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BEES INTERIM REPORT

Building energy end-use study - Year 4

ACHIEVED CONDITIONS

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BEES (BUILDING END-USE STUDY) YEAR 4: ACHIEVED CONDITIONS

BRANZ Study Report SR 260/4

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Reference

Bishop, R., Camilleri, M & Isaacs, N. (2011). BEES (Building energy end-use study) Year 4: Achieved conditions, BRANZ study report 260/4, Judgeford.

energy solutions

BEES publications can be downloaded from the BEES website - http://www.branz.co.nz/bees

Following is a list of other reports in the BEES Year 4 series:

- Saville-Smith, K. (2011). BEES (Building energy end-use study) Year 4: Insight into barriers, BRANZ study report 260/1, Judgeford.
- Camilleri, M., & Babylon, W.M (2011). BEES (Building energy end-use study) Year 4: Detailed monitoring, BRANZ study report 260/2, Judgeford.
- Bishop, R., Camilleri, M & Isaacs, N. (2011). BEES (Building energy end-use study) Year 4: Delivered daylighting, BRANZ study report 260/3, Judgeford.
- Bishop, R., Camilleri, M. & Burrough, L. (2011). BEES (Building energy end-use study) Year 4: Temperature Control, BRANZ study report 260/5, Judgeford.
- Bishop, R. (2011). BEES (Building energy end-use study) Year 4: Electrical loads, BRANZ study report 260/6, Judgeford.
- Isaacs, N. (2011). BEES (Building energy end-use study) Year 4: From Warehouses to Shops - Changing Uses in the Non-residential Buildings Sector, BRANZ study report 260/7, Judgeford.

PREFACE

Understanding how energy and water resources are used in non-residential buildings is key to improving the energy and water efficiency of New Zealand's building stock. More efficient buildings will help reduce greenhouse gas emissions and enhance business competitiveness. The Building Energy End-use Study (BEES) is taking the first step towards this by establishing where and how energy and water resources are used in non-residential buildings and what factors drive the use of these resources.

The BEES study started in 2007 and will run for six years, gathering information on energy and water use through carrying out surveys and monitoring non-residential buildings. By analysing the information we have gathered, we aim to answer eight key research questions about resource use in buildings:

1. What is the aggregate energy and water use of non-residential buildings in New Zealand?
2. What is the average energy and water use per unit area per year?
3. What characterises the buildings that use the most energy and water?
4. What is the average energy use per unit area for different categories of building use?
5. What are the distributions of energy and water use?
6. What are the determinants of water and energy use patterns e.g. structure, form, function, occupancy, building management etc?
7. Where are the critical intervention points to improve resource use efficiency?
8. What are the likely future changes as the building stock type and distribution change?

Understanding the importance and interaction of users, owners and those who service non-residential buildings is also an important component of the study.

For the BEES study, non-residential buildings have been defined using categories in the New Zealand Building Code, but in general terms the study is mainly looking at commercial Office and Retail buildings. These vary from small corner store dairies to large multi-storey Office buildings. For more information on the building types included in the study please refer to BRANZ report SR224 Building Energy End-use Study (BEES) Years 1 & 2 (2009) available on the BEES website (www.branz.co.nz/BEES).

The study has two main methods of data collection – a high level survey of buildings and businesses, and intensive detailed monitoring of individual premises.

The high level survey initially involved collecting data about a large number of buildings. From this large sample, a smaller survey of businesses within buildings was carried out which included a phone survey, and collecting records of energy and water use and data on floor areas. The information will enable a picture to be built up of the total and average energy and water use in non-residential buildings, the intensity of this use and resources used by different categories of building use, answering research questions 1-4.

The detailed monitoring of individual premises involves energy and indoor condition monitoring, occupant questionnaires and a number of audits, including: appliances, lighting, building, hot water, water, and equipment.

This report presents data and analysis drawn from the detailed monitoring carried out during the fourth year of this six year study. The data includes temperature, relative humidity, carbon dioxide (air quality) and lighting levels in non-residential spaces. The analysis of this data is very valuable as it gives us indications of where energy savings can be made through interventions such as more sophisticated thermostats for temperature controls that sense occupancy and are linked to the weather forecast or simpler measures such as better use of natural ventilation to prevent overheating and improve air quality. The data and analysis in this report contributes to answering research questions six and seven. This is one of seven interim reports giving a snapshot of analyses completed to date. When all data collection has been completed further analysis will be reported on with the full sample including relationships between end-uses, building types and services.

At this stage of the project, not all the data we need to fully answer the research questions is available. This report only provides analysis and results on buildings less than 9,000 m^2 (size strata 1-4 of the BEES sample). It does not cover the full range of building sizes, so these results are not representative of the non-residential building stock. In the remaining two years of the BEES study, further analysis will be carried out using the full sample which will include buildings greater than 9,000 m^2.

SUMMARY

- This report presents weekday daytime analysis of BEES spaces that have had temperature, lighting, relative humidity and carbon dioxide measurements recorded for a period of 2-3 weeks each.
- Temperature, lighting, relative humidity and carbon dioxide data has been separated by building type (Office, Retail and Other) and analysed against ‘ideal conditions’ for different seasons (Summer, Winter and intermediate).
- The measured spaces presented in this report are all from buildings less than 9,000 m2. These buildings are more likely to have smaller individually controlled heating and cooling devices compared to the larger buildings where most will have centrally controlled HVAC.
- During year 5 of BEES buildings over 9,000 m2 will be monitored and analysed.

This Topic report provides analysis of the data from monitoring of space conditions (temperature, humidity, illuminance and air quality) from buildings less than 9,000 m^2. Measurements were made of temperature, relative humidity, illuminance and carbon dioxide every 10 minutes for 2-3 weeks in each premise. Temperature and relative humidity were measured in multiple spaces within each premise. Carbon dioxide is measured to give an understanding of the air quality within the spaces and the ventilation rates. Results are presented by the time of year monitoring was completed (Summer, Winter or Intermediate seasons) and by building type (Office, Retail or Other).

Data analysis examines the weekday performance of spaces, between 10am and 4pm as most spaces are occupied during these hours.

Temperature

In summer, 100% of offices measured had an average temperature greater than 20°C, and 10% can be considered to be overheating regularly with an average temperature over 26°C.

Retail spaces are similar to offices in summer, while Other spaces have a higher percentage of spaces both in the lower and higher temperature ranges.

In winter, 10% of offices can be considered to have a temperature that is too low to be healthy, with an average temperature below 16°C. Just under half of the offices are considered to be comfortable for at least half of the time (55% have an average temperature below 20°C).

Retail spaces are similar to offices during winter and Other spaces have lower average temperatures than offices.

The control of temperatures is looked at in another BEES topic report - Bishop, R., Camilleri, M. & Burrough, L. 2011.

Relative humidity

The relative humidity in the majority of monitored spaces (80%) can be considered healthy as they are within the range of 40% and 60%.

Ventilation has a strong effect on the humidities in a space. The more ventilation the lower the humidity usually is. In winter Retail spaces frequently had lower humidites than Office and Other spaces; this is likely to be due to excess ventilation.

Most of the offices (80%) in winter show indoor dewpoints higher than outdoors, which indicates a net generation of moisture within the space. In summer the opposite occurs, about 80% of the Offices show that the dewpoint is reduced compared to outside. This indicates a net reduction of moisture within the space. This is probably due to dehumidification during air-conditioning, or possibly excess ventilation of the spaces with outside air at night.

Lighting

About 65% of Office spaces recorded mean lux levels lower than the desired level of 320 lux, with almost 20% recording mean values under 100 lux. The highest 20% of measurements were above 500 lux and a further 5% of Office spaces had average illuminance over 1,000 lux.

Retail spaces had a slightly lower number of spaces at 55% with mean lux levels lower than the desired level of 320 lux and 20% below 100 lux. The top 25% of the spaces measured during this study had mean daily illuminance over 640 lux, and about 10% had mean illuminance over 1,000 lux.

Other spaces had the lowest number of spaces below the desired lux levels of 320 lux at 70%, and 30% below 100 lux. The top 20% had average illuminance measured over 600 lux. These were kitchens and workrooms, but also a warehouse and a storeroom. 5% averaged over 1,000 lux.

Air Quality

The air quality in the BEES premises was measured by logging the concentration of CO_2 in the space. Spaces with CO2 less than 600 ppm have air exchange rates higher than required to maintain good air quality. This can cause higher heating and cooling loads than necessary.

The mean weekday CO_2 concentrations were measured at less than 600 ppm in:

- more than 80% of the Retail and Other spaces in all seasons
- 70% of Offices in the intermediate season
- about 20% of the Offices in winter
- half of the Offices in summer

At the other extreme, about 5% of monitored spaces average over 1000 ppm during normal working hours, and about 15% exceed this at some time each day. These spaces are receiving insufficient fresh air.

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1. INTRODUCTION

This Topic Report provides analysis of the data from monitoring of space conditions (temperature, humidity, illuminance and air quality (CO_2 levels)) of the initial sample of BEES premises. This comprises the measurements from approximately 240 spaces within 75 premises within 60 BEES buildings.

The HOBO U12 data loggers used recorded (dry-bulb) temperature, relative humidity and illuminance levels, every ten minutes when the premises were being monitored (typically 2-3 weeks). Usually, three of these loggers were placed throughout the premises, with as many as seven for a large premise, and a single separate Telaire 7001 carbon dioxide data logger was placed in a central, reasonably representative, space.

Most of the analysis of the data in this report examines the weekday performance of spaces, between 10 am and 4 pm. These were the hours when most of the premises were occupied, and the space conditions were considered to have stabilised.

Graphically, the data from individual monitoring points is converted to a recurring 24-hour load profile.

Statistical summaries of the results for each variable are segregated by season (summer, winter and intermediate) and building type (Office, Retail and Other).

The number of spaces that were monitored, by space type (Office, Retail and Other) and season (Winter, intermediate seasons and Summer), are given in Table 1.

Table 1: Number of spaces monitored by type, season and measurement

Number of spaces with measures for:	**Offices**			**Retail**			**Other**			**Total**		
	Winter	Int.	Summer	W	I	S	W	I	S	W	I	S
Temp (°C)	55	56	31	6	22	20	12	24	15	73	102	66
RH (%)	56	55	32	4	22	20	11	25	15	71	102	67
Lux	50	48	30	7	19	15	11	25	14	68	92	59
CO2 (ppm)	11	13	11	1	13	8	2	1	1	14	27	20

"Office" spaces include those recorded as Offices (99), Reception (22), Meeting Rooms (15), Conference Rooms (3), and Laboratories (3). "Retail" spaces included those recorded as Shops (47) and Showroom (1). "Other" spaces included those recorded as Kitchens (28), Storerooms (10), Workrooms (7), Warehouses (2), Lounges (2), Dining Room (1), and Bakery (1).

All statistics reported in this summary are for weekdays (Monday – Friday) between 10 am and 4 pm. The conditions in the monitored spaces had generally stabilised during these times, and were considered to be representative of normal working conditions.

1.1 Space temperatures

Table 2 summarises the temperatures recorded so far in BEES. The minimum (and maximum) temperatures reported here are the average of the daily minima/maxima during the monitoring period, not the extreme recorded minima/maxima.

NB: These initial results must be qualified by noting that the sample size is relatively small, and the premises monitored did not include buildings over 9,000 m^2.

Table 2: Summary of temperature recorded in BEES

	Temperature	Mean	Minimum	Maximum
Offices, Winter	>26°C			
	>24°C			5%
	>22°C	10%		20%
	>20°C	45%	20%	75%
	>18°C	75%	40%	
	>16°C	90%	80%	
Offices, Intermediate seasons	>26°C			
	>24°C	10%		20%
	>22°C	35%	25%	50%
	>20°C	80%	50%	85%
	>18°C	90%	80%	
Offices, Summer	>26°C	10%		25%
	>24°C	45%	20%	60%
	>22°C	75%	70%	85%
	>20°C	100%	90%	

The temperature distributions for Retail and Other spaces generally followed those for Offices, many fewer of these types of spaces were monitored to date, so they are not summarised separately here.

Daily average temperature swings for Offices were about twice as high in Winter (averaging ± 2.5°C) as in Summer (averaging ± 1.2°C).

1.2 Air quality

The air quality in the BEES premises was measured by logging the concentration of CO_2 in the space. Spaces with CO_2 concentrations less than about 600 ppm have air exchange rates much higher (300% or more) than required to maintain good air quality. This can cause higher heating and cooling loads when outdoor air is colder or hotter than indoors.

The mean weekday CO_2 concentrations were measured at less than 600 ppm in more than 80% of the Retail and Other spaces in all seasons, and 70% of Offices in the intermediate season, indicating they are probably over-ventilated. About 20% of the Offices in winter and half of the Offices in summer were also in this category.

At the other extreme, about 5% of monitored spaces average over 1000 ppm during normal working hours, and about 15% exceed this at some time each day. These spaces are receiving insufficient fresh air. 1000 ppm is the target for maximum space CO2 concentration set by NZS 4303:1990 "Ventilation for Acceptable Indoor Air Quality".

1.3 Illuminance

An acceptable level to support clerical type activities is 320 lux. This is the recommended maintained illuminance for "Moderately Difficult" visual tasks, including routine office tasks, according to Table 3.1 of AS/NZS 1680.1:2006 "Interior and Workplace Lighting".

About 65% of Office spaces had recorded mean lux levels lower than 320 lux, with almost 20% recording mean values under 100 lux. Only the highest 20% of measurements were above 500 lux. About 5% of Office spaces had average illuminance over 1,000 lux.

About 55% of Retail spaces had recorded mean lux levels lower than 320 lux, with 20% below 100 lux. The top 25% of the spaces measured during this study had mean daily illuminance over 640 lux, and about 10% had mean illuminance over 1,000 lux.

Over 70% of "Other" spaces had mean lux levels lower than 320 lux, and 30% below 100 lux. The top 20% had average illuminance measured over 600 lux. These were Kitchens and workrooms, but also a warehouse and a storeroom. 5% averaged over 1,000 lux.

1.4 Humidity and Dewpoint

In all spaces, summer dewpoints were the highest measured (indicating high moisture content), and winter the lowest (indicating low moisture content).

About 80% of the Offices in winter show indoor dewpoints higher than outdoors, which indicates a net generation of moisture within the space. Other spaces show lower winter dewpoint rises than Offices. In intermediate seasons, they are similar to Offices.

In summer, about 80% of the Offices (and the other two space types) show that the dewpoint is reduced compared to outside. This indicates a net reduction of moisture within the space (probably due to dehumidification during air-conditioning, or possibly excess ventilation of the spaces with outside air at night).

About 80% of the sample had a measured mean relative humidity between 40% and 60%. The variation from the mean was typically ± 5-10%.

Retail spaces have some humidities that are lower than Office and Other spaces, generally caused by low winter humidities, presumably due to excess ventilation, and spaces classified as "Other" have slightly higher humidities.

2. MEASURED TEMPERATURES

2.1 Background

Space temperatures are important for ensuring thermal comfort for occupants.

Thermal comfort is a complex subject, and for example, the American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. (ASHRAE) devotes about 30 pages in its Fundamentals Handbook to aspects of thermal comfort. Figure 1, below, is a reproduction of Figure 5 from the 2001 version of that handbook, and shows the thermal comfort zones, as specified in ASHRAE Standard 55, where "80% of sedentary of slightly active persons find the environment thermally acceptable", considering different levels of clothing common in summer and winter.

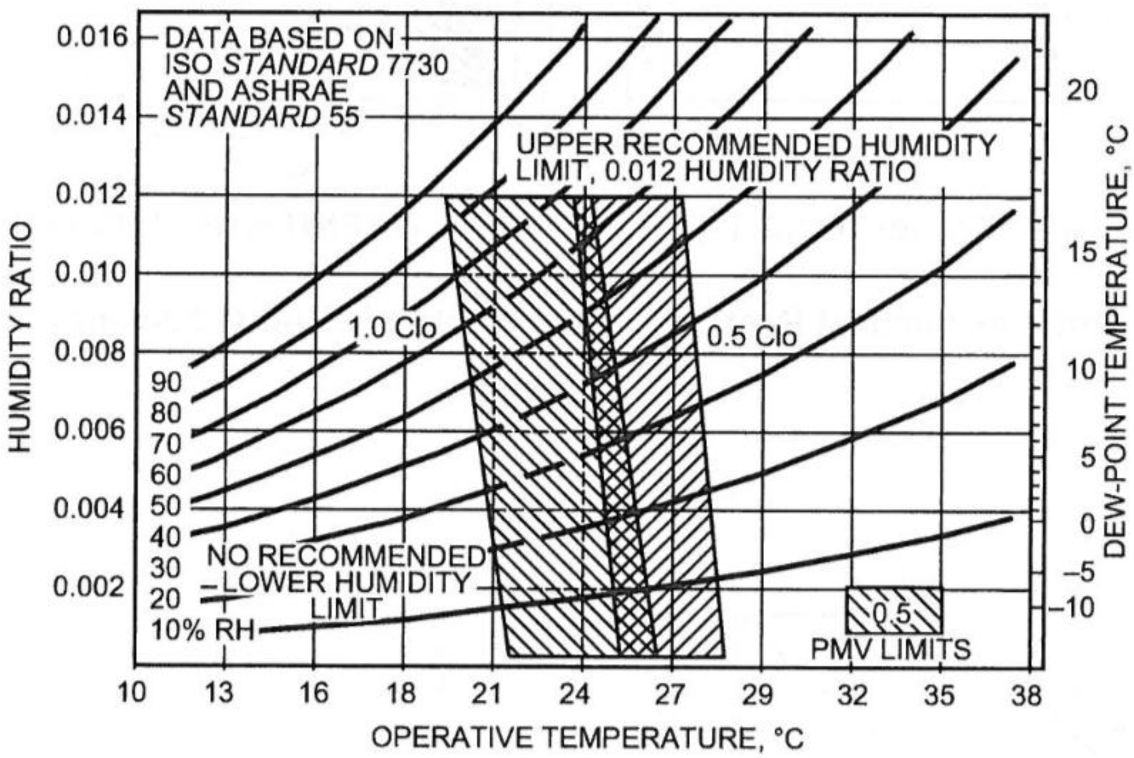

Figure 1: ASHRAE Summer and Winter Comfort Zones

The winter comfort zone has a lower operative temperature boundary of about 20°C and an upper one of 24°C. The summer comfort zone has a lower boundary of 23°C and an upper one of 27°C. The Handbook also states that "the upper and lower humidity levels of the comfort zones are less precise." For the purposes of this study, we will consider the winter comfort zone to be 20° - 24°C, and the summer one to be 23° - 27°C. Clo in Figure 1 in the unit for the thermal properties of clothing, a Clo of 1 represents a person wearing a typically business suit.

For the purposes of these analyses, we have segregated the data so that spaces recorded as either Office, Reception, Meeting Room, Conference Room, or Laboratory were grouped as "Offices," , while "Retail" includes Shops and Showrooms, and "Other" spaces include Kitchens, Storerooms, Work rooms, Warehouses, Lounges, Dining Rooms, and Bakeries.

Seasonal segregation was based on the dates of monitoring, using June/July/August as winter, and December/January/February as summer. Other seasons were called “intermediate”. When logging spanned two seasons, the one containing a greater number of monitored days was taken as the season.

2.2 Examples of typical temperature profiles

Examples of typical temperature profiles recorded in spaces are shown in Figure 2 through to Figure 5 below. Each of these represents the temperature for each weekday as a thin solid grey line, for each weekend day as a thin dashed red line, the mean value for all weekdays as a thick solid black line, and the mean value for all weekend days as a thick dashed red line.

The main temperature statistic reported from these profiles is the mean temperature on weekdays between 10 am and 4 pm (the middle of the normal working day, when temperatures would be expected to be controlled and reasonably stable).

The reported temperature “swing” (±°C) is the maximum of either (a) the “Average Standard Deviation” of the temperature during this time, or (b) half the difference between the mean daily maximum temperature and mean daily minimum temperature.

The variation in temperature profile shapes meant that these values were not consistently related to each other, and temperatures were not necessarily normally distributed, so standard deviation was not entirely appropriate. Thus, the maximum of these values was taken as representative of the average daily “swing".

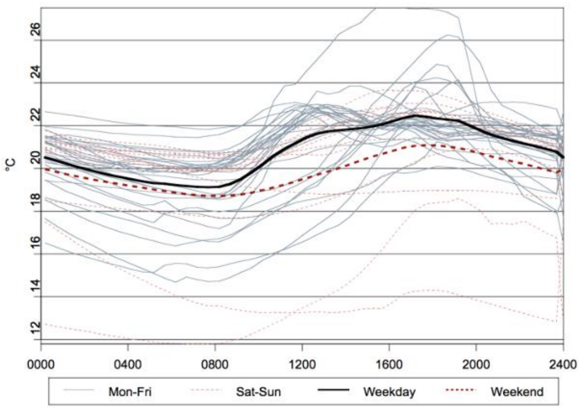

Figure 2: Space temperature profile – well controlled wave 21.4±0.8°C

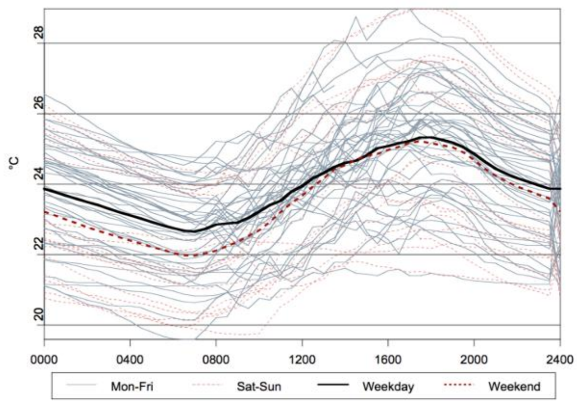

Figure 3: Space temperature profile – less well controlled wave 24.3±1.5°C

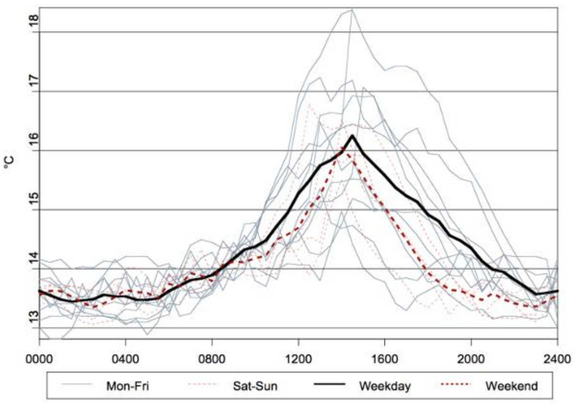

Figure 4: Space temperature profile – spiky profile 15.6±1.3°C

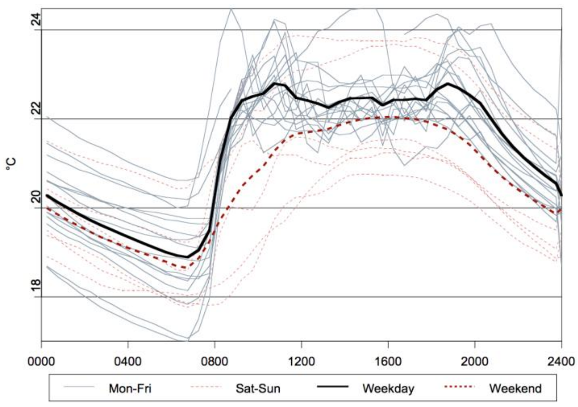

Figure 5: Space temperature profile – well controlled and flat 22.3±0.9°C

Figure 2 shows the temperature profile for a space where the temperature varied roughly as a sine wave, with the daily minimum temperature reached about 19°C about 8 am. The temperature rose all day to a peak of about 23°C at about 5 pm, then dropped overnight. Most weekdays showed a pattern similar to this, as seen by the sheaf of thin grey lines above the dark one. The lowest temperature recorded was about 15°C, and the highest about 27°C. Weekend temperatures, as shown by the dotted red line, usually showed a similar pattern about a degree lower.

The weekday 10 am to 4 pm mean temperature was 21.4°C, with a swing of ±0.8°C.

Figure 3 shows the temperature profile for another space with a similar sine wave shaped temperature profile. This building has much more day-to-day variability than that the previous one. This building showed a weekday 10 am to 4 pm mean temperature of 24.3°C, with a swing of ±1.5°C. This is the swing of the weekday average temperature; the effect of the day-to-day variability is not addressed in this statistical analysis.

Figure 4 shows a different shaped profile, one that has a distinct afternoon peak. This is for a workroom, apparently intermittently heated, which varied from about 13.5°C from 10 pm to 6 am, to a peak of just over 16°C in the mid-afternoon. Weekend temperatures were similar, but slightly lower. The weekday 10 am to 4 pm mean temperature was 15.6°C, with a swing of ±1.3°C.

Figure 5 shows a different shaped profile, with a quite well controlled and constant temperature during working hours. This space typically cooled to about 19°C overnight, but was rapidly heated to over 22°C at 8 am, and generally maintained this temperature until about 8 pm.

There was some variation from day-to-day, with peak temperatures observed over 24°C at various times on different days, and minima of about 21°C during working hours.

Weekend temperatures in Figure 5 were similar, but lower, and showed more of a sine-wave pattern, which might indicate that the temperature was "floating". The weekday 10 am to 4 pm mean temperature was 22.3°C, with a swing of ±0.9°C. This is one of the few locations that showed temperatures consistently in the accepted "comfort zone".

2.3 Measured temperature summaries

Figure 6 shows the summary of the weekday temperatures measured in all the spaces listed as "Offices" in winter conditions. The mean weekday temperature between 10 am and 4 pm is shown as the blue diamond, with points above representing the mean plus average standard deviation, and the average daily maximum (during this time interval). The points below similarly represent minimum temperatures.

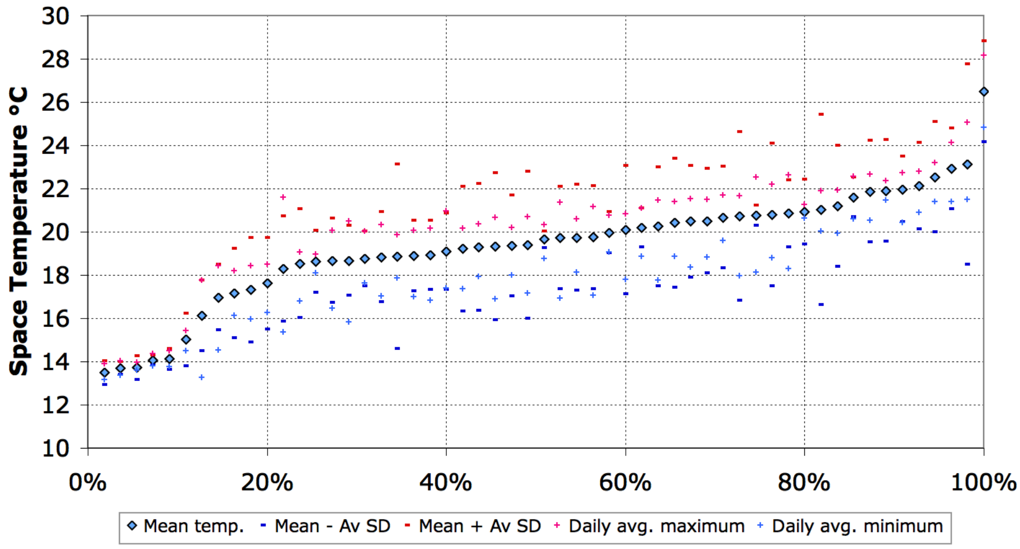

Figure 6: Winter office temperatures

As can be seen, only about 45% of Office spaces recorded mean temperatures above 20°C, and only about 10% above 22°C (the ASHRAE "comfort" temperature). However, about 75% exceeded 18°C, and only 10% had mean temperatures below 16°C.

In terms of average daily minimum space temperatures recorded on workdays from 10 am – 4 pm, 75% were below 18°C, and only 10% had minima above 20°C. These are rather cold conditions, and indicate that much of the initial sample of buildings is not maintaining "comfort" by conventional standards.

A similar analysis was performed on the two other types of spaces, "Retail" and "Other". The results were generally similar, though there were fewer points in these categories. So, for a comparison, the distribution of mean temperatures for the three space types is shown on the same graph, as Figure 7 below.

In this graph, Offices are shown as the blue diamonds, Retail as green circles, and Other as red squares.

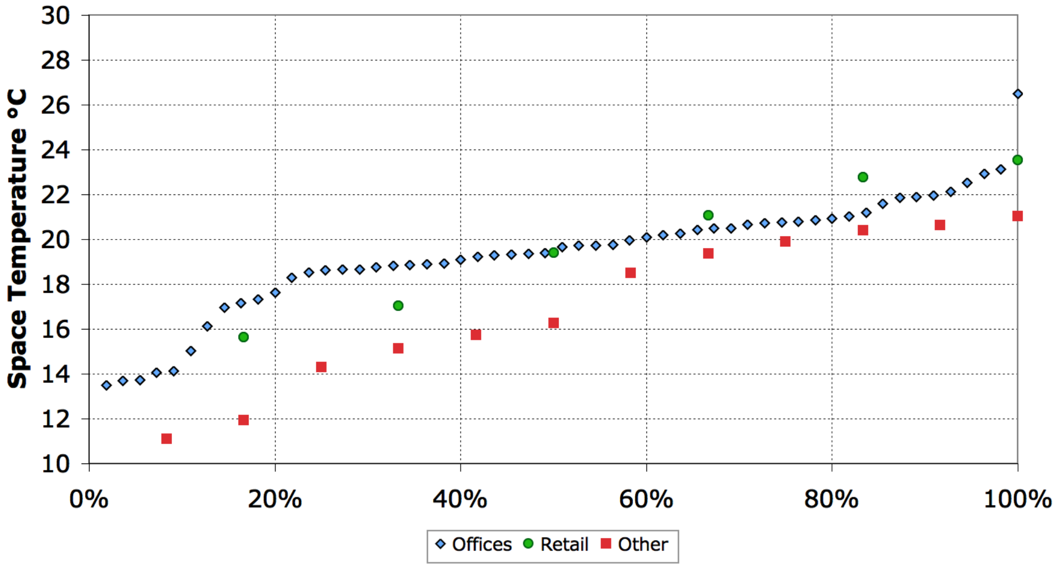

Figure 7: Winter daily average temperature comparison

As can be seen, based on a very small sample of Retail premises, Offices and Retail temperatures are about the same in winter. "Other" spaces, though, show much lower temperatures than Offices.

A similar analysis was performed on Office temperatures in summer. The results of this are shown in Figure 8. The graph is formatted the same as Figure 6 above.

In summers, Office temperatures are warmer, unsurprisingly. All the mean daily (weekday, 10 am – 4 pm) temperatures are above 20°C. Only one has a mean temperature above 27°C, the upper bound of the summer "comfort zone".

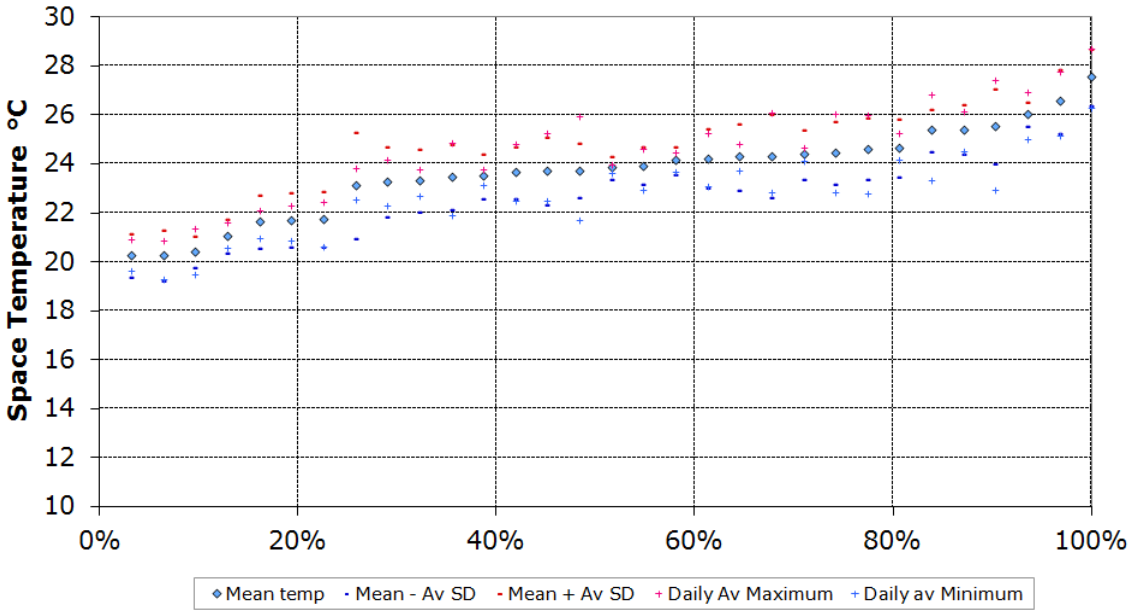

Figure 8: Summer office temperatures

The summer temperatures show a generally lower daily "swing" than in winter. Only about 25% of spaces show average daily maximum temperatures above 26°C.

A comparison of the different space types' summer temperatures is shown in Figure 9. This shows a generally similar result to Figure 7, as Office and Retail spaces again show a very similar distribution of daily mean temperatures. Other spaces had extreme mean temperatures slightly higher (20% at 26°C or above) and lower (20% at or below 20°C) than the other two groups. This is not surprising, given the range of activities in the "Other" spaces, and the likelihood of them being unconditioned or only partially conditioned.

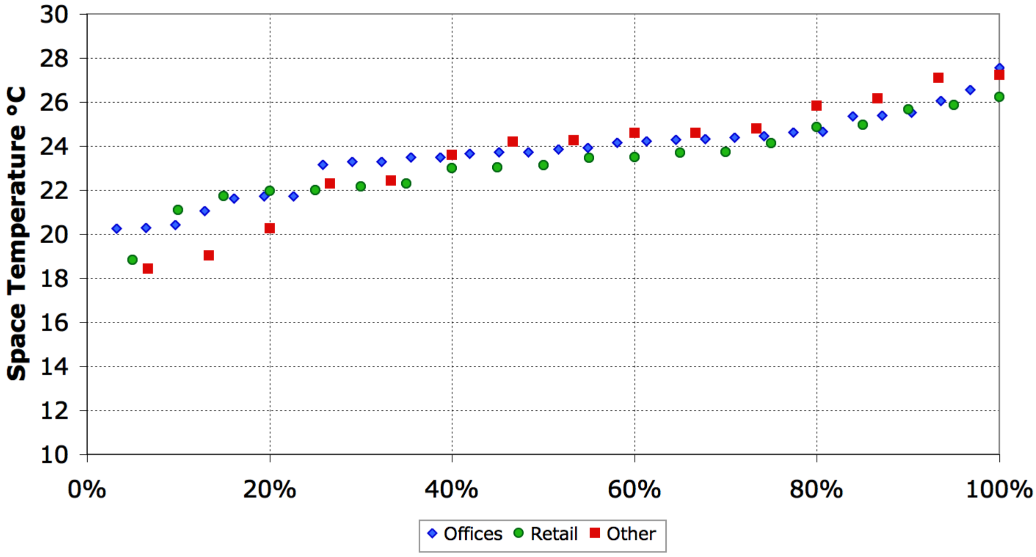

Figure 9: Summer daily average temperature comparison

For completeness, the intermediate seasonal temperatures are also plotted in the same format as winter and summer above. Figure 10 shows the distribution of mean daily Office temperatures during the intermediate season.

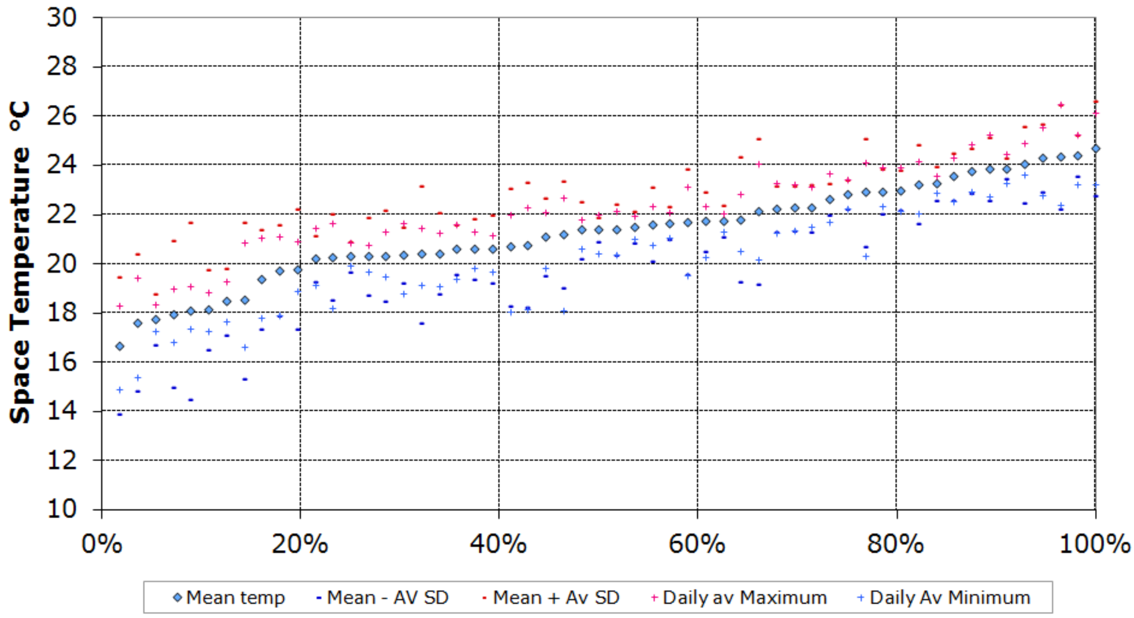

Figure 10: Intermediate season office temperatures

As shown, 80% of monitored Office spaces have mean weekday temperatures above 20°C, and only about 10% above 24°C. Most spaces have comfortable temperatures (using the ASHRAE definitions of comfort, as shown in Figure 1) during intermediate seasons.

However, about 20% of these Offices have daily average minimum temperatures below 18°C, which is distinctly cool, and another 30% have daily average maximum temperatures above 24°C.

Figure 11 shows the comparison of the different types of spaces' average space temperatures during the intermediate seasons.

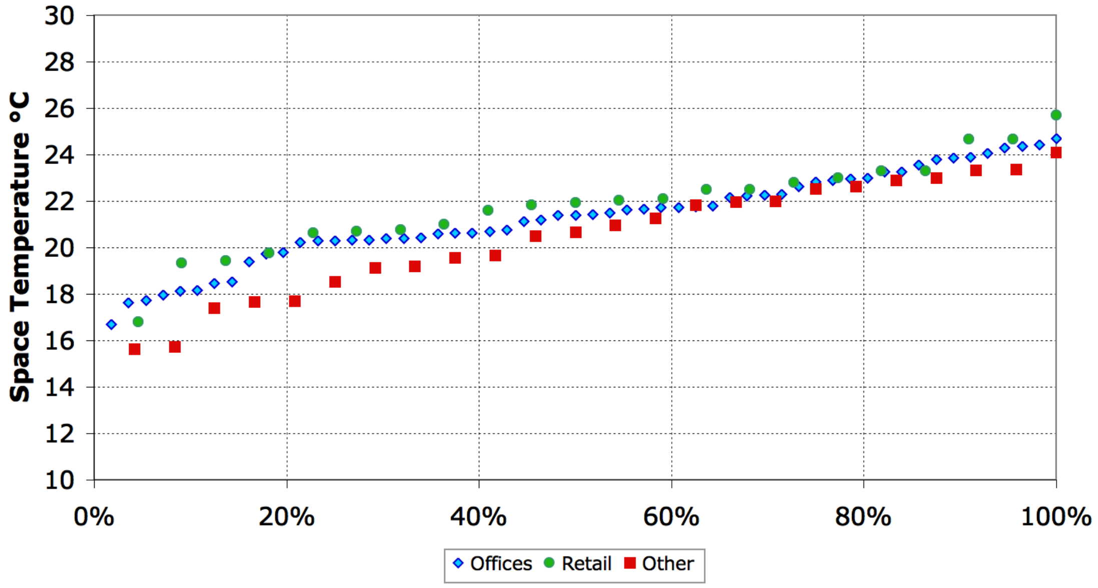

Figure 11: Intermediate season daily average temperature comparison

As can be seen, again the weekday averages temperatures of Office and Retail spaces are very similarly distributed. Again the "Other" spaces show lower average temperatures, including two with weekday average temperatures below 16°C. (One was a workroom that stayed cooler than outdoors, and the other was an apparently very well-ventilated kitchen.)

Another way of viewing the temperature data is by comparing the daily temperature "swing" up and down from the mean, to the mean temperature. This is shown in Figure 12, for the Offices measured in Winter. It shows the same data as in Figure 6, from a different perspective.

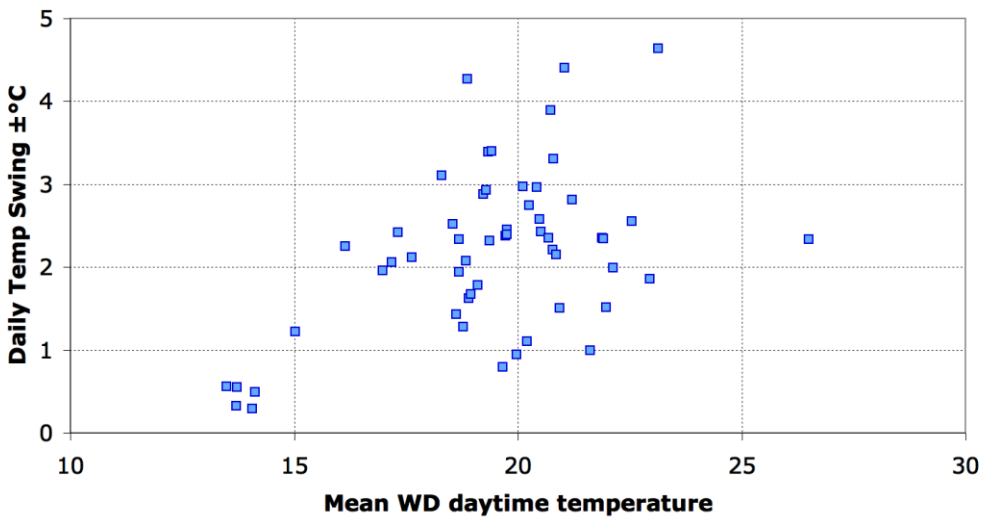

Figure 12: Winter office daily average temperatures and swings

Figure 12 illustrates that the temperature swings of many of the spaces were quite significant, in three cases nearly ±5°C! The ASHRAE "comfort zone" is only about ±2°C, so these swings could cause occupants to be both too hot and too cold each day! This tends to suggest poor control of heating systems in these spaces.

The five spaces shown at the lower left are cold, and hardly vary during the day. Most of the remaining spaces have average swings of over ±2°C.

When these are compared to the summer data, as shown in Figure 13, on the same axes, the relative stability of the summer temperatures becomes clear.

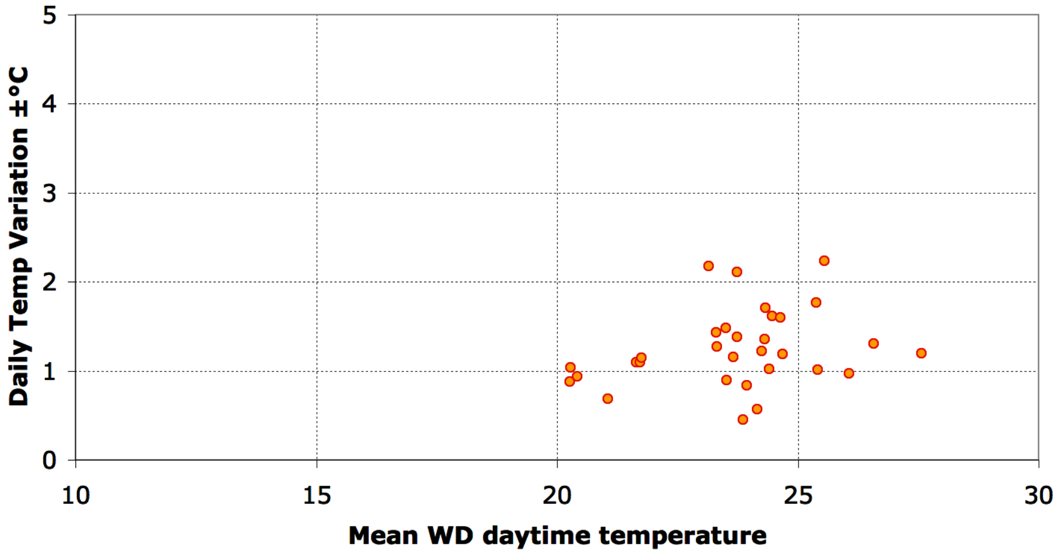

Figure 13: Summer office daily average temperatures and swings

The summer temperature swings are much lower, averaging about ±1°C. These lower temperature swings suggest that the cooling systems may be better sized to the loads they face, and/or that they are better controlled, so they do not "over cool" their spaces, though an analysis of the causes of this is beyond the scope of this report.

3. AIR QUALITY (CARBON DIOXIDE) MEASUREMENTS

The simplest measure of the air quality of a space is by its carbon dioxide (CO_2) content. While other pollutants can affect indoor air quality, CO_2 is a direct measure of human metabolism, and not out-gassed by materials. Thus the concentration of CO_2 can be used to indicate the amount of outside air ventilation, in litres/second per person.

New Zealand Standard NZS 4303:1990 "Ventilation for Acceptable Indoor Air Quality" defines the amount of ventilation required to provide good indoor air quality. Appendix D of that Standard shows a calculation procedure to relate the amount of outside air supplied to a space (in L/s per person, where 10 L/s per person is recommended for most spaces, in the "Ventilation Rate Procedure"), to the difference in concentration of CO_2 between indoors and outdoors. Alternatively, a concentration of 1,000 ppm CO_2 complies using the Indoor Air Quality Procedure.

Figure 14 through to Figure 17 show four representative space CO_2 concentration profiles.

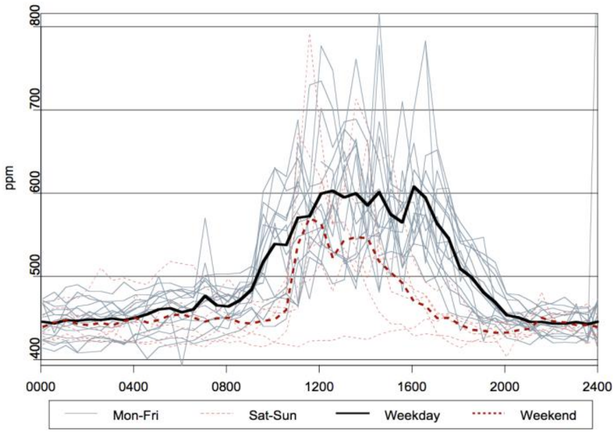

Figure 14: Typical space CO_2 profile – excellent ventilation 450-600 ppm

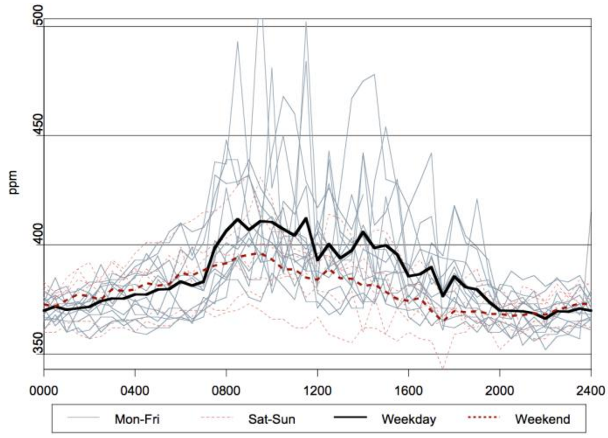

Figure 15: Typical space CO_2 profile – acceptable ventilation 340-450 ppm

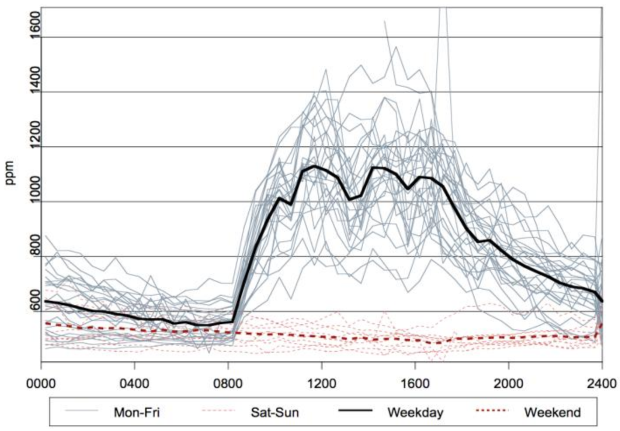

Figure 16: Typical space CO_2 profile – inadequate day ventilation 600-1100 ppm

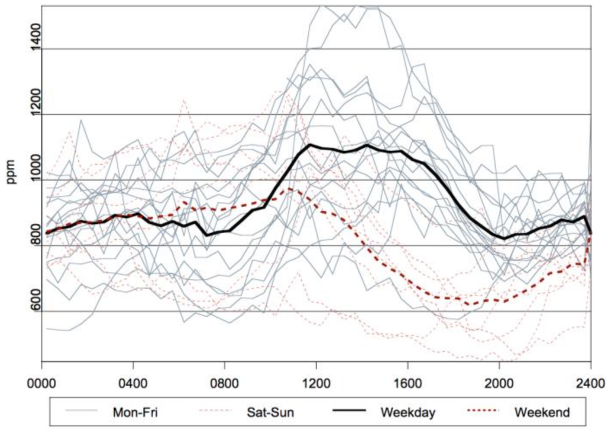

Figure 17: Typical space CO_2 profile inadequate ventilation 800-1100 ppm

Figure 14 shows the CO_2 concentration profile for a space with good ventilation. It varies from about 450 ppm overnight to an average of about 560 ppm during the middle of the working day. The average day peak is about 700 ppm and the absolute peak is about 800 ppm.

Figure 15 shows the CO_2 concentration profile for a space with excessive ventilation (compared to its occupancy). It varies from about 340 ppm overnight to an average of about 400 ppm during the middle of the working day. The average day peak is about 450 ppm and the absolute peak is about 520 ppm.

Figure 16 and Figure 17 show the CO_2 concentration profiles for spaces with insufficient ventilation. The space in Figure 16 varies from about 600 ppm overnight to an average of about 1100 ppm during the middle of the working day. The space in Figure 17 rarely drops below 800 ppm and again averages about 1100 ppm during the working day. Both of these spaces exceed the recommended 1000 ppm level from NZS 4303:1990 (Indoor Air Quality Procedure).

The daytime CO_2 concentration in outdoor air (OA) in urban environments is typically 450 ppm. Using this value, the amount of fresh air supplied to a space, per person, can be calculated using Figure 25. Reading vertically up from the indoor CO_2 concentration to the green line representing a CO_2 concentration in outdoor air of 450 ppm, then horizontally across to the vertical axis, the number of litres per second of outside air supplied per person can be determined.

The importance of this is that bringing in more outside air than is necessary during periods of hot or cold weather increases the cooling or heating loads in a space. In some conditions, the outside air ventilation can be the dominant heat loss mode from a building, and lead to much more space heating to be required than would otherwise be the case.

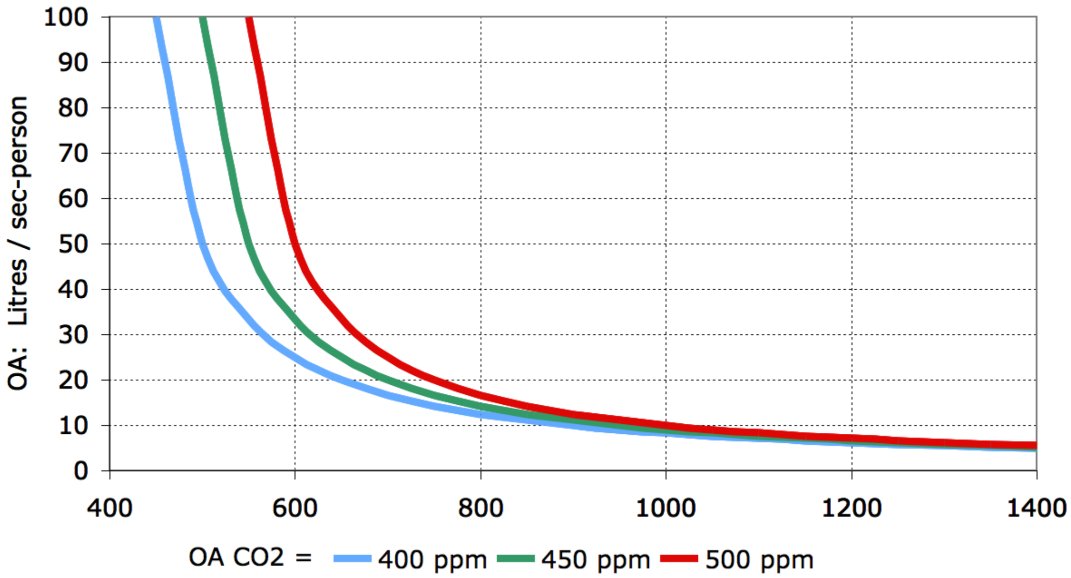

Figure 18: Calculated ventilation rate as a function of space CO2 content

As can be seen from Figure 18, if the space CO_2 concentration is measured as 800 ppm (assuming 450 ppm outside), then 15 L/s-person of outside air is being supplied, or a 50% higher air exchange (ventilation + infiltration) rate than required by the Standard for good air quality. If the space CO_2 concentration is measured as 600 ppm (assuming 450 ppm outside), then about 35 L/s-person of outside air is being supplied, or 250% more than required by the Standard. At 500 ppm, about 100 L/s-person of outside air is being supplied, or 900% more than required by the Standard.

In general, with space CO_2 concentrations less than about 600 ppm, it is difficult to estimate the actual air exchange rate due to its sensitivity to the actual meter accuracy (nominally ±50 ppm) and assumptions about the outside air CO_2 concentrations, except to note that the ventilation rate is much higher than necessary to maintain good air quality.

Figure 19 shows the range of measured CO_2 concentrations from this stage of the BEES, with the maximum concentration limited to 1000 ppm (for ease of viewing). The blue diamonds show the mean value measured on weekdays from 10 am – 4 pm, the tiny blue circles show the mean value recorded in the same time period on Sundays (when the space would be most likely to be vacant), the blue line the average maximum recorded on weekdays from 10 am – 4 pm, and the cross the average maximum recorded on weekdays (over 24 hours).

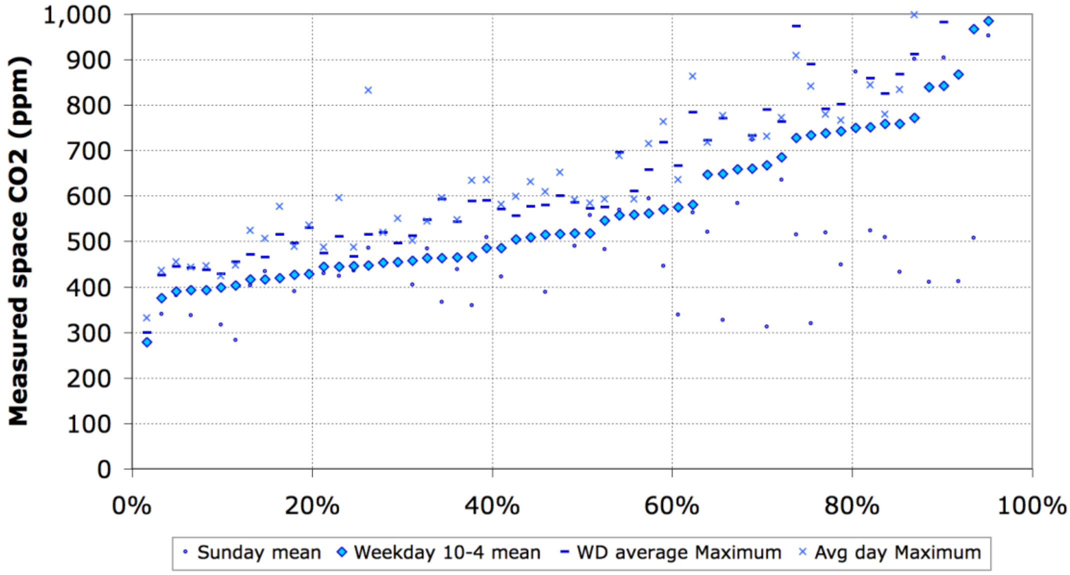

Figure 19: Measured CO_2 – weekday and Sunday mean and maximum

As can be seen, about 40% of the spaces monitored showed average CO_2 concentrations below 500 ppm. This indicates that these spaces are ventilated with outside air at more than ten times the required rate, and that this may cause excess heating and cooling loads. Another 25% of the spaces are between 500 and 600 ppm, showing excess ventilation rates of between 250% and 900%.

Figure 20 shows the full set of CO_2 measurements, including those exceeding 1000 ppm. As can be seen, at the high end of CO_2 concentrations, about 5% of spaces average over 1000 ppm during normal working hours, and about 15% exceed this at some time each day. These spaces are receiving insufficient fresh air.

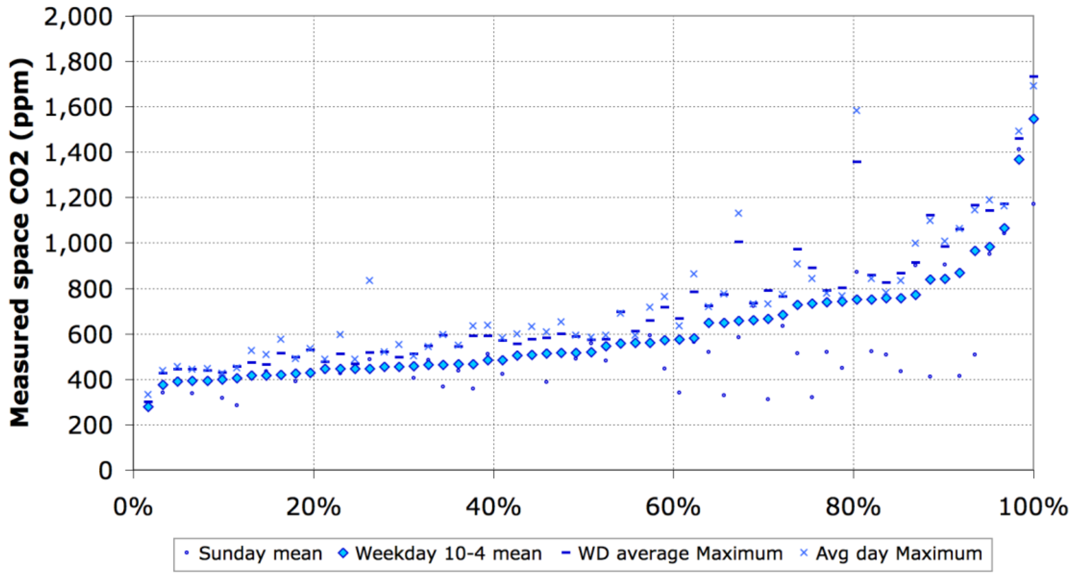

Figure 20: Measured space CO_2 contents (expanded range)

Although the sample is relatively limited, it can be segregated by space type and season. When this is done, the resulting distributions of CO_2 concentrations are plotted in Figure 21.

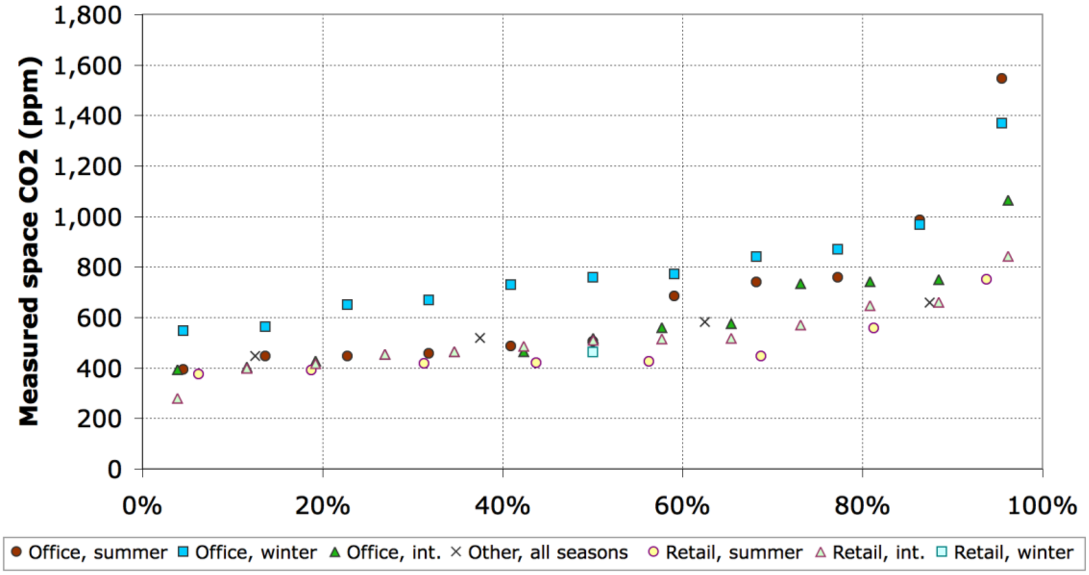

Figure 21: Mean weekday CO_2 by season and space type

As can be seen from Figure 21, more than 80% of the Retail and Other spaces in all seasons, and 70% of Offices in the intermediate seasons had CO_2 concentrations less than 600 ppm, indicating that they are over-ventilated. About 20% of the Offices in winter (light blue squares), and half of the Offices in summer were also in this category.

It is understandable that many Retail spaces would have low concentrations of CO_2, as it is common practice for these premises to leave doors open whenever they can to attract customers.

Likewise, in intermediate seasons it is common practice for buildings to maximise their outside air ventilation rates, as there are neither heating nor cooling penalties then. In fact, some larger commercial buildings use a "full fresh air economiser" as an energy saving strategy, displacing refrigerative cooling under moderate ambient temperature conditions.

Even with these considerations, the above analysis shows that the amount of ventilation in the New Zealand commercial buildings surveyed so far is rarely well controlled.

4. ILLUMINANCE MEASUREMENTS

The patterns of illuminance measured in the BEES buildings were reported in detail in a separate report, on the Daylighting Potential of New Zealand buildings (Bishop et al, 2011). This analysed the amount of daylight supplied to spaces, from decomposition of the illuminance profiles.

Figure 22 through to Figure 25 show four representative monitored illuminance profiles.

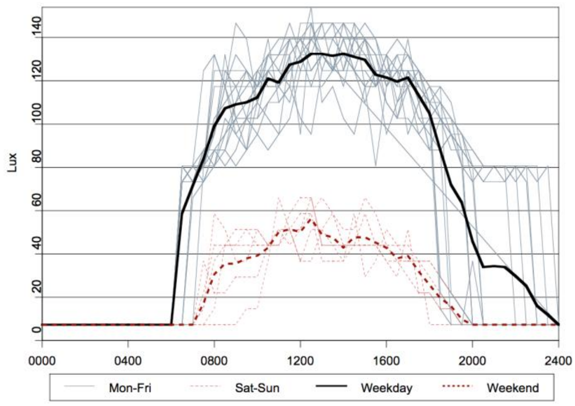

Figure 22: Typical space illuminance profile – day: 80-120 lux, night: 8 lux, consistent

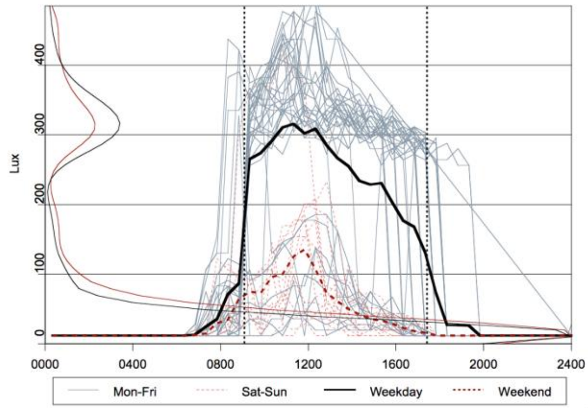

Figure 23: Typical space illuminance profile – day: 280-480 lux, night: 10 lux, varies

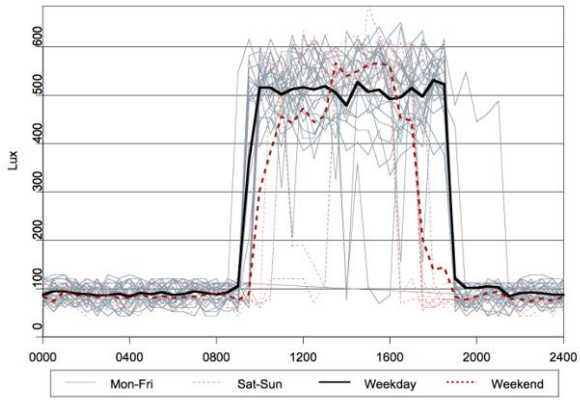

Figure 24: Typical space illuminance profile – day:450-600 lux, night: 80 lux, consistent

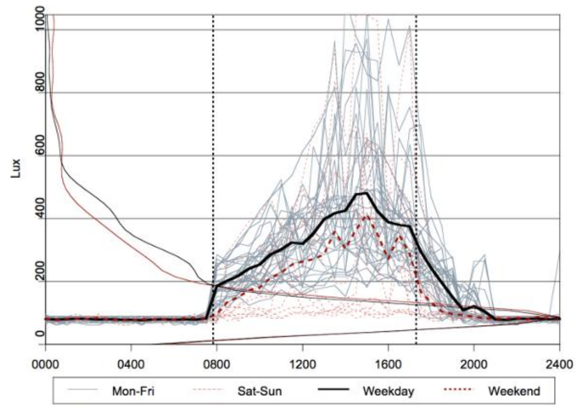

Figure 25: Typical space illuminance profile – day: 200-1000 lux, night: 80 lux, varies

Figure 22 shows the illuminance profile for a space with electric lighting operating all day, and good daylight during the middle of the day. It varies from about 80-140 lux during the middle of the working day with daylight averaging about 40 lux. The electric lights are switched on at about the same time each morning, but shut off at various times between 6 pm and midnight.

Figure 23 shows the illuminance profile for a space also with electric lighting operating all day, and good daylight in the morning. It varies from about 280-500 lux during the middle of the working day with daylight averaging about 80 lux. The electric lights are usually switched on 9 am, but shut off at various times between 3 pm and 8 pm, giving the downward-sloping afternoon average illuminance profile.

Figure 24 shows the illuminance profile for a space with electric lighting operating all day, and little or no daylight. It varies from about 450-600 lux during the middle of the working day. The electric lights are switched on and off at consistent times, leading to the “square wave” pattern.

Figure 25 shows the illuminance profile for a space with electric lighting and much daylight. It varies from about 300-1000 lux during the middle of the working day with daylight averaging about 300 lux. The electric lights are consistently switched on 8 am, and off between 6 pm and 7 pm, with occasionally evening lighting between 8 pm and 9 pm.

The distribution in daily average illuminance measured in Offices (Weekdays between 10 am and 4 pm) is shown in Figure 26.

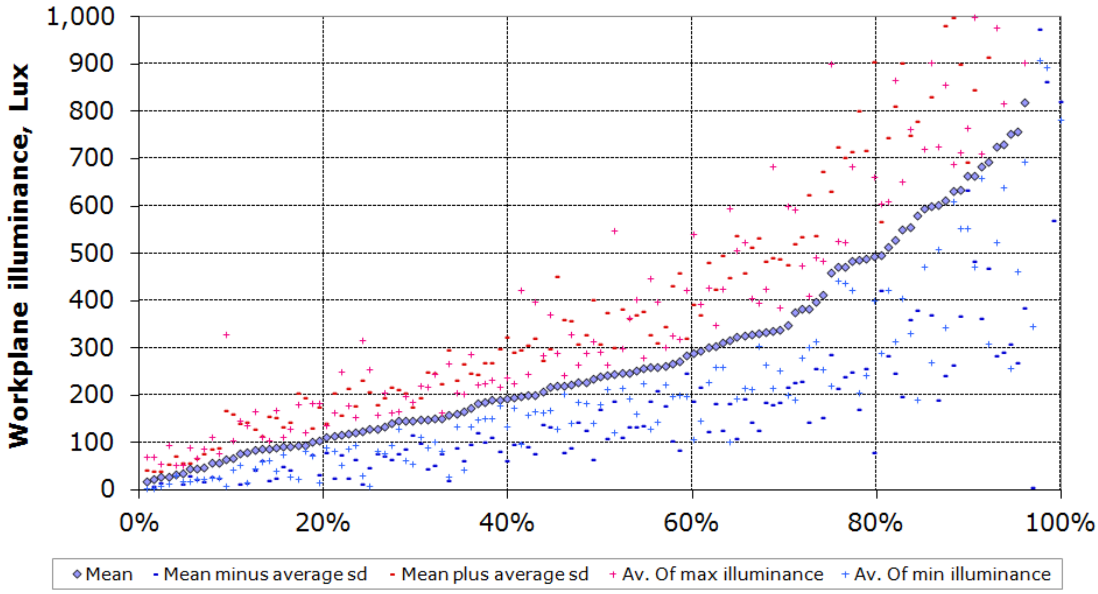

Figure 26: Office illuminance level distribution

The large blue diamonds in Figure 26 (and the following illuminance graphs) represent the mean value recorded during this time. The small red and blue bars show the mean plus or minus the average standard deviation, and the small crosses the average of the minimum and maximum illuminance recorded each weekday during this time span.

As can be seen from Figure 26, about 65% of Office spaces had recorded mean lux levels lower than the target of 320 lux (from AS/NZS 1680.1:2006 Interior and Workplace Lighting, Part 1: General principles and recommendations, Table 3.1, as the maintained illuminance for routine office tasks) with almost 20% recording mean values under 100 lux. Only the highest 20% of measurements were above 500 lux. About half of the spaces measured during this study had average daily maximum illuminance over 420 lux.

Figure 27 shows the same data set, but with the vertical range expanded to show the 5% of Offices where daily mean measurements that were over 1000 lux. One premise had an average daily maximum illuminance over 5000 lux!

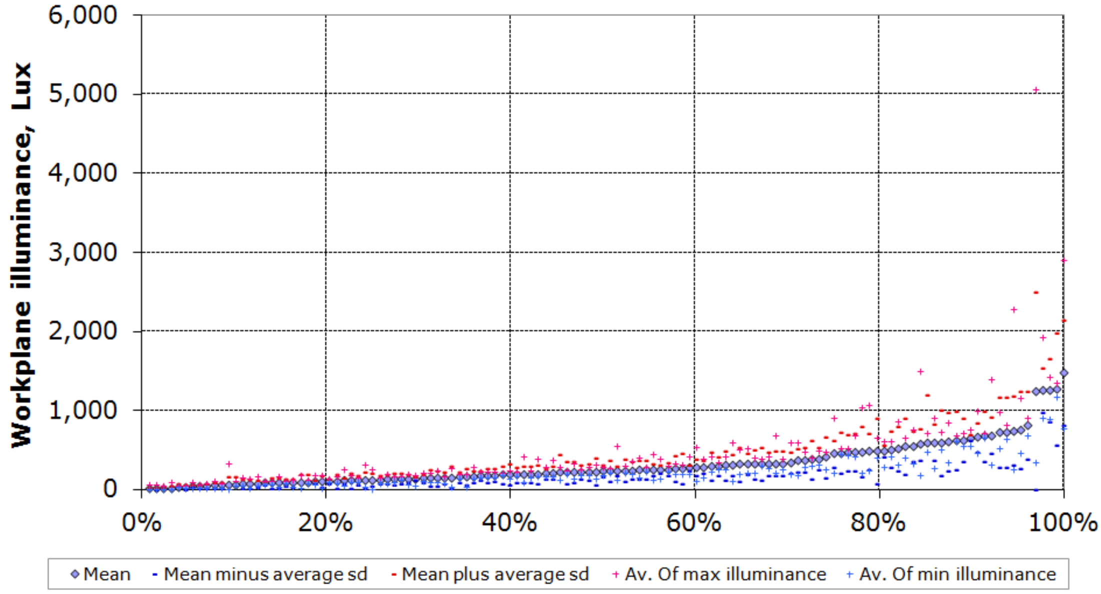

Figure 27: Office illuminance level distribution (expanded range)

Figure 28 presents the same type of data, but for Retail spaces. This continues to show the low illuminance levels seen in Offices, which is somewhat surprising, as Retail spaces are often thought to be over-illuminated in an attempt to sell more products.

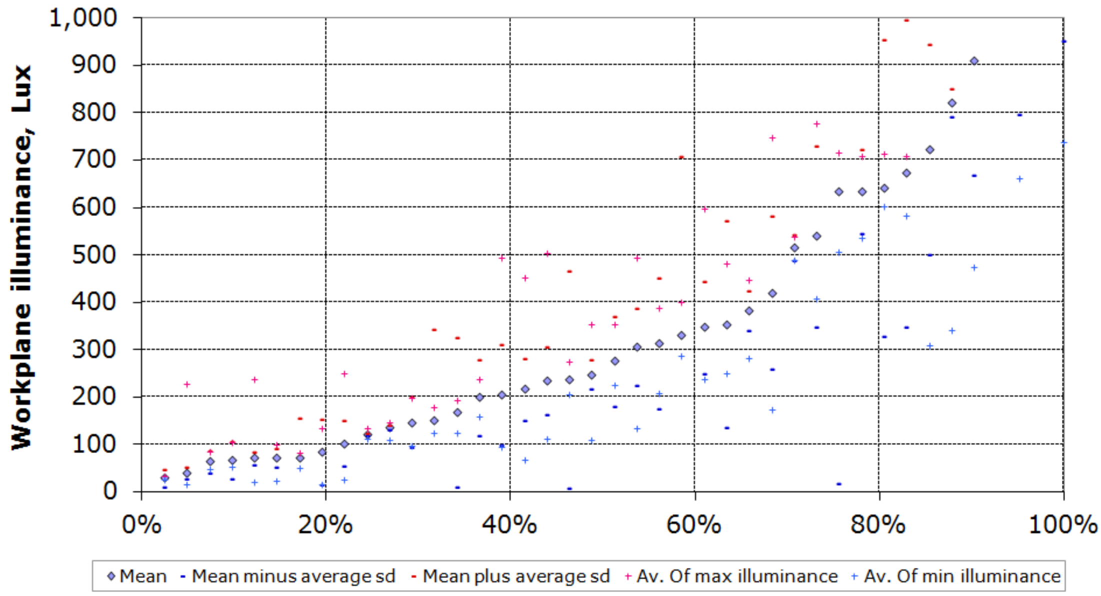

Figure 28: Retail space illuminance level distribution

As can be seen from Figure 28, like Offices, about 55% of Retail spaces had recorded mean lux levels lower than the 320 lux target, with 20% below 100 lux. However, 30% of premises had average illuminance measured over 500 lux. The top quarter of the spaces measured during this study had mean daily illuminance over 640 lux.

Figure 29 shows the same data set, but with the vertical range expanded to show the 10% of retail spaces where daily mean measurements that were over 1000 lux.

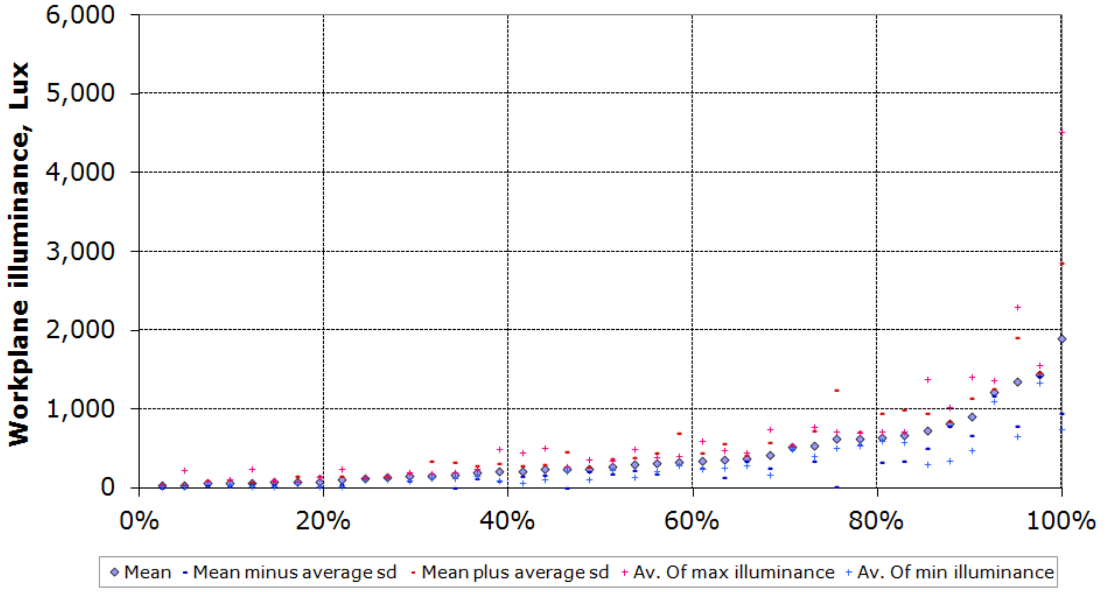

Figure 29: Retail space illuminance level distribution (expanded range)

Figure 30 presents the same type of data, for "Other" spaces. These spaces generally show even lower illuminances than Office and Retail spaces.

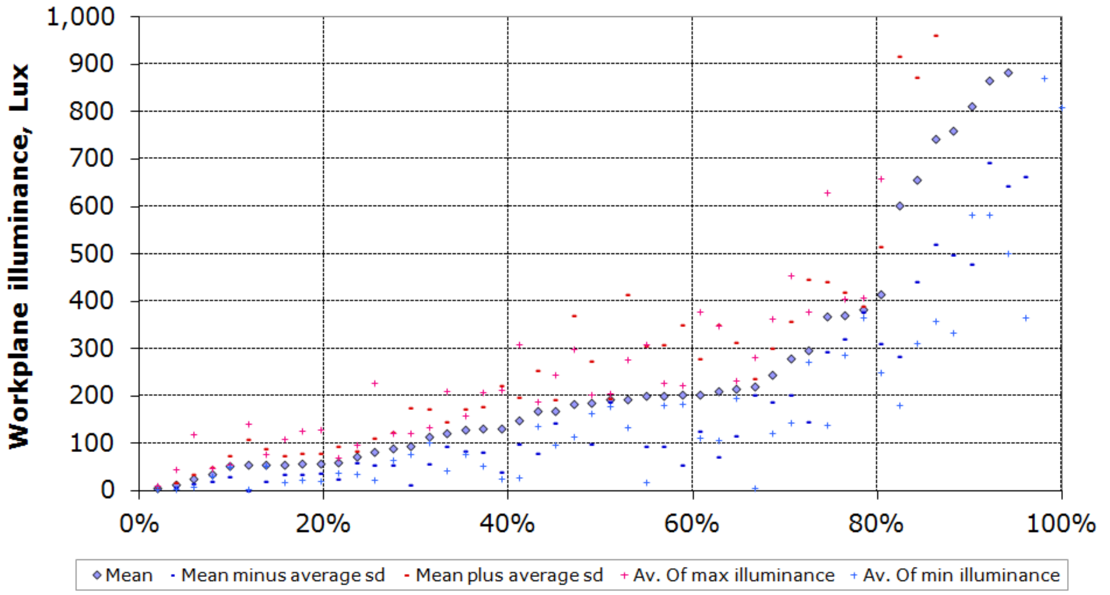

Figure 30: Other space illuminance level distribution

Figure 30 shows that the trend toward low illuminances is even more pronounced in Other spaces, with over 70% of Other spaces showing mean lux levels lower than 320 lux, and 30% below 100 lux. The top 20% of Other premises had average illuminance measured over 600 lux. These were Kitchens and workrooms, but also a warehouse and a storeroom. Several Kitchens were at the very low end of the illuminance distribution.

Figure 31 shows the same data set, but with the vertical range expanded to show the 5% of Other spaces where daily mean measurements that were over 1000 lux.

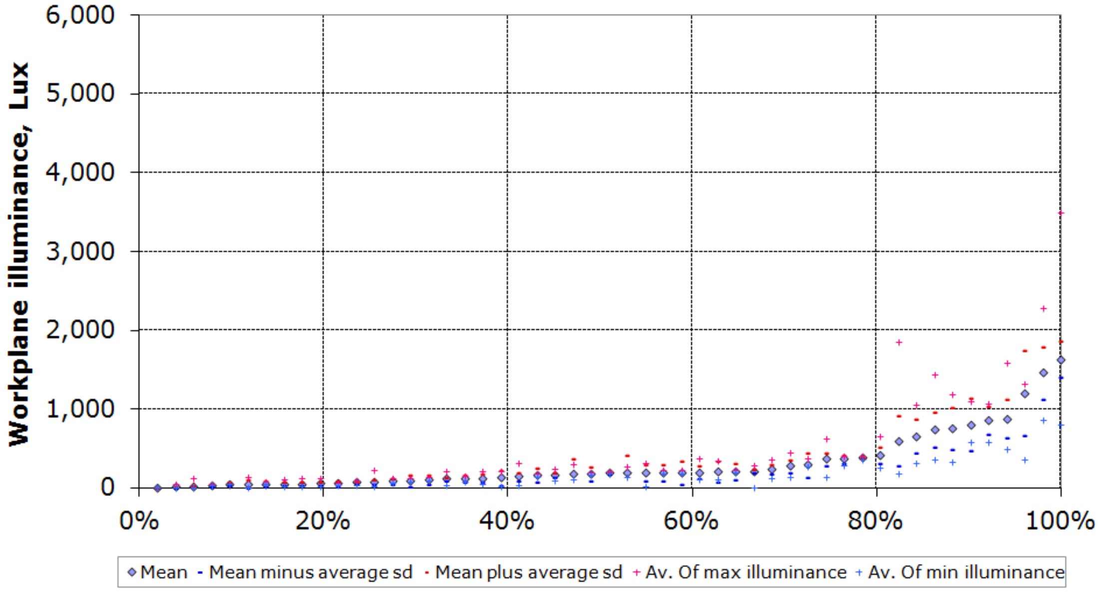

Figure 31: Other space illuminance level distribution (expanded range)

5. HUMIDITY AND DEWPOINT

The amount of moisture that air can hold without condensation increases with temperature, as warmer air can hold much more water than cold air. The amount of water held in air is called, variously, moisture content, absolute humidity, humidity ratio, vapour pressure, or dewpoint.

The first three quantities have units of g_{water} per $g_{dry\ air}$, vapour pressure has units of Pascals, and dewpoint has units of temperature (the temperature at which air of that moisture content becomes saturated, and its water content begins spontaneously condensing when cooled). Relative humidity is a measure of the moisture content of air, divided by the maximum moisture content at that temperature.

In this report, we focus on dewpoint rather than relative humidity, as it is a fundamental quantity. However, the distributions of relative humidity are also presented in this section.

Figure 32 through to Figure 35 shows the performance of a typical space, in terms of temperature, relative humidity, dewpoint, and carbon dioxide content of the air.

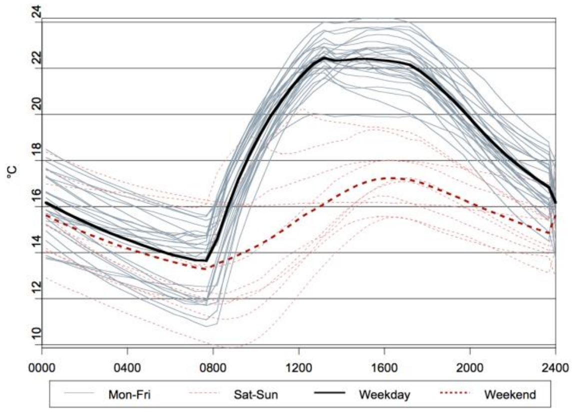

Figure 32: Office space temperature profile

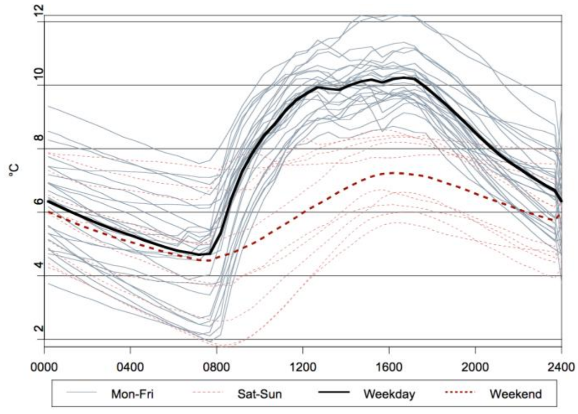

Figure 33: Office space dewpoint profile

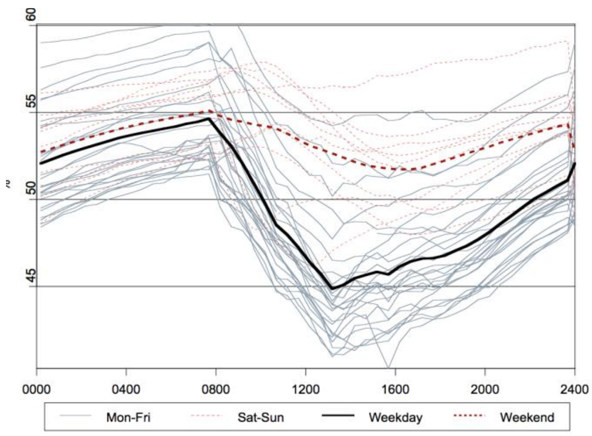

Figure 34: Office space relative humidity profile

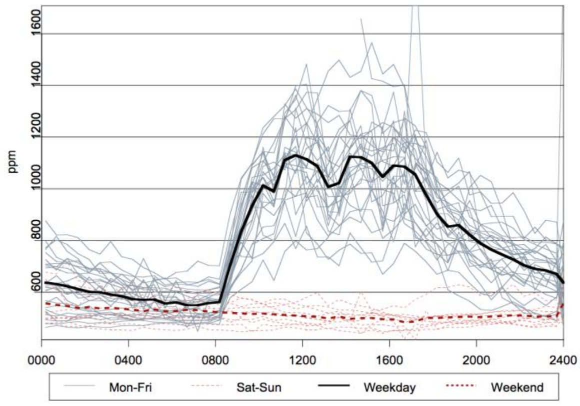

Figure 35: Office space CO_2 profile

Figure 32 through to Figure 35 shows the space condition profiles of a well-ventilated Office space monitored in winter. Figure 32 shows the temperature profile, with heating starting at 7 am each weekday morning. As the air temperature rises, without adding moisture to the air, the relative humidity starts to drop. However, the lower relative humidity causes some desorption of moisture from the space's structure and furnishings, causing the moisture content of the air to rise, and with it, the dewpoint.

Occupancy starts shortly after 8 am, as seen by the CO_2 profile in Figure 35. The presence of occupants add moisture and carbon dioxide to the space, and the dewpoint continues to rise. The temperature stabilises in the afternoon, and drops slightly, and the dewpoint continues to rise slowly, then from about 5 pm starts to fall.

This space had an average weekday (10 am – 4 pm) dewpoint of 8.9°C, ± 1.8°C. The average relative humidity was 48% ± 4% over this same period.

Figure 36 to Figure 39 show the same performance parameters for another typical space, except that this one was an actively cooled (and dehumidified) space in the summer.

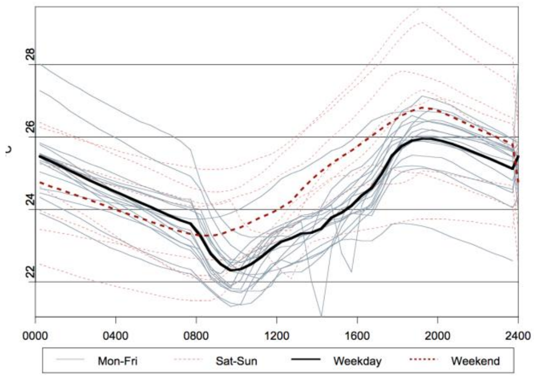

Figure 36: Cooled space – Temperature profile

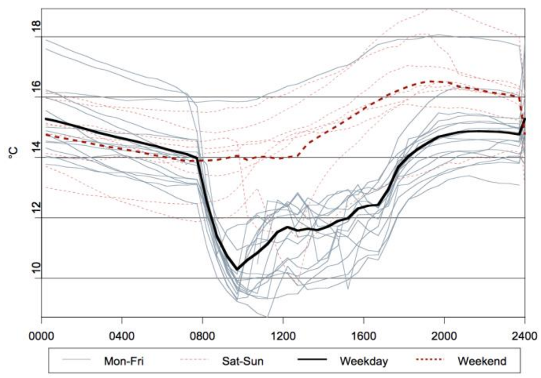

Figure 37: Cooled space – Dewpoint profile

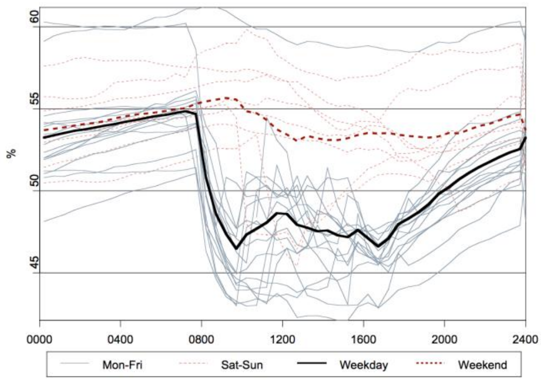

Figure 38: Cooled space – Relative humidity profile

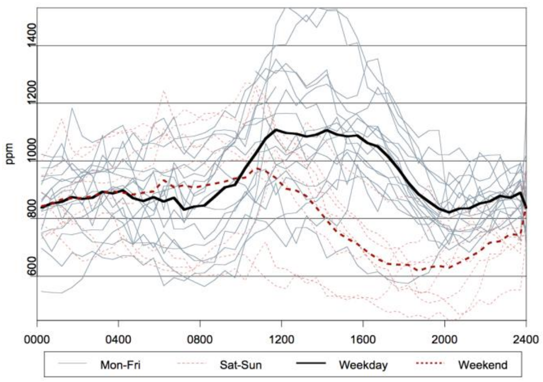

Figure 39: Cooled space - CO_2 profile

Figure 36 through to Figure 39 shows the space condition profiles of a poorly-ventilated retail space, monitored in summer. Figure 36 shows the temperature profile, with temperatures peaking in the early evening, and dropping slowly all night. The cooling starts about 7 am each weekday morning. The cooling system also dehumidifies the air in the space, shown by BOTH the dewpoint and relative humidity dropping quickly after the cooling starts.

From about 9 am, occupancy starts, as seen by the rise in the CO_2 profile in Figure 39 from that time. The presence of occupants add moisture and carbon dioxide to the space, and the dewpoint rises, and continues to rise all day. The relative humidity stays relatively stable throughout the day, as shown in Figure 38, as both the space temperature and the dewpoint are rising in tandem.

This space had an average weekday (10 am – 4 pm) dewpoint of 12.5°C, ± 2.3°C. The average relative humidity was 50% ± 5% over this same period.

The data set was segregated by season and building type. Figure 40 shows the measured average dewpoints for Office spaces (weekday 10 am – 4 pm) in each of the three season types.

As expected, the summer dewpoints are higher than intermediate seasons, which are in turn higher than winter. This is due to the moisture levels of indoor air generally tracking outdoor air, which has a higher moisture content (dewpoint) in summer.

The same patterns for Offices also held for Retail and Other spaces, as shown in Figure 41and Figure 42.

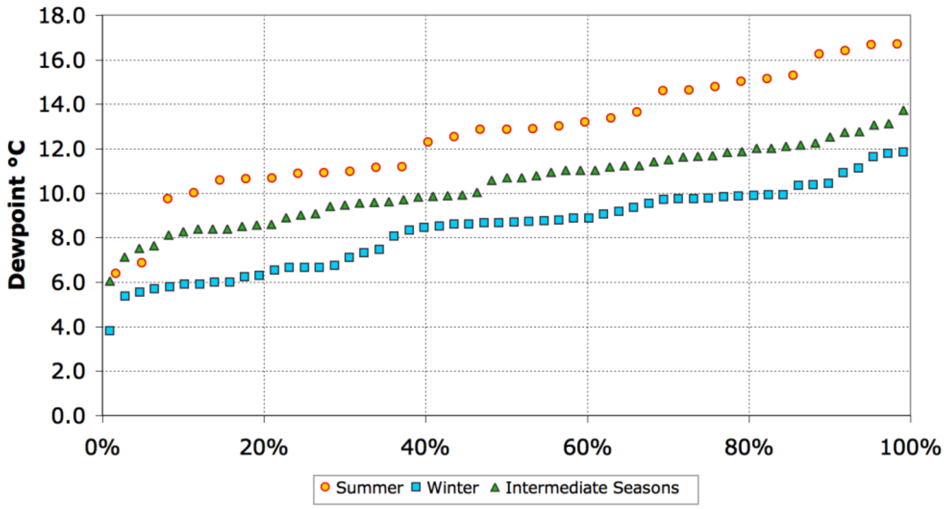

Figure 40: Office measured space dewpoints

The main difference between the dewpoints recorded in Offices, compared to Retail and Other spaces, are the higher winter dewpoints in Offices. Summer and intermediate seasonal dewpoints are very similar between all three building types.

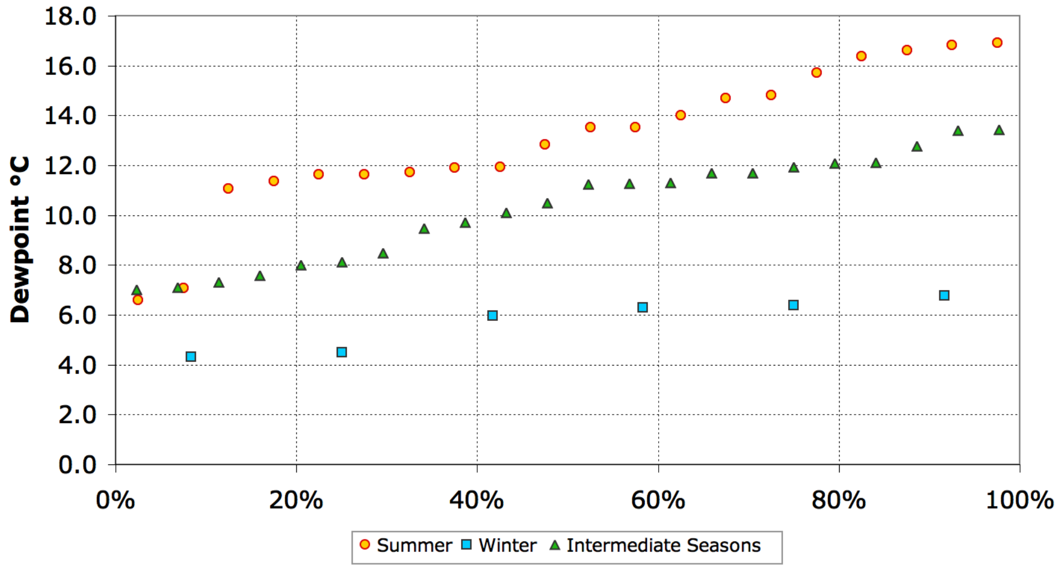

Figure 41: Retail measured space dewpoints

Retail spaces have lower winter dewpoints than the other two building types, possibly because they have more ventilation in winter, with the drier outdoor air then.

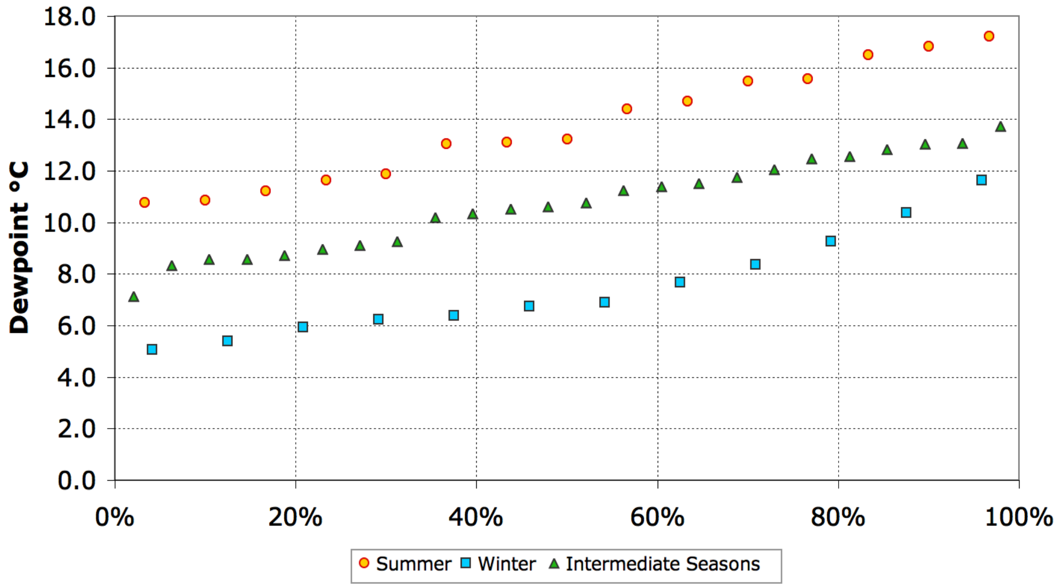

Figure 42: Other measured space dewpoints

Figure 43 shows the measured rise in dewpoint between indoor air and outdoor for Offices (for each weekday between 10 am and 4 pm, for sites where good daily dewpoint data was available).

As can be seen, the dewpoint rises are highest in winter, and lowest in summer. For about 20% of Offices in winter and intermediate seasons, and 80% of Offices in summer, dewpoint rises are measured as negative, indicating dehumidification, presumably by air-conditioning equipment.

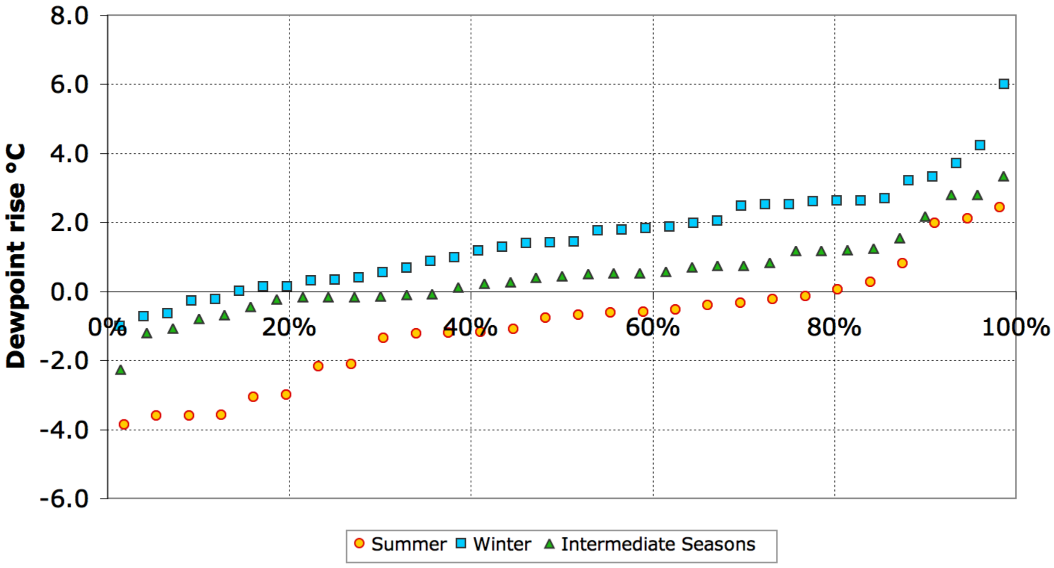

Figure 43: Office measured space dewpoint rises

About 80% of the Offices show dewpoint rises in winter, compared to outdoors, as the ventilation rates are usually only moderate in winter, so the generated humidity is not diluted with outdoor air. In summer, about 80% of the Offices show that the dewpoint is reduced compared to outside. In addition to air-conditioning, this may also be due to these Office spaces being flushed with outdoor air before 10 am, when the outdoor dewpoint is lower.

Figure 44 shows the measured dewpoint rises for Retail spaces.

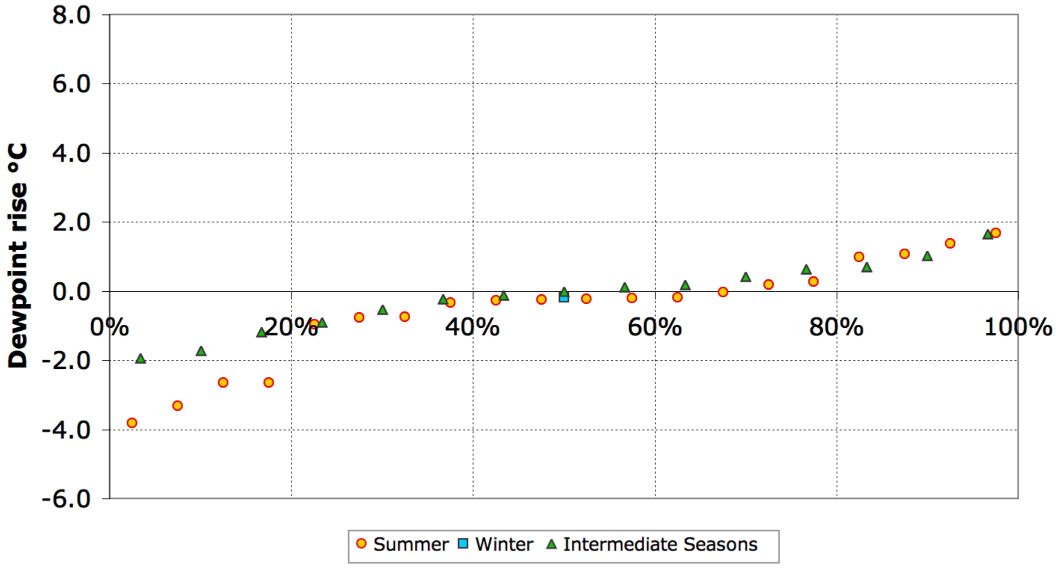

Figure 44: Retail measured space dewpoint rises

Unfortunately, there is only one measured winter dewpoint rises in a Retail space. Summer and Intermediate season dewpoint rises are very similar to Offices.

Figure 45 shows the measured dewpoint rises for Other spaces.

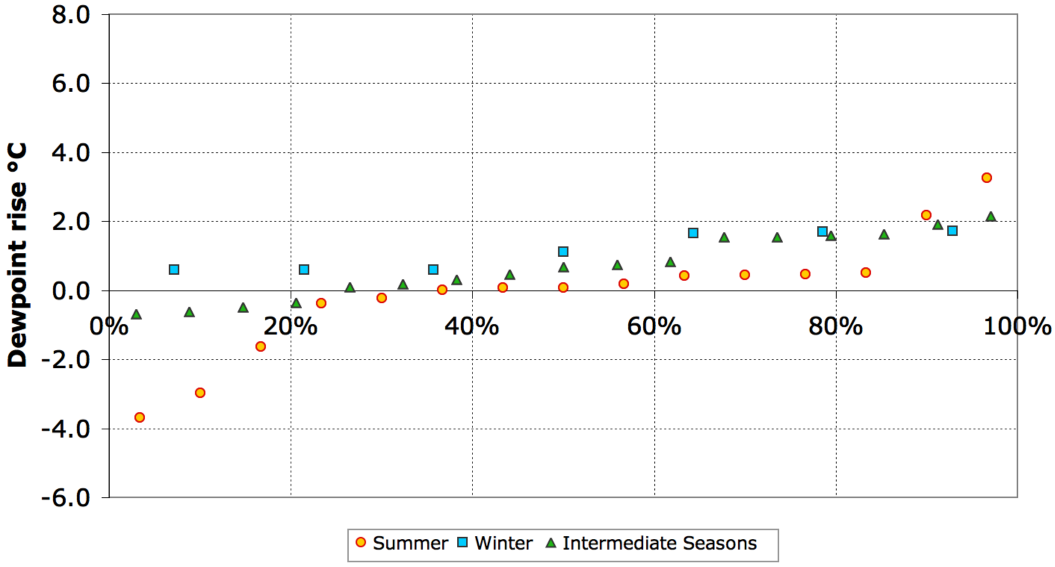

Figure 45: Other measured space dewpoint rises

The "Other" spaces have lower winter dewpoint rises than Offices. In intermediate seasons, they are similar to Offices, and in summer, all the space types are similar.

To show the amount of variation, for the Intermediate seasons, the entire distribution of dewpoints is plotted in Figure 46. The blue diamonds represent the mean value recorded on weekdays, 10 am – 4 pm. The small red and blue bars show the mean plus or minus the average standard deviation, and the small crosses the average of the minimum and maximum dewpoints recorded each weekday during this time span.

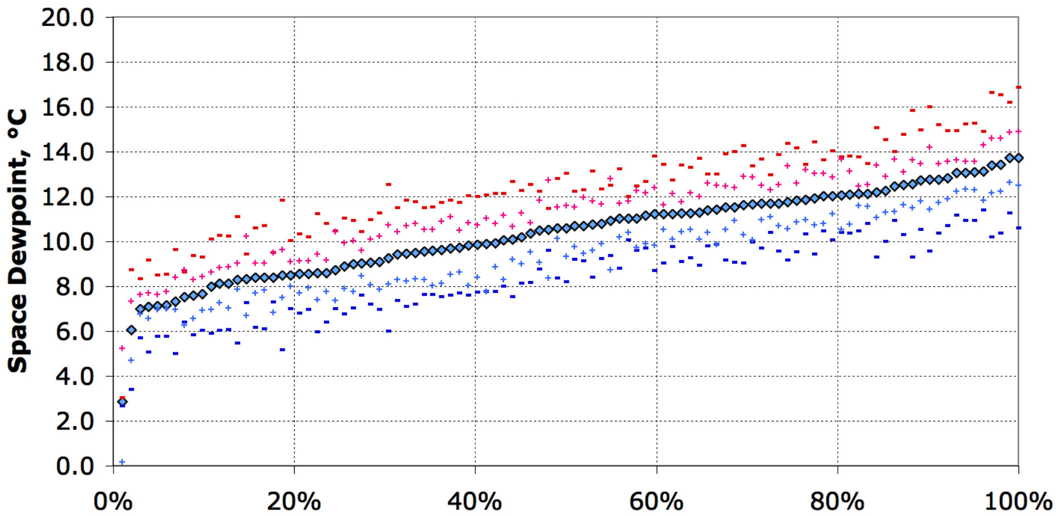

Figure 46: Intermediate season space dewpoints

As can be seen, the variation in dewpoint is typically about ± 2°C.

Finally, the relative humidities of the spaces are shown, in Figure 47. Again, the blue diamonds represent the mean value recorded on weekdays, 10 am – 4 pm. The small red and blue bars show the mean plus or minus the average standard deviation, and the small crosses the average of the minimum and maximum relative humidities recorded each weekday during this time span.

The importance of relative humidity is that electronic equipment prefers operating conditions near 50% (too high, and there may be condensation; too low and there may be static electricity discharges). There are also health effects of extreme relative humidities.

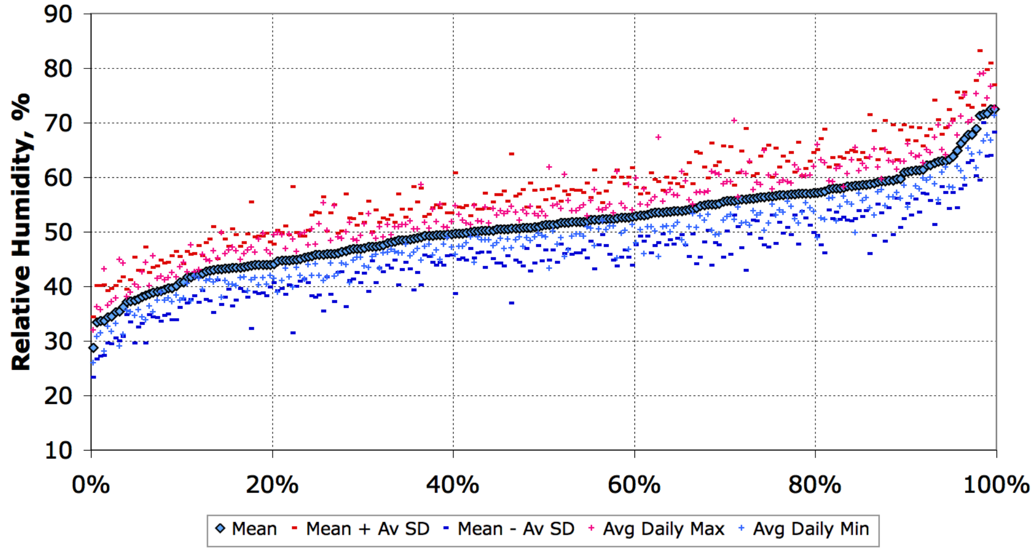

Figure 47: All relative humidities

As shown in Figure 47, about 80% of the sample had a measured mean relative humidity between 40% and 60%, in the optimal range. The variation from the mean was typically ± 5-10%.

Figure 48 shows the seasonal distribution of relative humidities.

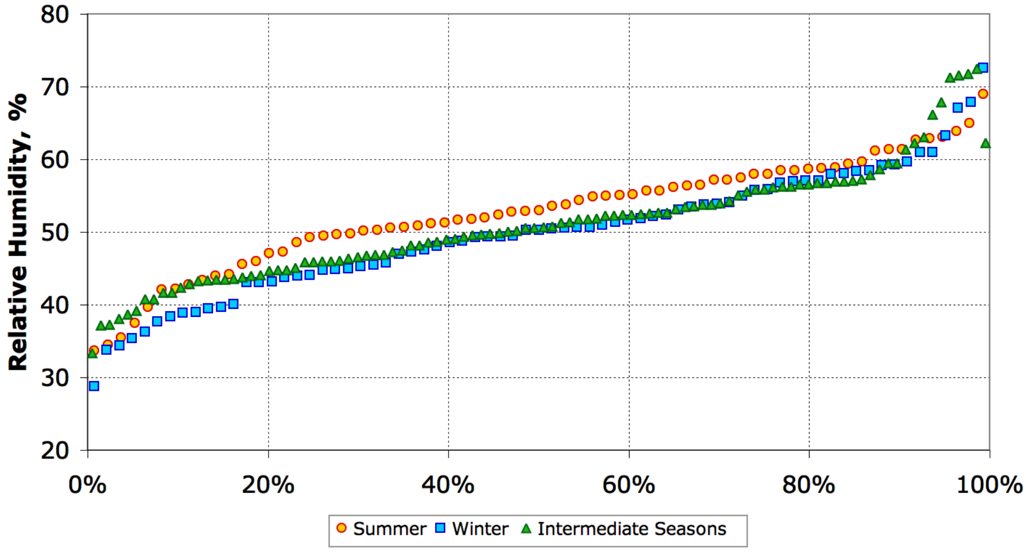

Figure 48: Seasonal relative humidities

As can be seen, there was very little difference between seasons, with summer humidities typically about 3% higher than other seasons. In winter, the lowest 15% of humidities were below about 40%. About 10% of space humidities were over 60%, in each of the seasons.

Figure 49 shows the distribution of relative humidities by building type.

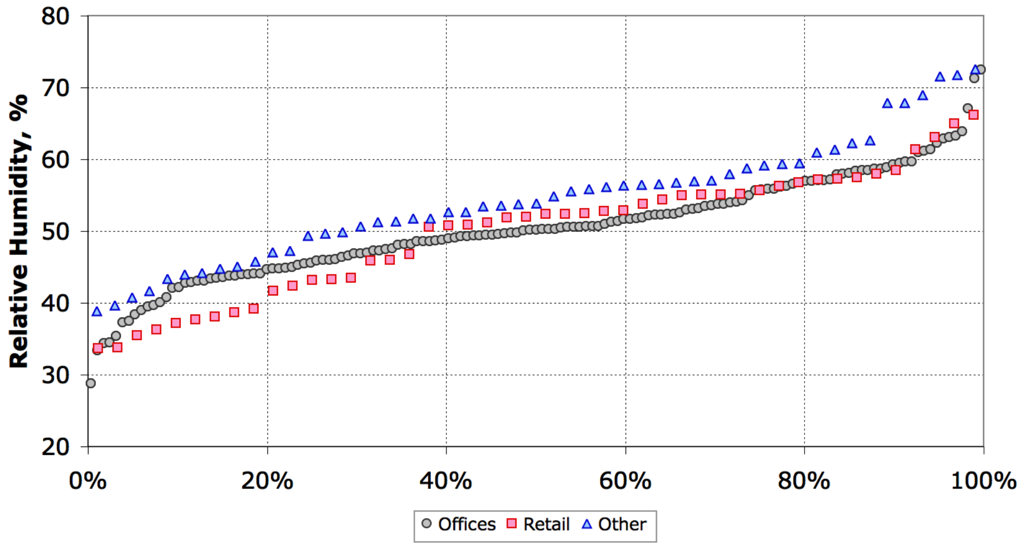

Figure 49: Relative humdities by building type

As can be seen, there is very little difference between building types. Retail spaces have some humidities that are lower than Offices and Other spaces, probably caused by low winter humidities due to excess ventilation, and spaces classified as "Other" have slightly higher humidities.

The higher relative humdities in the "Other" spaces could be caused by their generally lower temperatures than the other two types of spaces.

6. NEXT STEPS

This is an interim report giving early results on buildings less than 9,000 m^2.

Similar analysis will be carried out on buildings over 9,000 m^2 as what has been done in this report. Typically these larger buildings will have a centrally controlled heating, ventilation, air-conditioning (HVAC) system, so the results from this analysis could differ to what is presented for the smaller buildings in this report.

Case study work will also be done looking at the relationships between different building characteristics and the conditions achieved within these buildings.

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