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M J Cunningham
M R Bassett
D McQuade
M Beckett

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A Field Study of the Moisture Performance of Roofs of Occupied Newly Constructed Timber Framed Houses

M. J. CUNNINGHAM*
M. R. BASSETT*
D. McQUADE*
M. BECKETT*

The moisture performance of the timber framing of the roofs of seven newly constructed houses has been studied over one year of occupation in three different New Zealand climate zones, the principle aim being to acquire data to check the performance of SMAHT, a numerical model of structural moisture behaviour. Good data was obtained for this purpose. Higher than expected air-change rates were measured into the roof cavities. Consequently detailing such as vapour barriers and deliberate ventilation became irrelevant, no excessive moisture contents were observed, and no long drying transient was observed. For these houses, winter moisture contents were higher for higher external relative humidities and higher winter mean external temperatures.

INTRODUCTION

EXISTING engineering design tools [1, 2] for predicting the moisture performance of structures have a number of shortcomings; mathematical models are being developed [3–12] to allow the construction of design tools to overcome these shortcomings, in particular, to allow properly for moisture storage, and transient moisture behaviour, and to properly account for all major moisture transfer mechanisms, and in particular, air change into the structure.

However sophisticated these models may be, they are of little ultimate value if they are not validated through laboratory and field comparisons; at this stage not many validation or comparison studies have been performed [4, 5, 8, 12, 13].

To meet that shortcoming, Cunningham has undertaken laboratory comparison studies of a model, SMAHT (Simulation of Moisture And Heat Transfer) [11], with encouraging results [12, 13]. However, laboratory studies alone are not enough to engender confidence in the validity of a model because laboratory test specimens are small and can only approximate as-built structures, and because some driving forces are difficult to simulate in the laboratory (e.g. night sky radiation and cross ventilation of cavities) and occupant behaviour can only be guessed at. Consequently, a field study was initiated to generate data to allow SMAHT to be tested out under real conditions. This paper reports on the design, implementation and results of this field study. A later paper [14] reports on the comparison of the results obtained to those predicted by the numerical model SMAHT.

* BRANZ, Moonshine Road, Judgeford, Private Bag 50908, Porirua, New Zealand.

EXPERIMENTAL DESIGN

This field study was designed with two points in mind.

1. To study the transient drying and seasonal cyclic moisture behaviour of cathedral roofs (known in the New Zealand building trade as *skillion roofs*) in newly built New Zealand houses over a representative range of New Zealand climates.
2. To allow the checking of the validity and accuracy of a numerical model of the moisture performance of building structures.

The above criteria were arrived at as a result of a number of fundamental decisions made early in the programme, which had important technical and financial consequences. These decisions were:

Timber framed houses would be studied, and timber moisture content would be taken as the chief parameter of interest. The bulk of New Zealand housing is timber framed. Although timber is vulnerable to very high moisture contents, it is more likely that other problems such as wet insulation or linings will be of real concern; nevertheless timber, being highly hygroscopic, responds readily to the overall moisture state of the structure around it, so timber moisture content provides an important diagnostic measurement for the moisture performance of the structure. Timber structures are 2 or 3 dimensional, and not 1 dimensional layers as is assumed in simple design tools or some mathematical models [3, 8, 10], which places more demanding requirements on modelling of these structures.

New built houses would be studied. New houses were chosen to allow the study of the moisture drying transient which it was thought, before the test, could be of several weeks or months duration. If excessive construction moisture is enclosed in a structure the drying transient is of critical importance. This choice would also allow the instrumentation to be placed within the timber framing while the building was still under construction.

Occupied houses would be studied. Some of the validation studies carried out in the past have been on unoccupied buildings [5, 8]. However, it can be argued that no validation can be regarded as fully complete unless it has been carried out on an occupied house, since it is well known that occupant life-style has a very important bearing on the moisture performance of the building, both directly through the way and amount of moisture that occupants might generate, and indirectly in how the occupants affect the driving forces of ventilation, air changes in the structure and vapour diffusion.

Measurements would be taken over a period of one year from occupancy. At least one year of observation is necessary to allow both the transient drying of the structure to be followed, and the seasonal effects to be observed. Observation over a second year would have been desirable but was not economically feasible.

Cathedral roofs would be the principal part of the structure examined. It was decided to concentrate on timber moisture contents of cathedral (or skillion) roofs for a number of reasons:

(a) Before the experiment began, it was believed that skillion roofs were more prone to moisture problems. This belief was based on the idea that these roofs have very small cavities and consequently are not well ventilated; and on reports of specific problems in some New Zealand skillion roofs.
(b) There have been very few reported moisture problems in walls of New Zealand houses.
(c) Vapour barriers sometimes appear in roofs, and in particular skillion roofs in New Zealand building construction practise. On the other hand, the only form in which vapour barriers appear in the walls of New Zealand houses is as a foil coating to a proprietary gypsum plaster board; indeed, deliberate use of wall vapour barriers in the form say of a polyethylene membrane is very seldom practised in New Zealand. Since the vapour barrier is traditionally regarded internationally as an important component in the moisture management of a structure, it was felt important to study structures that could contain this element.

A representative sample of New Zealand climates would be studied. Climate is clearly a factor in the moisture behaviour of a structure so it was felt necessary to ensure that the major climate regions in New Zealand were included in the study. This decision had important financial implications as it considerably increased the cost of the study over one that might have involved houses in one region only. On the other hand it also considerably increased the value and credibility of the results and the consequent modelling studies. This wide geographic spread of the houses is one of the unique features of this study.

As well as the factors considered above, there were two technical considerations which had major consequences on the experimental design.

Redundancy

A study of this size, complexity, and remoteness from the central working site must take a realistic approach to the probability of potentially serious data loss problems such as home owners pulling out of the study before completion, serious instrument drift or failure, data loss through power outages or datalogger failure, etc. To meet these issues, redundancy at all levels had to be built into the study and protocols developed for instrument maintenance in the field.

Instrumentation

Since the data was to be used to check the performance of a mathematical model, all quantities necessary to allow that validation had to be measured. This consideration dictated the choice of type and location of instrumentation. In particular, this implied that air change rates into the roof cavity had to be measured. Such a measurement had not been attempted before and posed unique problems.

These factors taken together resulted in the design of a study that is unique in many respects. To the authors' knowledge, this is the only study for model comparison purposes on the continuous moisture behaviour of the structure of occupied houses across a range of climates. Yet such studies must be carried out if the present moisture models under development are to be shown to be able to reproduce field conditions. It is also the only study to attempt to measure the important factor of cavity air change rates.

Perhaps the most extensive field study for model validation purposes is the Canada Mortgage and Housing Corporation study set up to validate the model WALLDRY [8]. There hourly data logging of moisture contents was taken over 12 to 18 months on 3 buildings; that data was collected on unoccupied test huts with specially designed walls, not "real" occupied houses. Furthermore that study was carried out essentially only in one climate zone. Cleary and Sonderegger [5] report a shorter 4 month study done on one unoccupied house which was used to support a simple mathematical model.

EXPERIMENTAL DETAILS

Eight houses under construction were selected. To give a good sample of New Zealand climatic conditions at reasonable cost the following climate zones and locations were selected: humid and cool—Invercargill and Dunedin; dry and cool—Queenstown; humid and mild—Auckland; dry and mild, no choice, see location map Fig. 1. No house was chosen in a mild dry climate as it was believed that little useful or interesting information would be gained about timber moisture contents under these conditions.

Redundancy requirements also had to be met for the overall reliability of the study as mentioned above. Redundancy was built in at all levels. At the highest level, redundancy was built in by choosing at least two houses in each climate area. To be precise, 3 houses were chosen in the humid and cool zone, one in Invercargill and two

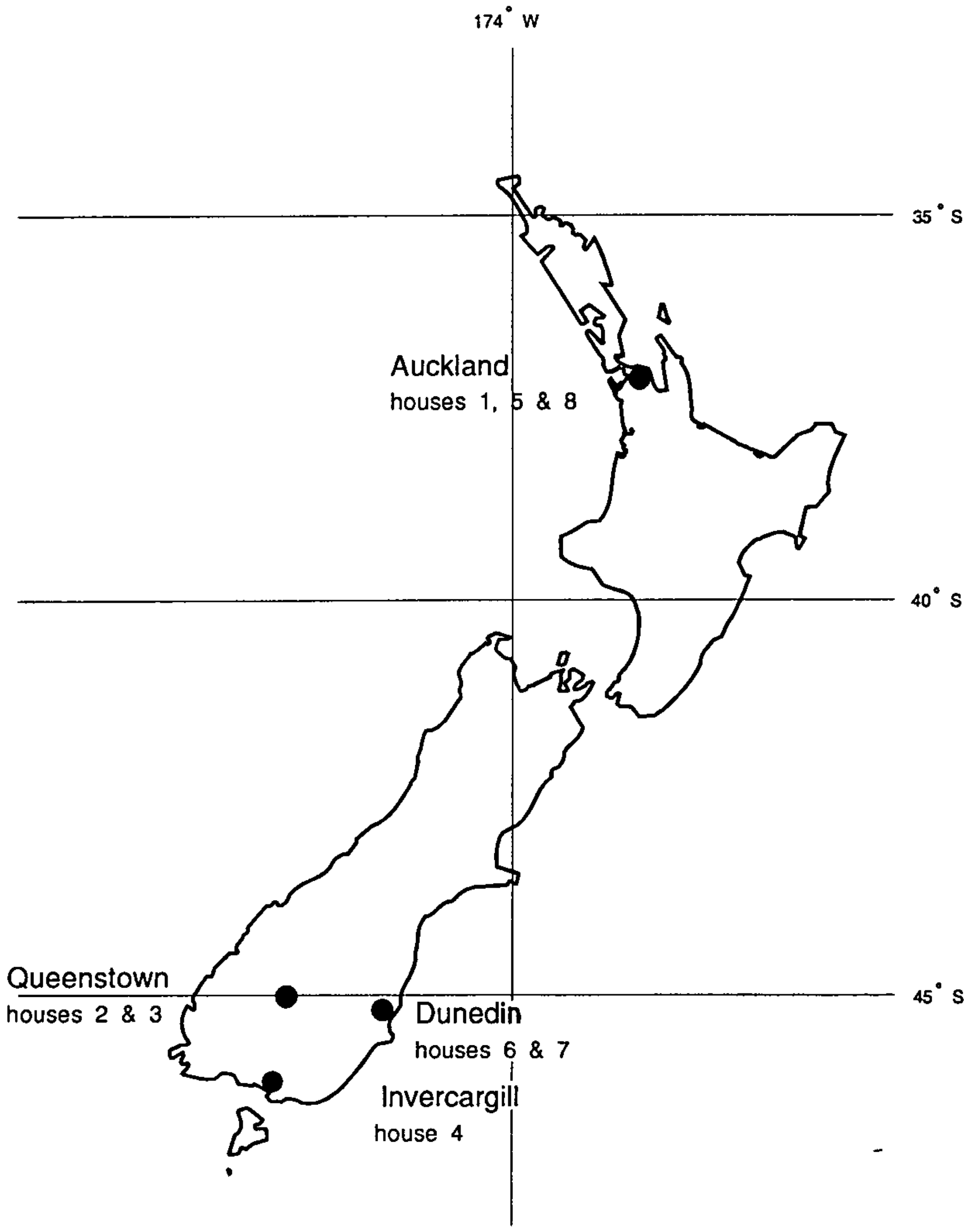


Fig. 1. Location map.

in Dunedin, two houses were chosen in the dry and cool region at Queenstown and three houses were chosen in the humid and mild region at Auckland.

Redundancy was designed in at lower levels in a number of ways, e.g. by providing the dataloggers used with limited battery back-up capability (one or two hours), and designing them to self-restart upon power-up after a power outage; several different rafters in the same general roof area were instrumented to allow for redundant collection of data; critical temperatures were measured with both thermocouples and thermistors; sensors meant to back each other up were not brought back to the same board within the datalogger where possible, etc.

Details of the houses studied are contained in Table 1, while Fig. 2 shows cross sections of the skillion roofs of each house. House 1 did not have its ceiling lining installed until the end of the study, so its results are of little value and will not be discussed here. Two houses were instrumented in the (southern) winter of 1989, 3 in the summer of 1989–90 (including the house which subsequently did not have its ceiling lined), and 3 in the winter of 1990. As can be seen the houses ranged from small and inexpensive (house 8) to large and very expensive (house 5). In only one case (house 3) was a vapour barrier used.

INSTRUMENTATION

Instrumentation consisted of a datalogged system of thermocouples, thermistors, relative humidity sensors, moisture probes, and condensation sensors.

The thermocouples were T-type and used in a differential mode. One junction was installed at the point of interest and the other junction was used as a temperature reference. All thermocouples had their reference junction inserted in the middle of an insulated 90 mm diameter, 75 mm deep cylindrical block of steel. The thermal inertia provided by this system meant that the reference junction temperature changed only slowly. The actual temperature within the cylinder was measured by two thermistors. The output of the thermocouples was multiplexed into a $\times 1000$ amplifier in the datalogger.

The thermistors were each provided with their own driving and linearizing circuitry powered from the datalogger, adjusted to give 10 mV/°C.

The relative humidity sensors were of a capacitive type and were also provided with their own driving and linearizing circuitry powered from the datalogger, adjusted in this case to give 10 mV/% RH. These were calibrated before going into the field with a two-pressure relative humidity generator.

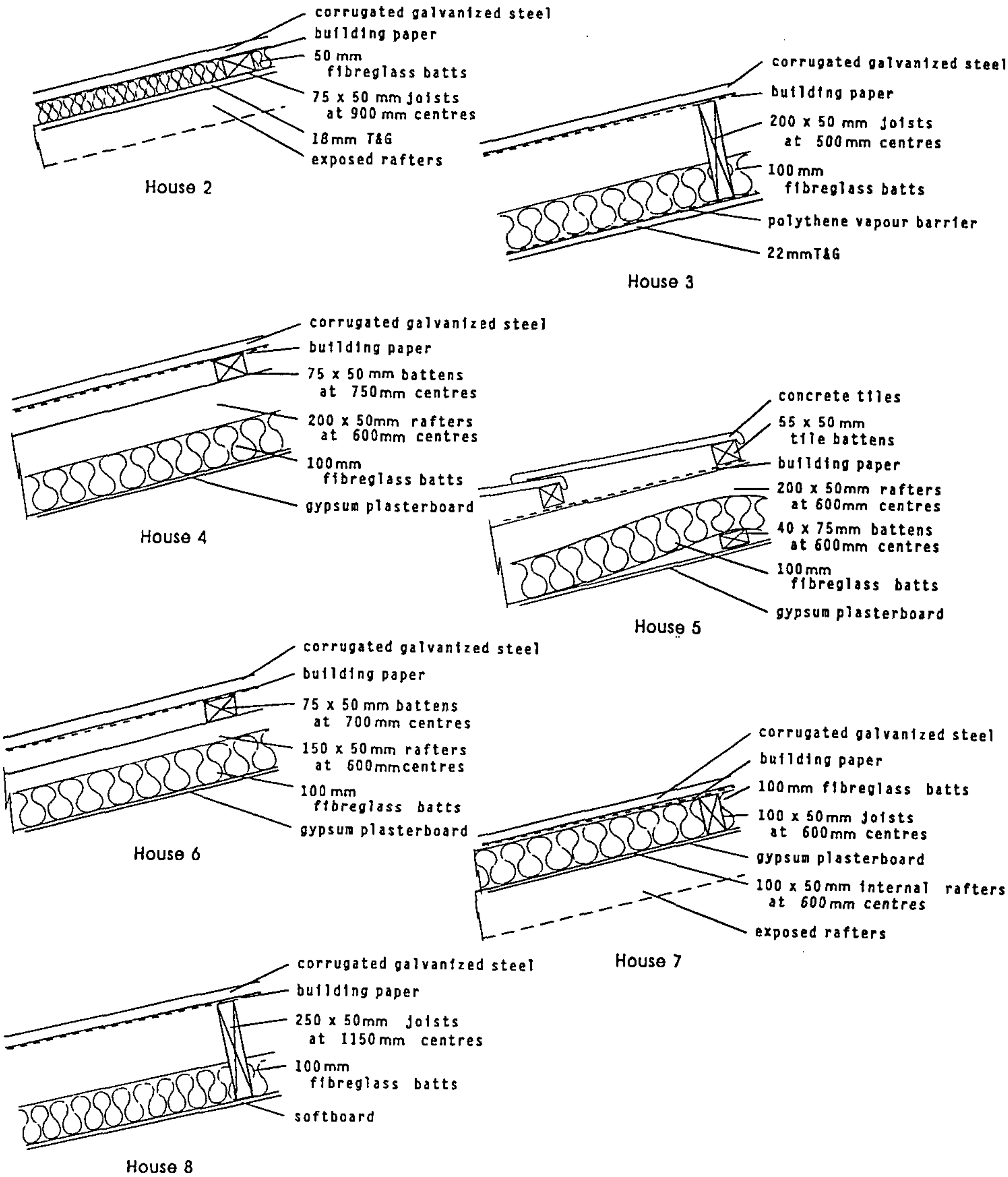


Fig. 2. Roofing details of the houses studied.

The moisture probes were resistive in action. They consisted of a pair of gold-plated brass 1 cm square electrodes embedded 5 mm apart in the timber to be measured. Their calibration and properties have been described in detail elsewhere [15]. In this study they were multiplexed into a log-amplifier within the datalogger which gave -10 mV to 1 V output according to the size of the resistance.

The condensation sensors were also resistive in action. They were used to detect the presence of moisture absorbed within building paper by measuring the fall in resistivity of the building paper as it becomes wetter. As described elsewhere [13], these probes consisted of two 2 mm diameter screws, acting as electrodes, bolted through the building paper under investigation. These too were multiplexed into a log-amplifier within the datalogger.

The dataloggers were designed and constructed at BRANZ. They consisted of 54 channels multiplexed either directly to a 12-bit A–D converter, or via a $\times 1000$ or log-amplifier under program choice. Data could be collected at a user-specified rate and stored on a cassette tape. For this task, data was collected once per hour for all channels except the moisture probe channels where data was collected once every four hours. The loggers

Table 1. Details of houses studied

House number	2	3	4	5	6	7	8
Location	Queenstown	Queenstown	Invercargill	Auckland	Dunedin	Dunedin	Auckland
Approx. floor area	120 m^2	170 m^2	380 m^2	260 m^2	310 m^2	230 m^2	65 m^2
Price bracket	Low/Middle	Middle	High	Very high	Middle	High	Low
Wall cladding	Fibre-reinforced cement board	Corrugated galvanized steel	Brick veneer	Fibre-reinforced cement board	Plastered polystyrene insulation	Brick veneer	Fibre-reinforced cement board
Ceiling lining	Tongue and groove timber	Tongue and groove timber	Gypsum plaster board	Gypsum plaster board	Gypsum plaster board	Gypsum plaster board	Wood softboard
Roof cladding	Corrugated galvanized steel	Corrugated galvanized steel	Long-run galvanized steel	Concrete tiles	Corrugated galvanized steel	Corrugated galvanized steel	Corrugated galvanized steel
Vapour barrier	No	Yes	No	No	No	No	No
No. of adults	1–4	1	2	2	2	2	2
No. of children	0	0–1	2	1	2	2	1
Instrumentation date	24/7/89	7/9/89	5/11/89	7/12/89	20/6/90	30/5/90	28/6/90
Logger started	19/12/89	17/1/90	23/4/90	8/6/90	11/3/91	20/8/90	6/11/90
Logger stopped	17/1/91	17/1/91	14/5/91	18/7/91	16/12/91	14/8/91	29/10/91

have a 1 to 2 hour battery back-up capability, and a power-fail restart system.

All measurements were taken to four significant figures, giving a resolution after conversion to physical units of 0.1°C for temperature measurements, 0.1% RH for relative humidity measurements and about 0.1% for moisture content. Overall accuracy depended on system considerations, and was generally constrained by factors other than the resolution of the individual sensors.

The moisture probes have a very high resistance when the wood is dry (several Gohm at 10% moisture content), and so consequently are vulnerable to high impedance short circuit paths at all points from the datalogger to the transducer, and are also susceptible to mains-hum inductive pickup at these high impedances. This effectively limited the driest timber moisture content they could read to about 8% moisture content, and at this level they were reliable to perhaps $\pm 2\%$ moisture content. At higher moisture contents and therefore lower impedances these problems disappear so the moisture probes are probably somewhat more accurate, perhaps $\pm 1\frac{1}{2}\%$. Cunningham [15] has shown that they become less accurate at very high moisture contents ($>25\%$) but values at this level were not read.

From laboratory experience it was known that the relative humidity probes were subject to drift, so while they were known by calibration to be accurate to $\pm 2\%$ RH upon installation, this figure could not be guaranteed to better than $\pm 10\%$ after one year's use since recalibration during use was not possible.

Observed drift with the thermistors is not large and it is estimated that their accuracy in use is about ± 0.5°C after allowing for sensor accuracy and drift, A–D accuracy, power supply regulation, line losses, cross talk etc. The thermocouples use thermistors to derive their absolute temperature, so can be no more accurate than this ± 0.5°C figure.

Condensation measurements are qualitative only.

Each house was instrumented once the roof had been clad, but before the ceiling had been lined. Instrumentation consisted of 20 thermocouples, 8 thermistors, 8 relative humidity sensors, 14 moisture probes, and 2 condensation probes. One datalogger channel was shorted and one channel was open-circuited. Each moisture probe, relative humidity sensor and condensation probe had one of the thermocouples or thermistors placed near it to allow the temperature at that sensor to be measured. Within the skillion roof, three or four rafters were instrumented at different levels. At each point within the rafter at least one moisture probe and one thermocouple were placed in the middle of the rafter, but at selected points moisture probes and thermocouples were placed at the top, bottom and side of the rafter, and thermistors and relative humidity probes placed adjacent to the rafter. Condensation probes were placed in the building paper above the rafter. Other locations in the roof space, not necessarily the skillion roof, were also instrumented. To measure indoor conditions, a relative humidity sensor and a thermistor were placed inside the living space at each of two separate locations, arranged to protrude into the room through the wall lining. Outdoor conditions were measured by placing a relative humidity sensor and thermistor on the south (shaded) side of the house under the eaves. The instrumentation wiring was collected together in a loom at a common point, and later when the house was completed and occupied and the power was on, the datalogger was installed, the loom connected to it, and data acquisition commenced.

Some houses had spot values taken of their timber moisture contents about once per month between the installation of the instrumentation while the house was still under construction and unoccupied, and subsequent power-on around the time of occupancy.

Once the datalogger was running, each house was visited once a month and the cassette tape of collected data removed and replaced by an empty tape. At that stage a maintenance protocol was observed in which the performance of the datalogger was checked and each sensor was read manually. What maintenance that was necessary and could be undertaken on site was done. The carrying of spare circuit boards allowed quite extensive field maintenance to be undertaken on the datalogger, but less could be done for defective sensors as most of these were inaccessible.

The full data tapes were loaded into central computing facilities and data reduction undertaken, which allowed the raw data to be converted to physical quantities such as moisture content percent, temperature in Celsius etc.

After about six months, average ventilation rates in the living space and two roof cavities of 6 houses were measured using a passive tracer approach developed by Deitz [16]. The method involves placing a series of tracer gas emitters that release tracer at a known rate in each zone of interest, together with absorbers that are later analysed to give the mean tracer concentration in the zone and hence the air change rate. By releasing different perfluorocarbon tracers in adjacent zones, air transfer rates between zones can also be inferred. In this study, different tracers were released into the living space, and two roof cavities (typically two skillion or one skillion and a pitched roof cavities). The emitter tubes were built into the roof cavities with provision for extracting them at project completion along small bore plastic tubes with a draw string. Sampler tubes were passed along similar tubes to start the sampling period and withdrawn a month later for analysis.

After one year the datalogger and all accessible instrumentation was removed.

RESULTS

Figure 3 shows the 24 hour mean of the moisture content of all probes placed in the centre of the timbers in the skillion roofs of the houses; Figure 4 shows the 24 hour mean of the wettest, driest and mean of all moisture probes placed in the house roof, irrespective of their location. Figure 5 shows the 24 hour mean of the indoor and outdoor humidities of each house (or just one of these if the sensor failed), while Fig. 6 shows the corresponding temperatures. In all these figures, 1 January 1990 is taken as day zero.

Air flow rates were calculated from measurements on houses 2, 3, 4, 5, 7 and 8. This data is contained in Table 2 with the measurement zones numbered 1, 2, 3 and the non tracer infected areas (mostly the outdoor air) numbered 0. The volume values that appear in this table are the volume of the cavity without the presence of insulation. In some cases, it was not possible to give a physical interpretation of the data without some further simplification as follows.

1. In houses 2 and 3, higher concentrations of living space tracer were found in the roof cavities than were measured in the living space itself. These two houses were modelled as two roof zones unconnected to a living space zone.
2. In houses 4 and 7 the tracer concentrations in the two roof zones were indistinguishable and therefore modelled as a single zone. In house 4 the two steeply sloping skillion roof cavities were linked at the ridge by openings that allowed air to pass freely between the two. The instrumented roof cavities in house 7 were separated with building paper which has clearly been ineffective as an air barrier.

The living space ventilation rates in houses 4, 5, 7 and 8 ranged from 0.6 to 1.6 ac/h and are typical of larger and more complicated (and hence less airtight) houses in New Zealand. There is little to compare the roof space data other than a series of measurements in 6 pitched roof cavities by Bassett [17] using another method that took greater care with mixing. The mean ventilation rate of 3.6 ac/h in house 2 is comparable to this data. The skillion roof data is unique and interesting because some high ventilation rates are indicated, take for example the skillion roof of house 4. In this case two steeply sloping cavities (one on the North side and the other on the South) were connected at the ridge. Wind pressures will have applied large pressure differences across this combination and driven air flows in a direction dependent on the wind direction. Outside air entered the other cavities at rates in the range 5 to 250 m^3/h, indicating that skillion roof cavities are better ventilated than was expected before the study began. Some of the inter-zone air flows are also significant, particularly those from the living areas into the roof in houses 5, 7 and 8.

Intermittent condensation was reported by the condensation probes on the building paper in houses 2, 3, 4 and 8. Occasionally this condensation persisted for several days, but usually it occurred at night time and evaporated at day. Independent tests showed that visible condensation occurs when the condensation probes measure somewhere between 1 and 10 Mohm, although even at 1 Mohm the quantity is not high, in the order of 10 to 100 g of condensation per square metre of building paper surface. The total time during which the condensation probes reported a resistance of less than 10 Mohm throughout the period of observation has been accumulated and is reported in days as an entry in Table 3. Values of much less than 1 Mohm were never reported, implying that significant amounts of condensation did not accumulate in any of the houses.

The data from house 2 is worth special comment. This house was initially very poorly heated so the home owner decide to install a closed firebox wood-burning stove. The consequences of this action show clearly in the data. At about day 155 a hole was placed through the ceiling and roof. As the timber members in this house have small dimensions, see Fig. 2, the timber moisture contents in the vicinity rose immediately, and the internal temperature and relative humidity became identical to the outside values. At about day 160 the stove was installed and fired up. Moisture contents in the vicinity rapidly fell again, while the indoor temperature rose, and the indoor relative humidity fell.

In general, the timber moisture contents of all houses follow the relative humidities, sometimes even in close detail, see for example house 4 between days 330 and 400, where the moisture contents can be seen to be following the external relative humidity with a lag of 5 to 10 days.

Quality of the data. Given the size, complexity and field nature of the study, the overall reliability of the datalogging/instrumentation systems proved very satisfactory, partly due to the redundancy built into the study. However the following comments on the quality of data should be noted. House 8 has long periods of missing moisture probe data while other houses show fewer moisture probe data dropouts. Houses 5 and 6 were not successfully instrumented for internal relative humidity

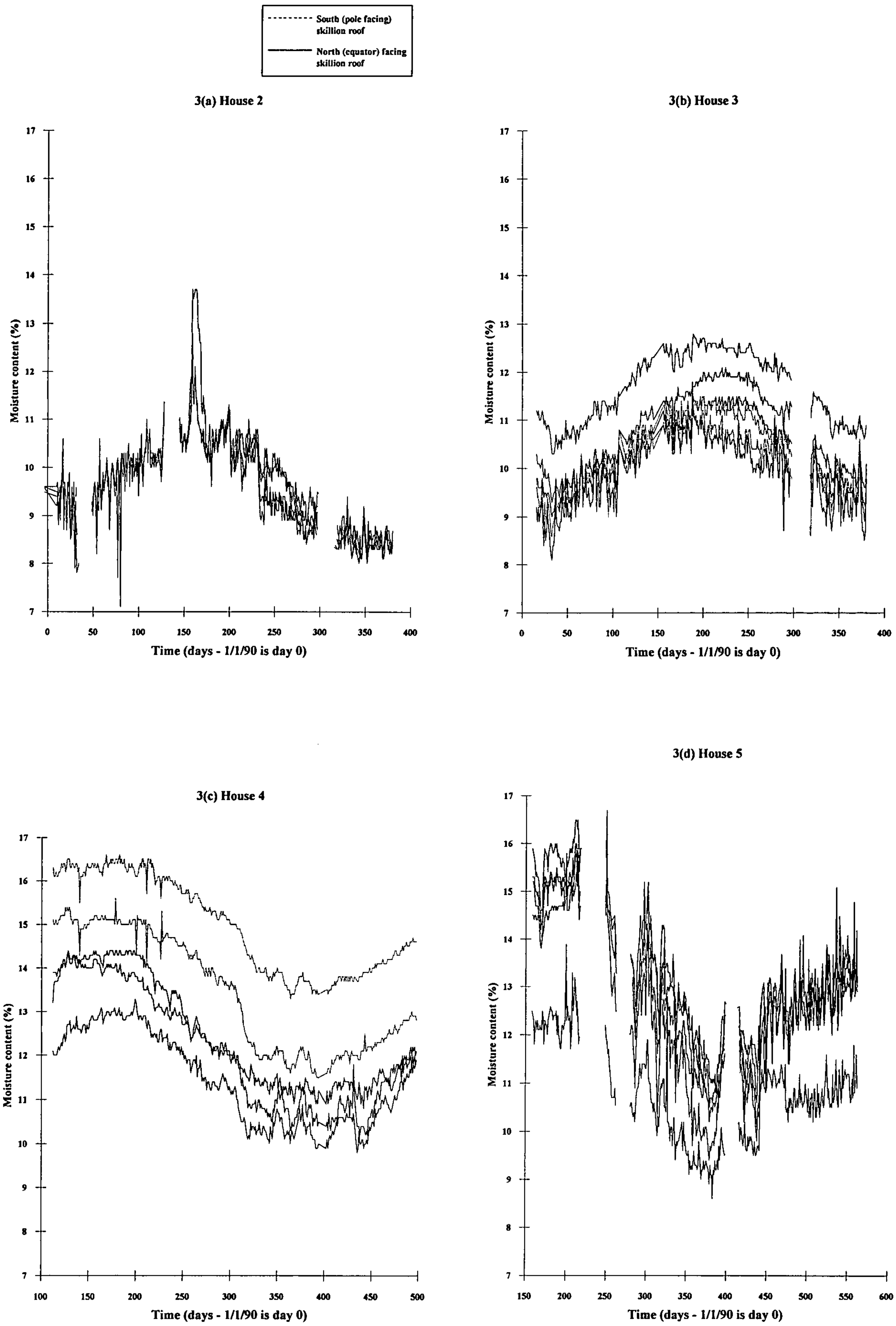

South (pole facing) skillion roof
North (equator) facing skillion roof
3(a) House 2
3(b) House 3
3(c) House 4
3(d) House 5
Moisture content (%)
Time (days - 1/1/90 is day 0)

Fig. 3(a)–(d).

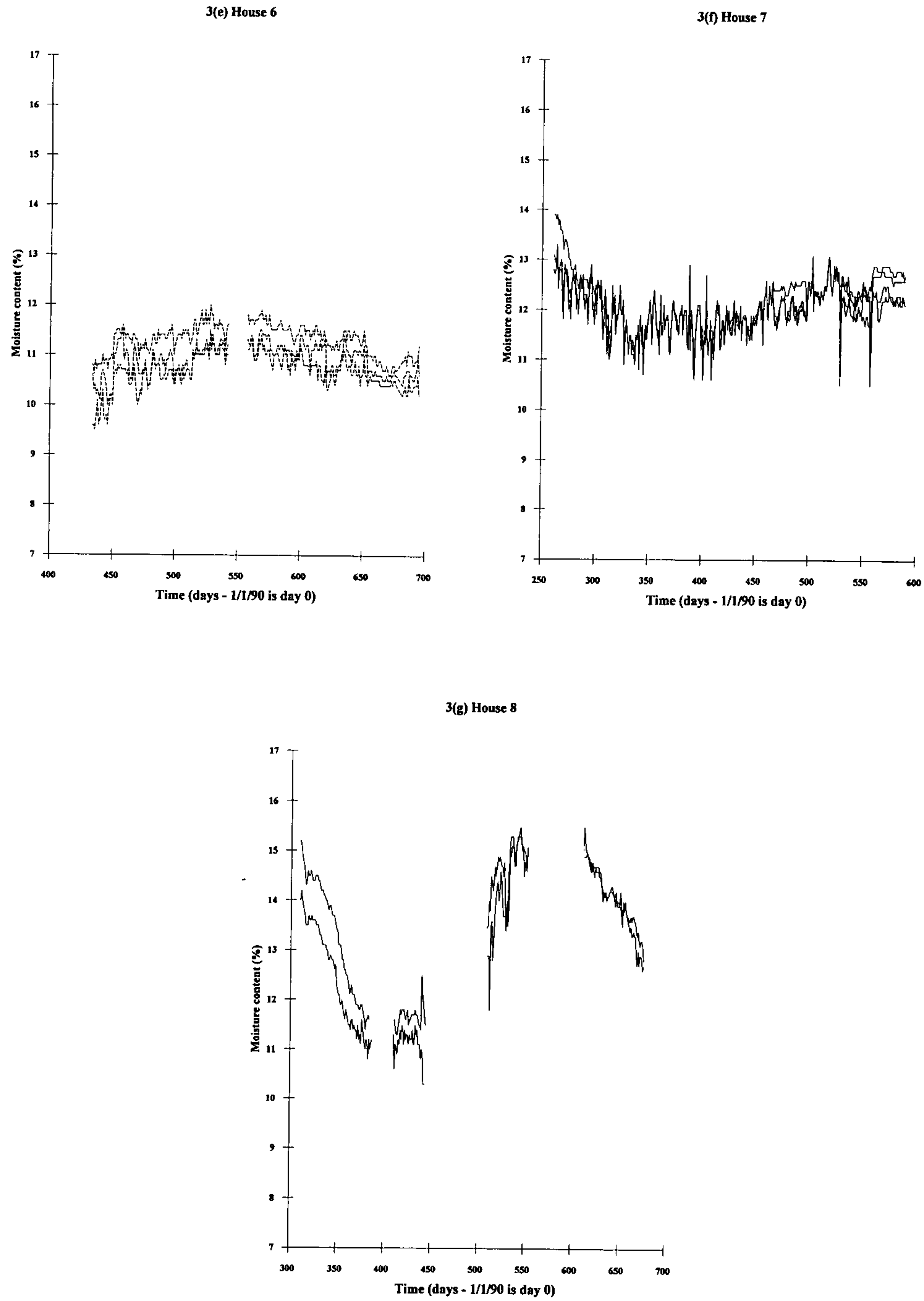


Fig. 3. Twenty-four hour mean of mid-timber moisture contents.

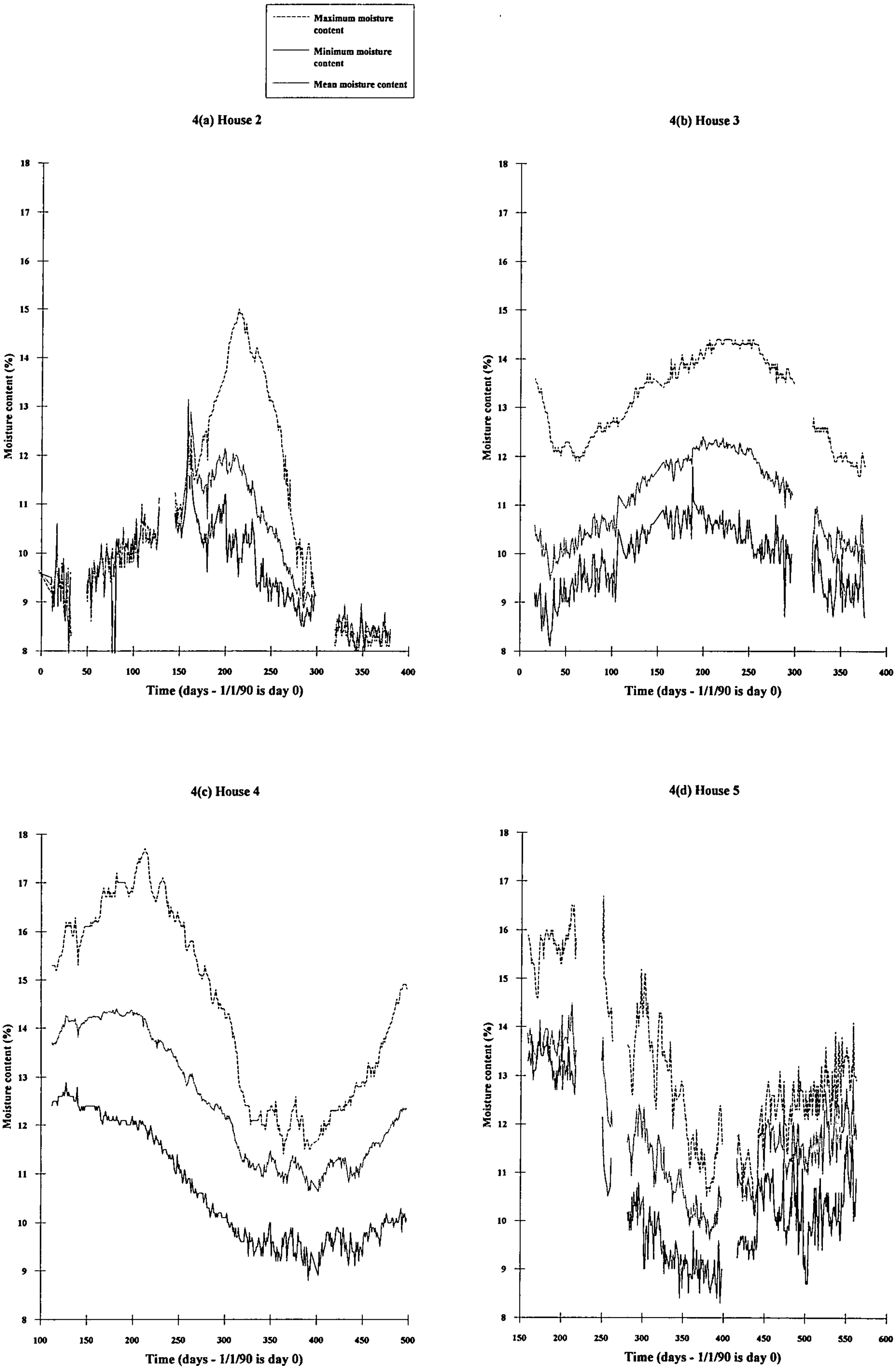

Maximum moisture content
Minimum moisture content
Mean moisture content
4(a) House 2
4(b) House 3
4(c) House 4
4(d) House 5
Moisture content (%)
Time (days - 1/1/90 is day 0)

Fig. 4(a)–(d).

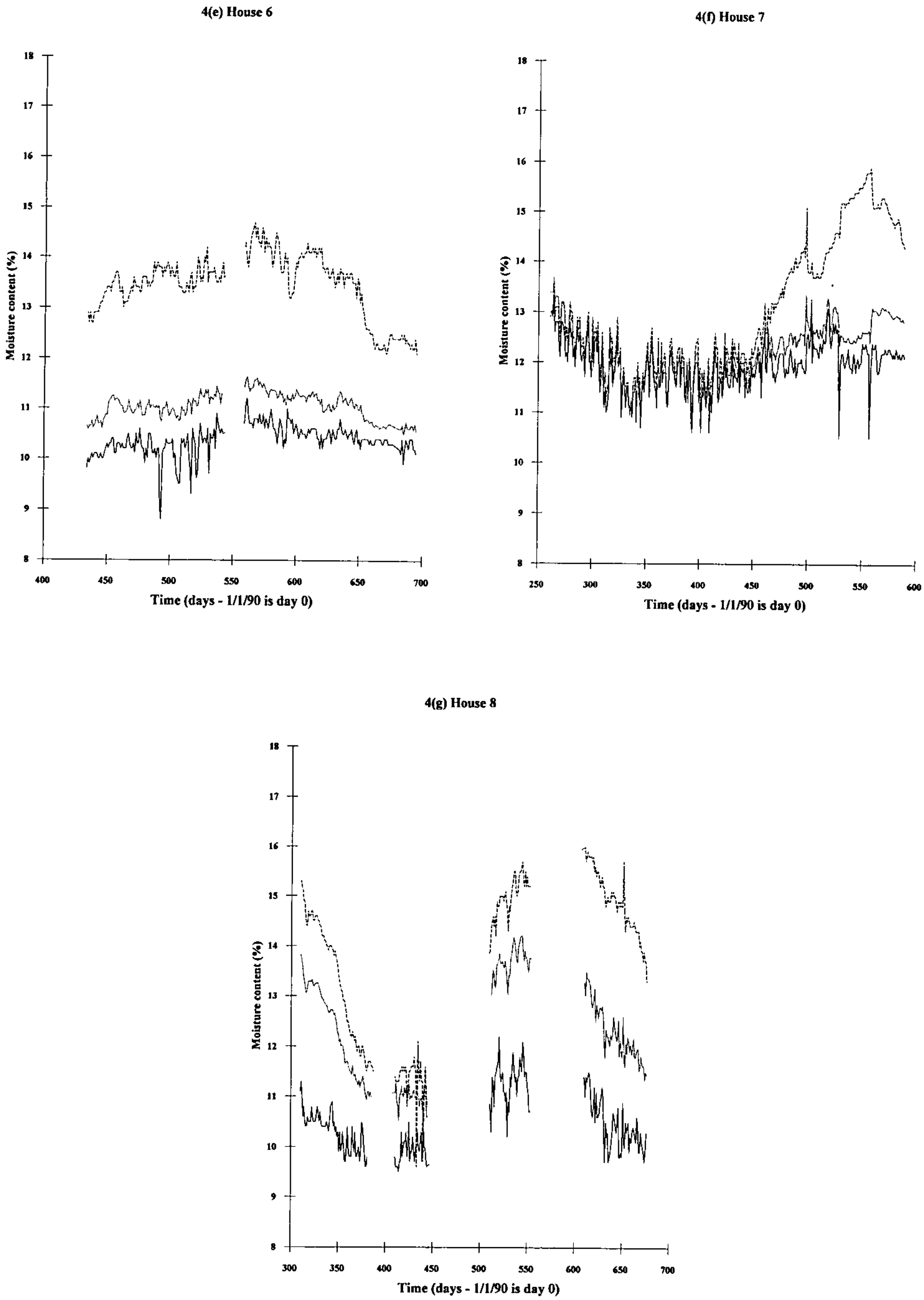


Fig. 4. Twenty-four hour mean of wettest, driest and mean-of-all timber moisture contents, irrespective of probe location.

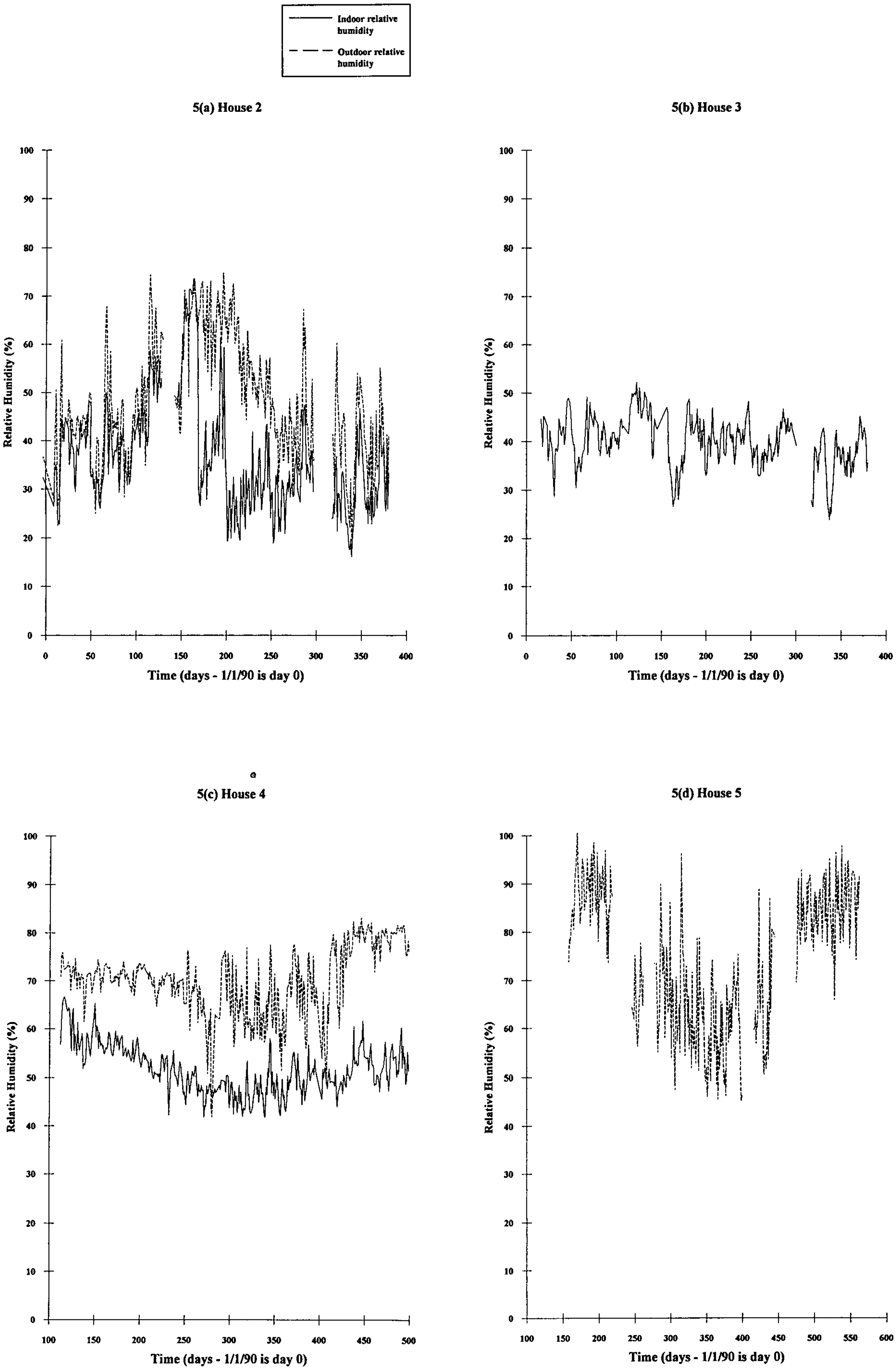

Indoor relative humidity
Outdoor relative humidity
5(a) House 2
5(b) House 3
5(c) House 4
5(d) House 5
Relative Humidity (%)
Time (days - 1/1/90 is day 0)

Fig. 5(a)–(d).

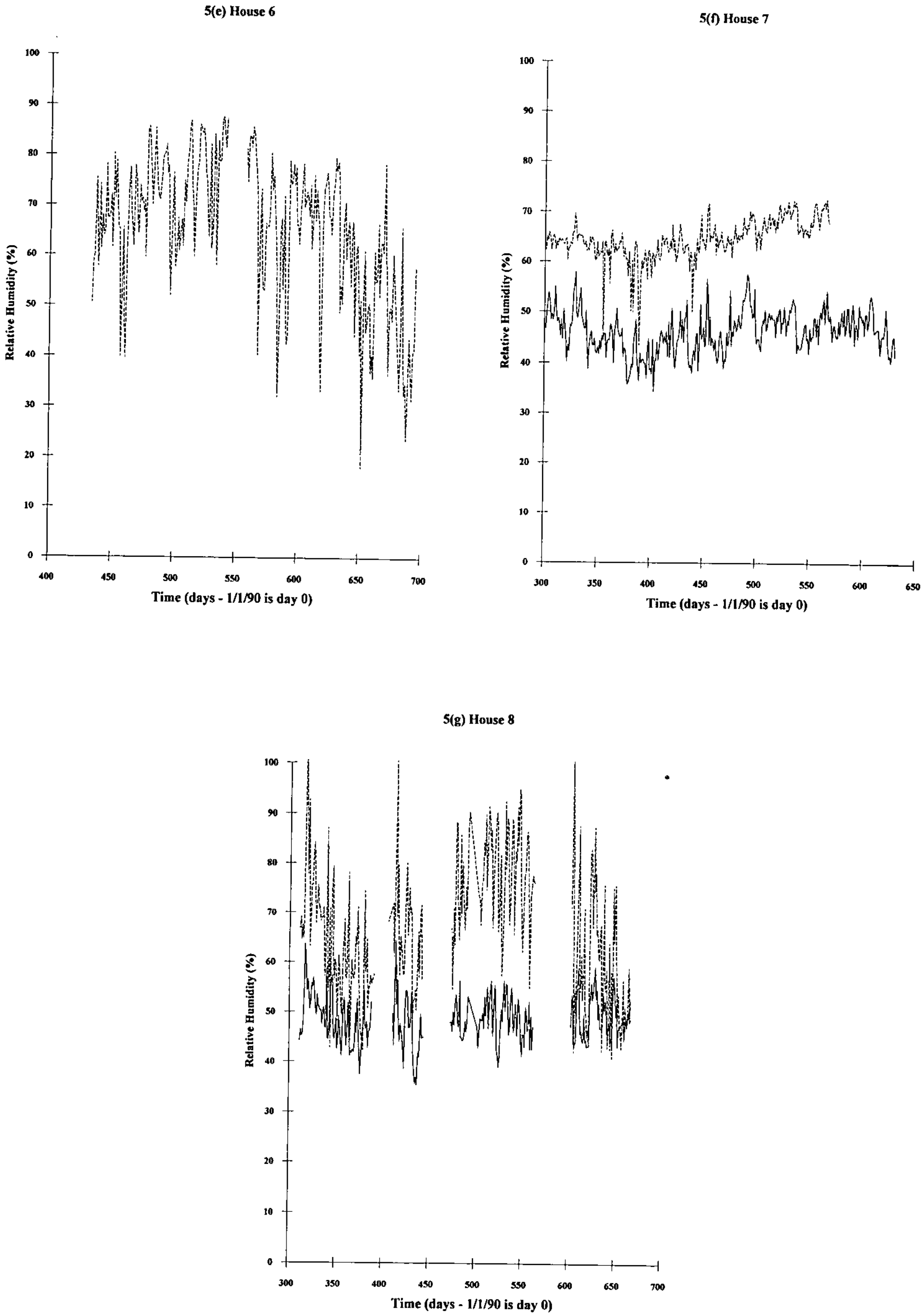


Fig. 5. Twenty-four hour mean of indoor and outdoor humidities.

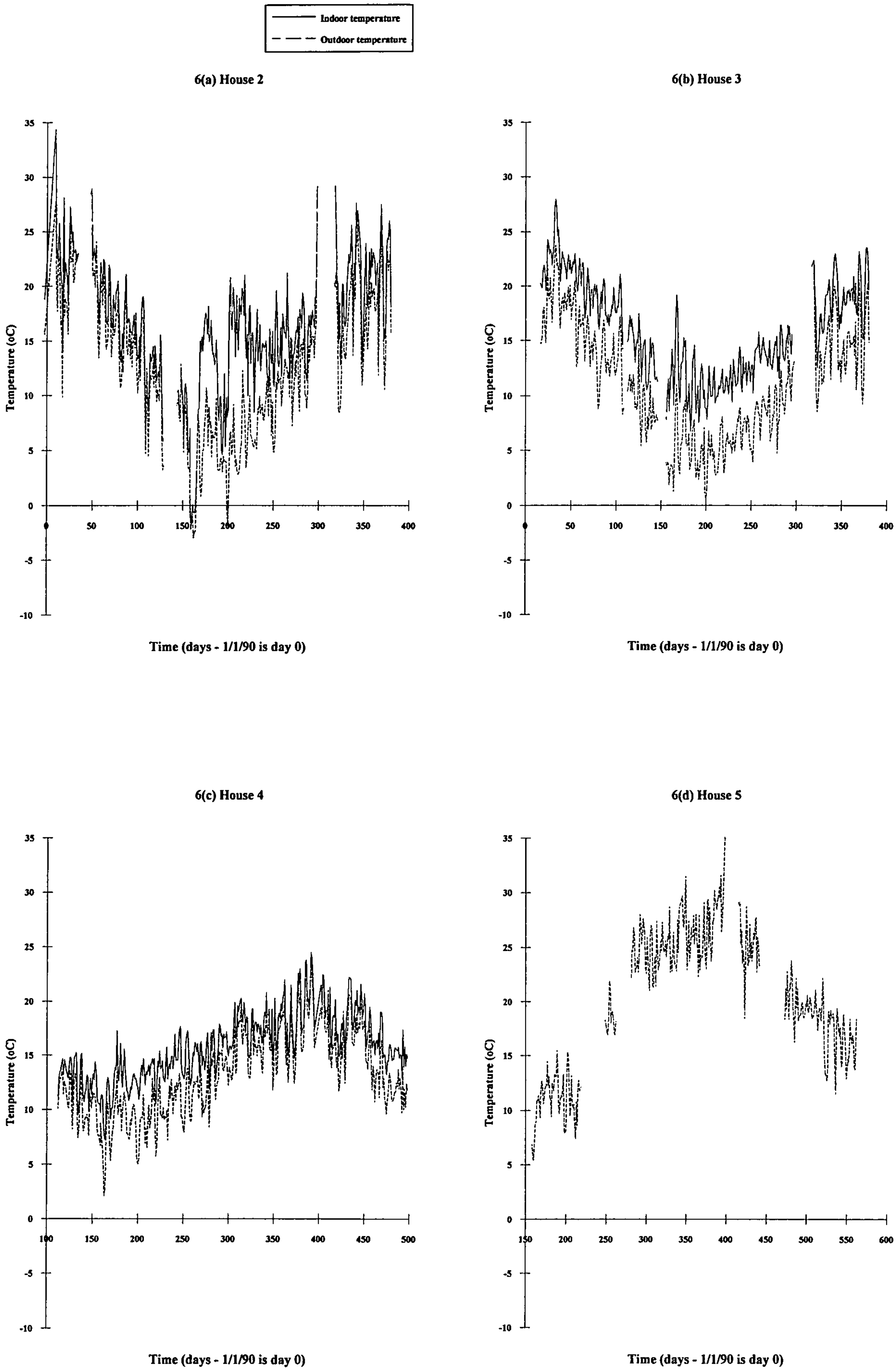
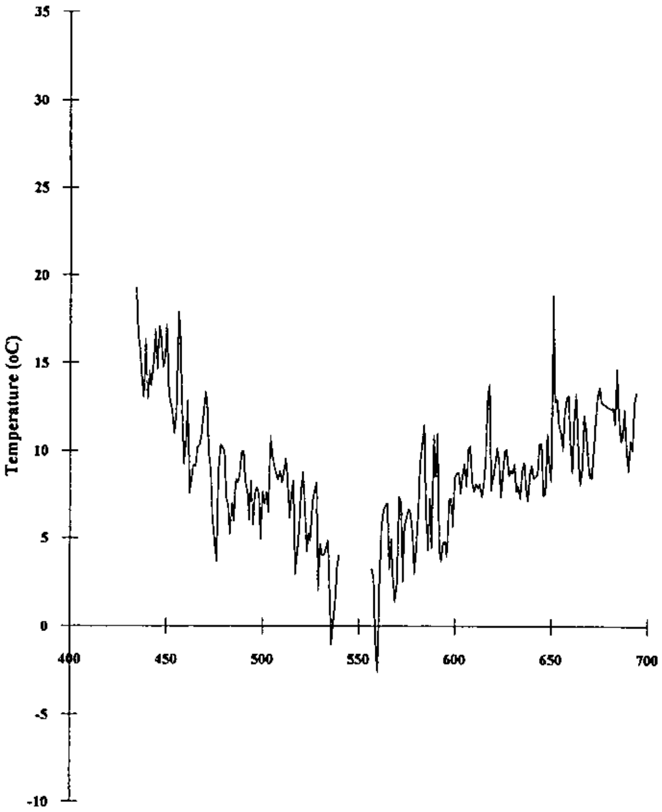

Indoor temperature
Outdoor temperature
6(a) House 2
6(b) House 3
6(c) House 4
6(d) House 5
Temperature (oC)
Time (days - 1/1/90 is day 0)

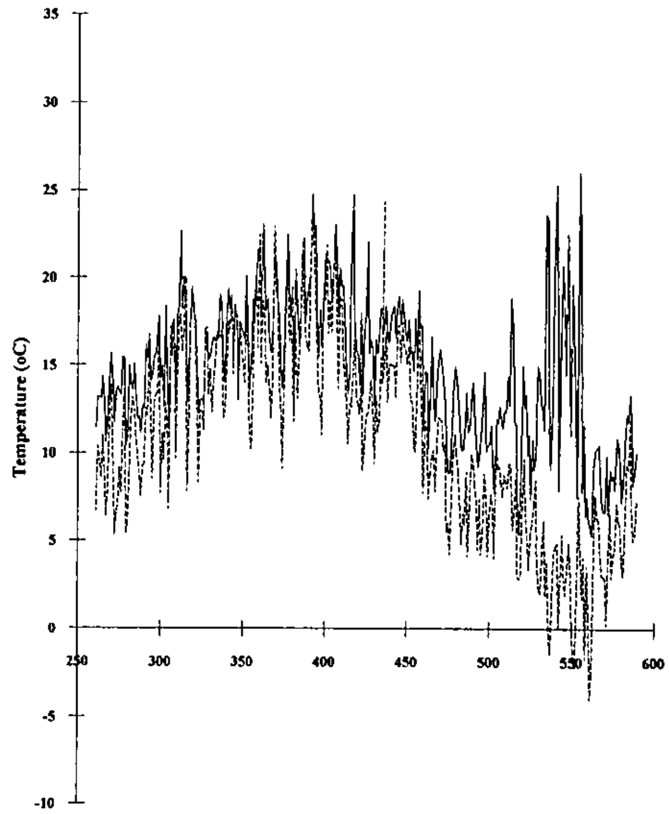
Fig. 6(a)–(d).

6(e) House 6



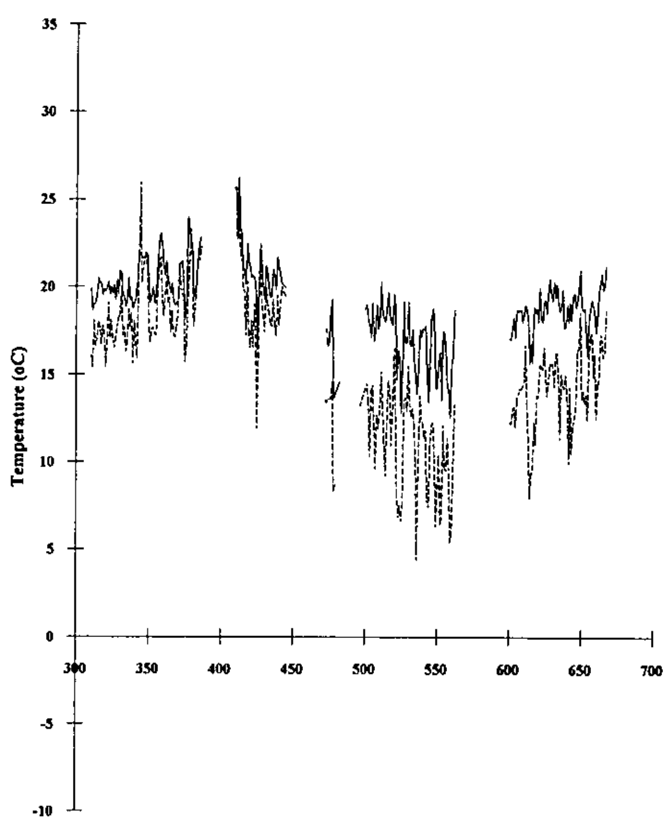
Time (days - 1/1/90 is day 0)

6(f) House 7



Time (days - 1/1/90 is day 0)

6(g) House 8



Time (days - 1/1/90 is day 0)

Fig. 6. Twenty-four hour mean of indoor and outdoor temperatures.

Table 2. Interzone airflows

House 2

Origin of air	Zone volume m³	To skillion Zone 1 m³/h	To pitched Zone 2 m³/h
From exterior, zone 0		190	150
From skillion, zone 1	1.5		100
From pitched, zone 2	69	50	

House 3

Origin of Air	Zone volume m³	To skillion Zone 1 m³/h	To skillion Zone 2 m³/h
From exterior, zone 0		4.6	0.5
From skillion, zone 1	0.87		1.6
From skillion, zone 2	0.75	0.26	

House 4

Origin of air	Zone volume m³	To skillion Zone 1 m³/h	To living space Zone 2 m³/h
From exterior, zone 0		1500	330
From skillion, zone 1	130		57
From living space, zone 2	250	450	

House 5

Origin of air	Zone volume m³	To skillion Zone 1 m³/h	To skillion Zone 2 m³/h	To living space Zone 3 m³/h
Exterior, zone 0		94	120	1000
From skillion, zone 1	10		17	4.9
From skillion, zone 2	2.2	22		13
From living space, zone 3	720	33	12	

House 7

Origin of air	Zone volume m³	To skillion and pitched Zone 1, m³/h	To living space Zone 2 m³/h
From exterior, zone 0		250	370
From skillion and pitched, zone 1	360		57
From living space, zone 2	570	140	

House 8

Origin of air	Zone volume m³	To skillion Zone 1 m³/h	To skillion Zone 2 m³/h	To living space Zone 3 m³/h
Exterior, zone 0		6.5	7.5	200
From skillion, zone 1	0.57		0.7	1.3
From skillion, zone 2	0.57	0.7		3.6
From living space, zone 3	160	1.7	6.5	

and temperature. The external relative humidity sensor in house 3 failed very early in the experiment, while that for house 7 failed after day 523. The external humidity sensor for house 4 became noisy and erratic after about day 300. As mentioned earlier, because of known drift performance of the relative humidity sensors, relative humidity taken towards the end of the collection phase will be less accurate than that at the beginning.

The quality of air-change rate data measured with the passive tracer method hinges on the assumption that air in the zones is well mixed, so that air leaving the zone carries away an average concentration of tracer. In the living spaces and pitched roof zones it was possible to space out the emitters and absorbers at recommended distances from the exterior surfaces. As a result, the average variation in tracer concentration measured at the absorber locations was typical of living space ventilation rate measurements at around 20% of the mean. In the smaller skillion roof cavities it was not possible to space the emitters at standard distances from roof and ceiling surfaces so there was some risk of higher than average concentration tracer leaving the zone. It was noted, however, that the obvious leakage openings into the skillion roof cavities were at the perimeter, defined generally by framing timber with many large leakage openings. While it was possible to place samplers and emitters an adequate distance from these leakage openings, it is likely that plug flow ventilation processes through the cavity will have invalidated the assumption of uniformly mixed tracer in the zone. Tracer concentrations measured at different points in skillion cavities were more variable than in the larger zones, with the average variation being 70% of the mean. As a result, the air change rates reported for the skillion roof cavities have to be regarded as indicative (perhaps no more than the order of magnitude). The data is nevertheless useful because it is unique in New Zealand.

Trends. It might be expected that some national trends could be seen in the moisture performance of these groups of houses, e.g. colder climates or homes in a lower socio-economic bracket might be associated with wetter timbers. In general one might expect the climate and the occupants and their lifestyle to be important variables influencing the moisture performance of the structure. In an attempt to uncover trends of this nature, suitable independent variables measuring the moisture load upon the structure were chosen as: the house cost, as a measure of the socio-economic bracket of the occupants; year average internal relative humidity as a measure of the living patterns of the occupants; and year mean and winter mean (mean of days 180 to 210 or days 545 to 575) external temperature and relative humidity as measures of the external climate. Dependent variables measuring the moisture response of the structure were chosen as: the maximum winter peak moisture content; the maximum summer/winter moisture content range (i.e. the winter peak moisture content minus the summer trough moisture content); and the number of days of significant condensation on the building paper. This data plus the rank of each value from house to house is contained in Table 3.

To analyse trends, the dependent and independent variables were correlated using Spearman's rank order technique. This a non-parametric technique comparing the ranks of the variables, e.g. wettest to most expensive, or wettest to most humid. If rank orders of two variables are identical then the Spearman's correlation will be 100%. The results of this test together with their significance level are contained in Table 4.

The table shows that the external relative humidity correlates with the winter peak maximum moisture content at the 2% significance level, that the winter mean external temperature correlates with the winter peak maximum moisture content at the 3% significance level, and shows weaker correlations between internal relative humidity and winter peak maximum moisture content (at the 11% significance level) and between cost and summer/winter moisture content range (at the 13% significance level). No other correlations are significant.

From these correlations the following trends can be inferred for these 7 houses:

1. Relative humidities, particularly the external relative humidities, are important factors associated with peak timber moisture contents.
2. Colder winter temperatures are associated with *drier* timbers (for this sample of houses).
3. There tends to be a wider swing of moisture contents in cheaper houses, but on the other hand, housing cost and therefore socio-economic level of the house occupants is not associated with peak values of moisture contents or condensation quantities.

DISCUSSION

The prime motivation for performing this study was to gather data to allow the assessment of the performance of a numerical model for the moisture behaviour of the building structure. This is examined in detail in a later paper. However, some results have been obtained which are useful and interesting in their own right, independent of model considerations.

Table 3. Moisture performance parameters and their rank for each house

House number	2	3	4	5	6	7	8
Cost rank	6	5	2	1	4	3	7
Internal RH year mean value	37%	38%	53%	—	—	46%	54%
Rank of internal RH year mean	5	4	2	—	—	3	1
External RH year mean value	48%	—	70%	75%	65%	66%	69%
Rank of external RH year mean	6	—	2	1	5	4	3
Winter mean external RH	65%	—	71%	88%	70%	—	77%
Rank of winter mean external RH	5	—	3	1	4	—	2
External temperature mean value	12.9°C	11.0°C	10.4°C	19.7°C	8.8°C	10.9°C	15.4°C
Rank of external temperature	3	4	6	1	7	5	2
Winter mean external temperature	4.7°C	4.4°C	6.4°C	11.6°C	2.7°C	3.9°C	9.5°C
Rank of winter mean external temperature	4	5	3	1	7	6	2
Winter peak max moisture content	15.5%	14.5%	17.5%	16%	14.5%	15.5%	16%
Rank of winter peak max moisture content	4=	6=	1	2=	6=	4=	2=
Summer/winter moisture content range	6.8%	2.5%	5.7%	1.2%	2.5%	3.5%	6.0%
Rank of summer/winter moisture content range	1	5=	3	7	5=	4	2
Days of condensation	23.6	1.0	73.8	0	0	0	6.6
Rank of days of condensation	2	4	1	5=	5=	5=	3

Table 4. Spearman's correlation and significance level between moisture performance parameters

	Winter peak max moisture content		Summer/winter moisture content range		Days of condensation	
	Correlation	Significance	Correlation	Significance	Correlation	Significance
Cost	0.33	0.47	−0.63	0.13	−0.26	0.57
Year mean internal RH	0.80	0.11	−0.05	0.93	0.21	0.74
Year mean external RH	0.83	0.02	−0.11	0.82	0.13	0.78
Winter mean RH	0.56	0.32	−0.60	0.28	−0.36	0.55
External temperature	0.33	0.47	−0.02	0.97	0.0	1.0
Winter mean temperature	0.80	0.03	0.07	0.88	0.33	0.46

The most significant single fact is that no moisture problems have been observed. No houses had a construction moisture problem; no significant moisture accumulated in the timbers of any house; no significant condensation formed on the building paper; the lack of vapour barriers in all but one house was of no significance.

Conventional wisdom states the skillion roofs are more susceptible to moisture problems, because they have only narrow, if any, spaces for air movement. The same wisdom states that these roofs will be even more vulnerable if there is no vapour barrier, as this allows for easier access of room moisture into the roof space. These suppositions are not borne out for the houses in this study.

This study shows that the main reason for good moisture performance for these roofs is the higher than expected air-change rates into and out of the roof space, particularly from the outside. Conventional wisdom that states that skillion roofs are air-tight is incorrect for the roof types instrumented in this study. Even structures which have large sheets of material, such as long-run steel claddings and gypsum plaster board ceilings, in practice have many paths available for air to enter the roof space particularly from the outside, e.g. at the eaves and between overlaps in the steel sheets.

Higher than expected air-change rates into roofs, particularly from the outside, have also been reported in Europe by Hens [18]. The evidence being accumulated suggests that more research effort should be directed towards uncovering the nature and extent of air change via all paths in and out of the cavities of structures.

This is not to say that moisture problems have not been reported in New Zealand roofs; however it appears now that these have causes due to other than that the roofs are of a particular design, are not deliberately ventilated, or have no vapour barrier. Two classes of roof moisture problem, aside from direct rain penetration, are known and have been studied in New Zealand. They are solar driven moisture transfer [19], in which some of the moisture soaked into absorbent roofing materials is driven into the structure by solar radiation; and transfer of moisture into the roof space from the sub-floor space [20], when these cavities are connected by, for example, an open wall cavity or other air flow paths. It is believed that some of the problems reported as due to roof detailing issues such as lack of vapour barriers or deliberate ventilation, were in fact solar driven moisture transfer problems.

A drying transient is evident in the data, in that all houses and all timber moisture contents (except the wettest timber in house 7) are reported drier after one year of occupancy. However the amount of drying is not large, only a few percent moisture content. The bulk of the timber moisture had dried in these houses before data-logging commenced. Houses 7 and 8, which had spot measurements of their moisture contents taken between the installation of the instrumentation while the houses were still under construction and unoccupied and subsequent power-on, had some timber moisture contents enclosed above fibre-saturation, 30% moisture content, but these had dried to below 20% moisture content within a month.

The broad association of relative humidity with peak timber moisture contents is unsurprising. On the other hand, the fact that the winter mean external relative humidity does not correlate well with the peak timber moisture content while the year mean external relative humidity does, highlights both the fact that single parameters will not explain moisture behaviour, and that this sample is small.

The association of colder temperatures with drier timbers is interesting. Firstly, this reflects the nature of the climate zones: Queenstown for example, although cold is also dry, while the Auckland zone although warm is also humid. Secondly, colder climates tend to imply more heating by the occupant, lowering internal relative humidities, and hence structural moisture contents. Again this highlights the fact that plausible conjectures on moisture performance around single parameters are not necessarily correct.

The wider swing of moisture contents in cheaper houses is difficult to explain and may be due to other unrelated effects such as the particular internal and external climates that these houses are in.

CONCLUSIONS

The moisture performance of the timber framing of the roofs of seven newly constructed houses has been studied over one year of occupation in three different New Zealand climate zones, the principle aim being to acquire data to be used to check the performance of a numerical model SMAHT of structural moisture behaviour. To date, not many field studies for model validation purposes have been carried out. Good data sets to achieve this aim have been acquired, and their use for model comparison studies is described in a later paper.

To obtain data economically for this purpose required careful experimental design and in particular required the measurement of air-change rates into the roof cavity from outdoors, indoors, and in some cases from other building cavities. Cavity air-change measurements have not been carried out before despite the fact that the information collected is critical to the understanding of the moisture performance of the structure. The technique used here can only be regarded as giving indicative results, as the basic assumption of good mixing within the zones is unlikely to be met within the skillion roof building cavities.

The air-change measurements showed that air-change into and out of the roof cavity, particularly from the outside, was larger than expected, and becomes a dominant feature in the moisture performance of the structure. Issues of structural detailing such as the presence of vapour barriers or deliberate ventilation become unimportant in the face of these high air-change rates. This also meant that no moisture problems were observed and most of the drying transient had ceased by the time data acquisition commenced.

The use of a rank correlation technique uncovered national trends in the data. It was found that colder winter temperatures are associated with drier timbers due in part to the fact that, for the climate zones under study, colder climates tended to be drier, and the warmer climates more humid. It was also found that there was a tendency for wetter timbers to be associated with higher external relative humidities, consistent with the high external air-changes measured into the roofs.

Other studies [18] also suggest high air-change rates are to be found into roof structures, so it is suggested that this somewhat neglected area of study needs more research effort to improve measurement techniques and obtain field data over a range of structures and climates, so as to improve our understanding of this important mechanism.

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