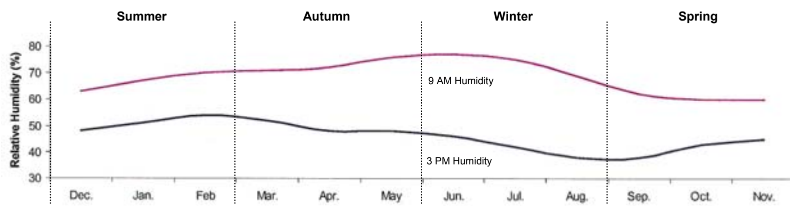

Figure 16. Relative humidity across months (Amberley)

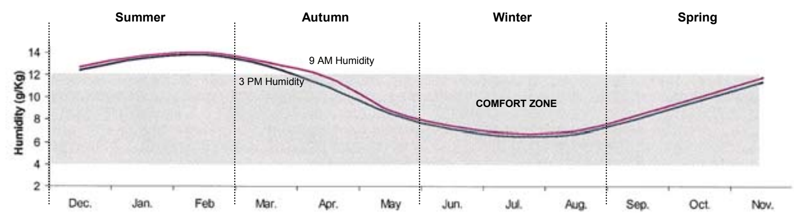

Figure 17. Specific humidity across months (Amberley)

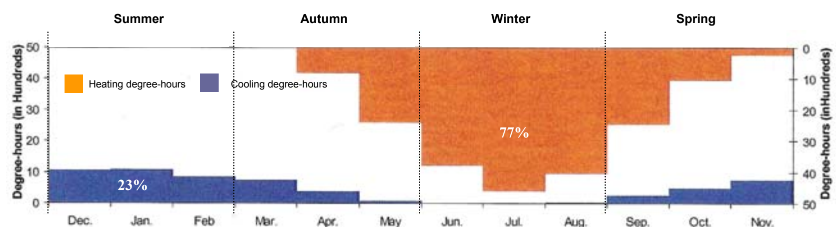

Figure 18. Heating / cooling degree-hours across months (Amberley)

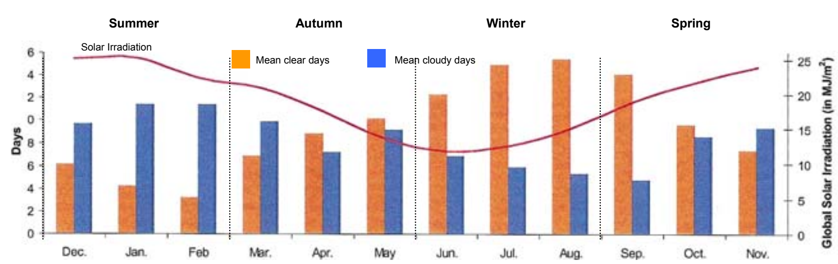

Figure 19. Sky conditions across months (Amberley)

condition favors passive solar heating in Amberley. Of the annual mean rainfall of 70 mm, which is approximately 74 days of rainfall, about 50% usually falls between December and March. Summer months receive the highest rainfall and winter months get the lowest.

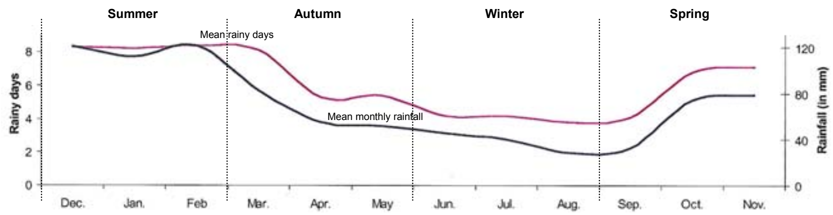

Figure 20. Rainfall across months (Amberley)

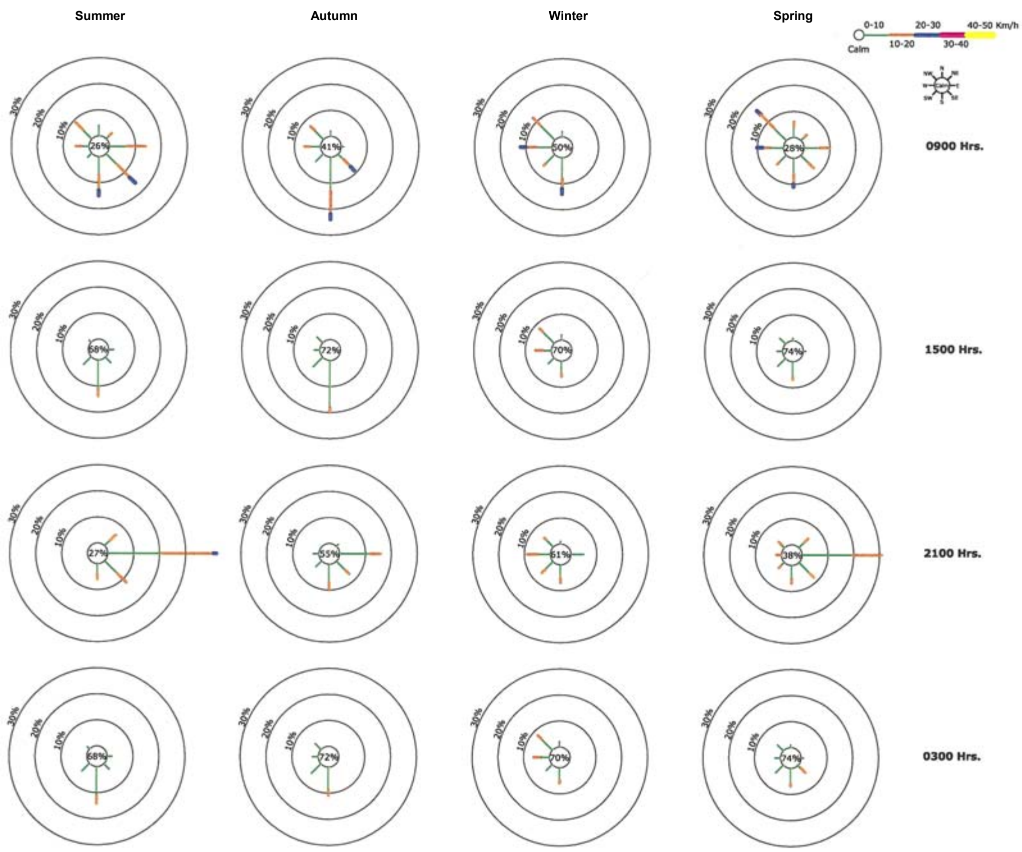

Figure 21. Wind roses across different time and seasons (Amberley)

The wind direction in Amberley is predominantly from east to south. The morning and evening wind is stronger compared to the afternoon wind. The morning wind in summer comes from the east to south directions, from the south in autumn and from the west in winter and spring. Calm period is very high (around 70%) in the afternoons. The afternoon wind blows from the south in summer and autumn whereas is dispersed along all the directions in winter and spring and has very less intensity. The evening wind always comes from the east and except in winter.

CLIMATE COMPARISION

Table1: Climate comparison of Mackay, Brisbane and Amberley

Climatic parameters	Mackay (coastal)	Brisbane (near to coast)	Amberley (inland)
Air Temperature			
Extreme maximum	39.4^0C	40.2^0C	44.3^0C
Mean daily maximum			
summer	30^0C	29^0C	31^0C
winter	21^0C	21^0C	21^0C
Mean daily minimum			
summer	23.0^0C	21^0C	20^0C
winter	13.0^0C	9^0C	5^0C
Extreme minimum	3.8^0C	1.6^0C	-4.9^0C
Mean diurnal range	6.3 – 8.6 degC	7.9 – 12.2 degC	10.9 – 16.3 degC
Heating degree hours (base 18^0C)	47%	81%	77%
Cooling degree hours (base neutral temperature*)	53%	19%	23%
Humidity	Humid for 8 months (October to May)	Humid for 5 months (November to March)	Humid for 4 months (December to March)
Sky Condition	Summer and Autumn months are cloudy; clear days prevail for winter and spring months		
Rainfall	Rainfall is the highest in summer and lowest in winter		
Wind	Wind is strong at all times		Wind is very weak

The extreme maximum temperature increases from the coast to inland, so do the mean daily maxima. On the other hand, the minimum temperature decreases from the coast to the inland. The extreme minimum temperature is well below zero in Amberley whereas it is highest in Mackay. The diurnal temperature range is greater inland than in the coastal area. This is because the water mass moderates the fluctuating diurnal temperature. Humidity is high for majority of the time in Mackay while only the summer months are humid in Amberley with high rainfall. Sky conditions and rainfall pattern are almost similar in all the three locations. Wind speed and directions however, are very different. Mackay experiences very windy condition at all times while Amberley experiences calm period for most of the time. Overall, diurnal temperature range, humidity levels and wind characteristics are the most distinguishing climatic feature between coastal and inland locations.

ANALYSIS

Climate analysis has been done using Building Bioclimatic chart and Mahoney tables.

* Neutral temperature (T_n) = 17.6 + 0.31*T_{av}, where T_{av} is average monthly temperature.

Building Bioclimatic chart

Givoni (1976) used the Psychrometric chart as the basis for defining the comfort zone and stretched out the probable extent of outdoor conditions under which certain passive control techniques could ensure indoor comfort. The Building Bioclimatic chart derived by Givoni (1976) provides suggestions for building design considering the local climatic conditions. Various control strategies, which ultimately lead to a climate-sensitive design, are suggested. Szokolay (1986) defined *control- potential zone* to describe the range of outdoor atmospheric conditions within which indoor comfort could be achieved by the various passive control techniques. In the Psychrometric chart, different zones are plotted to indicate different strategies depending upon the monthly temperature–humidity relationships. To identify comfort conditions, the climatic data of all months are plotted in the Building Bioclimatic chart, as shown in Figures 22-24. The line represents each month with mean minimum temperature and morning humidity; maximum temperature and afternoon humidity.

Temperature – humidity relationships indicate that Mackay experiences hot and humid conditions from October to April which can be moderated with wind movement. Night time heating is required from June to August as the temperature drops below comfortable range. Heating and cooling requirements in Mackay are almost equal for the whole year so the building designers should consider both heating and cooling strategies.

Brisbane is hot and humid in summer; the daytime temperature is almost in the comfort zone for the remaining months. The Building Bioclimatic chart suggests thermal mass along with arrangement for ventilation to maintain comfortable conditions in buildings. Night temperature drops below the comfortable range which requires some heating strategies. Overall, heating degree hour dominates cooling degree hour which necessitates addressing heating strategies for five months from May to September.

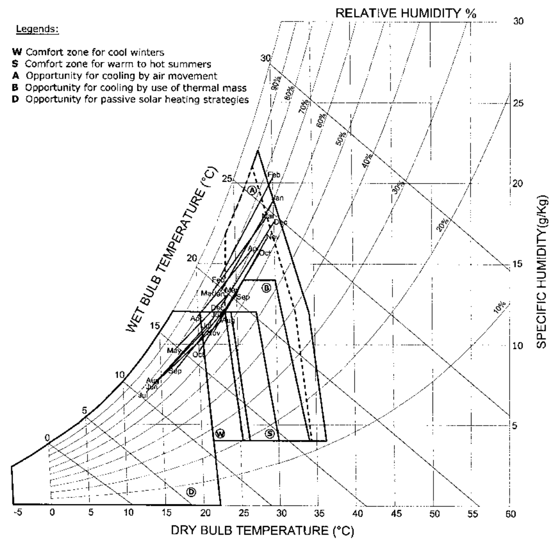

Figure 22. Building Bioclimatic chart (Mackay)

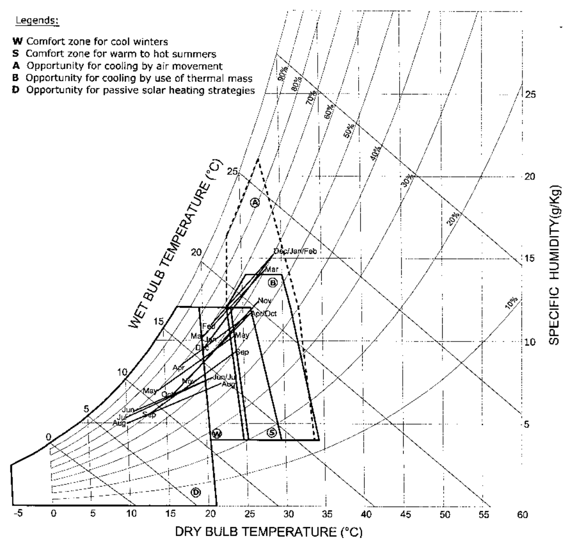

Figure 23. Building Bioclimatic chart (Brisbane)

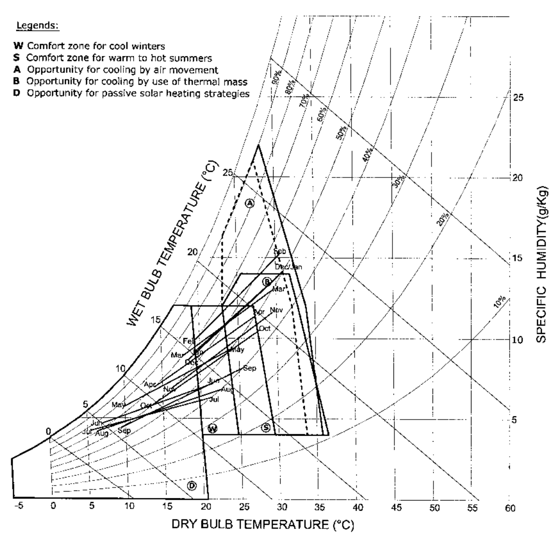

Figure 24. Building Bioclimatic chart (Amberley)

November to March require cooling arrangements. Thus, the building design in Brisbane should consider both heating and cooling strategies.

Amberley is also hot and humid in summer. Daytime temperatures in the March, April, October and November months fall outside the comfort zone but humidity remains in the comfortable range. For this condition, the Building Bioclimatic chart suggests having thermal mass to maintain thermal comfort. Cooling requirement is very significant from November to March and for rest of the months heating is necessary.

Mahoney tables

The Mahoney tables (Koenigsberger, et al., 1973) provide results of thermal comfort analysis using primarily temperature and humidity data, and make recommendations for pre-design guidelines.

These pre-design conditions are classified under certain climatic groups or indicators. The Mahoney tables involve six indicators (i.e., three 'humidity indicators', H1- H3, and three 'arid indicators', A1 –A3). The Mahoney tables indicate remedial action involving air movements for humid conditions in H1 and H2. Excess downpours may affect the building structure, so adequate rain protection is advised in H3. Similarly, for hot and arid conditions, thermal capacity (A1) is one of the options for making the indoor space comfortable. Climatic zones with nighttime temperature above the comfort limit are advised to make provisions for outdoor sleeping (A2). A building in an arid climate with lower temperature needs protection of the building from cold wind (A3).

From the Mahoney tables, it can be concluded that the buildings in Mackay need light, low thermal capacity walls, floors and roofs, as they contain humidity indicators (H1, H2 and H3) for eight months of the year as well as provision of good cross ventilation. Brisbane has got arid indicators (A1 and A3) for five months in a year which suggests the use of heavy external and internal walls and floors.

Amberley has arid indicators (A1) for all months which suggest the use of heavy external and internal walls and floors. The diurnal temperature range is more than 10 degC making it appropriate to use the thermal mass to flatten out the large temperature difference occurring in the buildings.

RECOMMENDATIONS ON THERMAL MASS

The usefulness of thermal mass in maintaining comfortable condition in building is well established especially in hot dry and composite climatic conditions. Thermal mass absorbs heat during the daytime and slows down the process of over heating the surroundings, and as the temperature of the surroundings drops down, it starts re-radiating the heat back to the surroundings. This process helps in stabilizing the temperature of the building as a whole. When the outside temperature is within the comfort zone, wind plays a major role in cooling down the thermal mass by convection heat exchange which accelerates the cooling process. Once the absorbed heat is lost, thermal mass is again ready to store heat for the next day. This is a cyclic process which in turn helps in maintaining the comfort condition in a building.

It is mostly accepted that thermal mass has no significant role in maintaining thermal comfort in warm humid climate zones. The vernacular architecture from hot humid regions is built mostly from low-mass materials, like timber. These buildings are considered appropriate for this climate as the indoor temperature drops rapidly in the evenings (Givoni, 1998). The functions of buildings have changed with time. In the past, buildings were just meant primarily for shelter from sun, wind and rain, but at present their functional requirements have changed significantly. Numerous activities are carried out inside the buildings which require a controlled environment as people spend most of their time inside buildings which demand thermal comfort during all seasons and at all times. It is very difficult to achieve

daytime comfort condition using low mass materials as they offer much less time lag in comparison to high mass materials.

An experimental study has proved that even if a building is continuously ventilated, thermal mass plays a significant role in lowering the indoor maximum temperature (Givoni, 1994). Thus, high mass buildings with provision of a good ventilation system can achieve comfortable conditions in hot humid climate. The thermal mass in winter months is always beneficial as it stores heat during the day and releases it when the surrounding temperature drops down.

CONCLUSION

This study has been conducted to understand the climatic conditions of three places that are located in the coast, near the coast and inland. It supports the fact that coastal location (Mackay) experiences small diurnal temperature range, high humidity and strong wind movement throughout the year. The inland location (Amberley) has large diurnal temperature range with weak wind speed. Brisbane, which is near the coast follows similar characteristics as the coastal locations. Thermal mass plays an important role in buildings to achieve comfort condition in indoor environment. Thermal mass along with good cross ventilation arrangement proved effective in maintaining thermal comfort in hot humid condition of Mackay and, composite climate of Brisbane and Amberley.

ACKNOWLEDGEMENT

This paper is an outcome of ongoing research on "Climate and design guidelines for major locations in Australia". I would like to thank Think Brick Australia for funding this research.

REFERENCES

1. ASHRAE (2001), *Handbook of Fundamentals*. Chapter 6: Psychrometrics.
2. Bureau of Meteorology, Australia. *Climate statistics for Australian locations*. Accessed online on 23rd September 2007 at http://www.bom.gov.au/climate/averages/tables/cw_040842.shtml for Brisbane, http://www.bom.gov.au/climate/averages/tables/cw_040004.shtml for Amberley, http://www.bom.gov.au/climate/averages/tables/cw_033119.shtml for Mackay.
3. Givoni, B. (1976) *Man, Climate and Architecture*. 2nd Ed. New York: Van Nostrand Reinhold.
4. Givoni, B. (1998) *Climate considerations in building and urban design*. New York: Van Nostrand Reinhold.
5. Givoni, B. Building design principles for hot humid regions. *Renewable Energy*, Vol.5, Part II, pp. 906-916, 1994.
6. Gonzalo, R. and Habermann, K. J. (2006) *Energy –efficient architecture: Basics for planning and construction*. Boston, MA: Birkhauser-Publishers for Architecture.
7. Hart, M. and de Dear, R. (2004) Weather sensitivity in household appliance energy end-use. *Energy and Buildings*, Vol.36, pp.161–174.
8. Kammerud R, Ceballos E, Curtis B, Place W, Anderson B. (1984) Ventilation cooling of residential buildings. *ASHRAE Transactions.* Vol. 90 Part 1B.
9. Koenigsberger, O. H., Ingersoll, T. G., Mayhew, A., Szokolay, S.V., (1973) *Manual of Tropical Housing and Building: Climatic Design*. India: Orient Longman.
10. Szokolay, S.V. (1986) Climate analysis based on the psychrometric chart. *International journal of Ambient Energy*, 7(4), pp.171-182.