Cool Home Pilot Data Logger Analysis: Evaluation

Summary

The analysis of the data logger temperature data is not yet complete and the analysis of utility usage data has not begun. However, the temperature data is showing clear patterns of program impacts consistent with expectations. The white roof coating is nearly eliminating the impact of solar heat gain through the roofs in the target houses. The indoor ceiling temperatures were reduced by about 5F on hot days while bedroom air temperatures declined by about half that amount. The heat gain from the ceiling was reduced by approximately 80% as ceiling temperatures dropped to within half a degree of 2nd floor indoor air temperatures and 2nd floor air temperatures became much more similar to first floor temperatures. The overall impacts of these temperature changes is to nearly remove the largest single source of heat gain to most of these flat roof row houses – solar gain through the roof. All graphical and statistical analyses performed supports the conclusion that the roof coating has worked as expected.

The impacts on ceiling temperatures were almost as large in houses with air conditioning and, somewhat unexpectedly, the impacts on air temperatures were also substantial despite the use of air conditioners before and after treatment.

The impacts of these changes on occupant health/safety/comfort and on energy usage is still being analyzed.

Data Collection

The Cool Home pilot collected temperature and humidity with data logger at 35 houses. Six of these houses were logged in the summer 2001 and treated before the summer of 2002. Six more houses were designated for the comparison group and did not receive treatment during the summer, leaving 23 houses with potential for short-term pre/post analysis. Three of these houses did not have any data from the second floor bedroom wall and one of the remaining houses did not receive any major treatments during the summer (no insulation or roof coat), leaving 19 houses for the pre/post analysis. All but two of these 19 houses have air conditioners.

Issues with data collection created two primary groups of logged houses with little overlap in their data. Eight houses only had logger data for June and the first half of July, seven houses only had data from mid July through August, and the remaining 4 houses had data spanning all of July and August. The lack of overlap in the periods covered for many houses, graphical analysis focussed on the two main groups separately, but all cases were combined for statistical analyses.

Temperature Time Series Profiles

The 2nd floor and outdoor temperatures for the twelve houses with early July data are shown in Figures 1 and 2. Figure 1 shows the five houses that did not have air conditioners in the logged front bedroom and Figure 2 shows the seven houses that did have front bedroom air conditioners. Each site's graph is labeled by the house ID and the location(s) of any air conditioners. The major program treatments are shown near the bottom of each graph where 1 means first roof coat, 2 means 2nd roof coat, N means roof insulation, and F means whole house fan. Any prior treatment at the start of the data period are shown for the first day of data (all were in the "Pre" condition except for job NAC2).

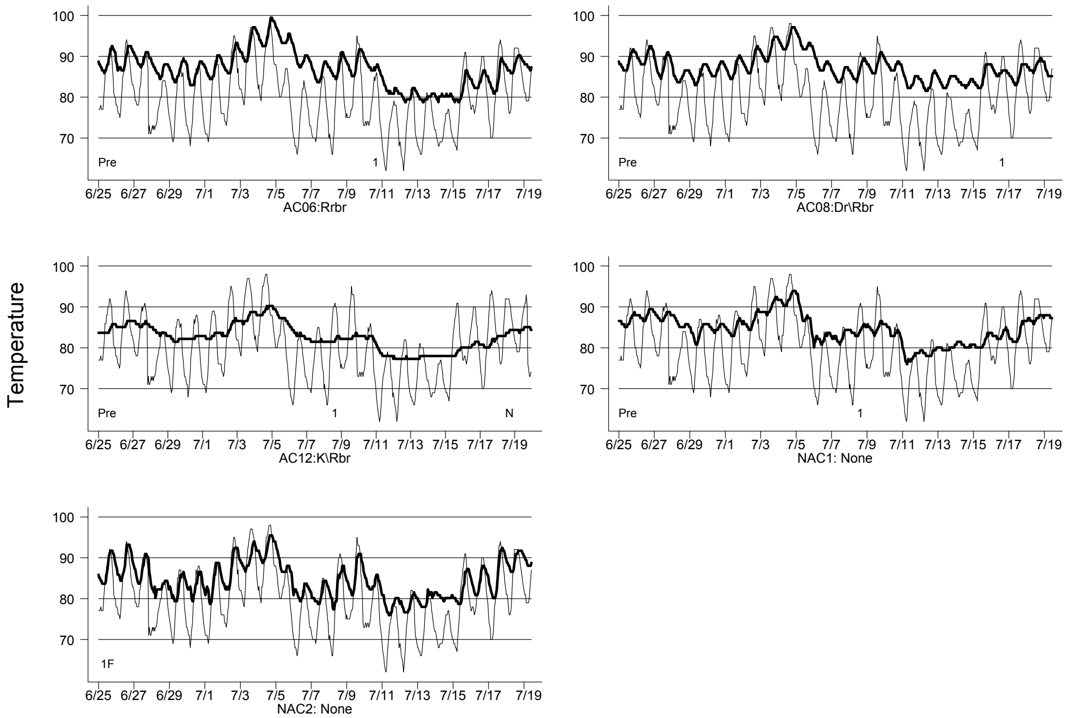

Figure 1. 2nd Floor Temperature Profiles for houses without front bedroom air conditioners and with early July data.

Figure 1 shows that four of the five houses without front bedroom air conditioning had quite similar temperature profiles. Houses AC06 and AC08 look almost identical (both also had shaded western exposures). Sites NAC1 and NAC2 are similar to AC06 and AC08 but NAC1 had smaller daily temperature swings (and cooler temperatures, perhaps due to unrecorded air conditioning?) while NAC2 had larger daily temperature swings (perhaps due to the presence of a whole house fan). Site AC12 was quite different from the others, with very small temperature swings and generally cooler temperatures implying air conditioning.

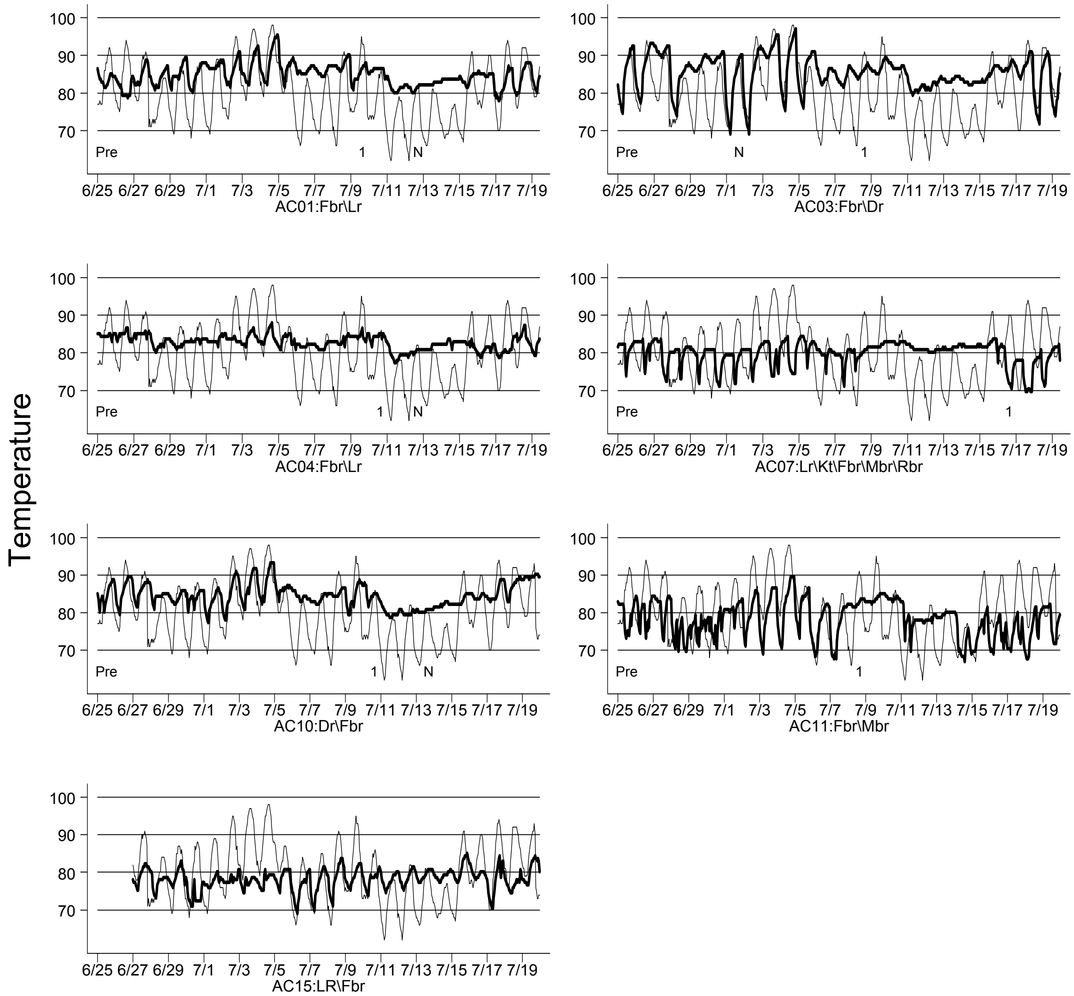

Figure 2. 2nd Floor Temperature Profiles for houses with front bedroom air conditioning and with early July data.

Figure 2 shows that the houses with front bedroom air conditioners tend to have wider variations in temperature profiles indicative of different air conditioning strategies and set points. The low temperatures and flattened peaks indicative of air conditioning are particularly obvious for AC07. The daily pattern in temperatures indicate that the air conditioner was likely running continuously in the day time (where the temperatures spiked downward) but was thermostatically controlled at night (where the temperature coasted up the low 80’s and remained flat). AC04 has somewhat higher temperatures than AC07 but also a flatter pattern, implying that the air conditioner may be cycling thermostatically most of the time (and at a relatively high set point). AC15 shows heavy air conditioning use with temperatures maintained in the 70s much of the time but with many days showing wide swings implying continuous air conditioner runtime. Site AC11 shows much wider swings indicative of heavy air conditioner use at night and a fairly high set point in the daytime (note the clipped peaks on many days). Sites AC01 and AC10 don’t appear very different from the sites without air conditioners through July 4th, but the temperature peaks appear to be flatter after then. Site AC03 exhibits an unusual pattern where indoor temperatures have large swings and are almost identical to outdoor temperatures for some days, but are then relatively flat on other days. This pattern could be due to intermittent but intensive use of a whole house fan, some type of data logger error, or intermittent night-time air conditioner use. The data from this site are suspect.

Figures 1 and 2 also show that most of these sites received initial roof coating and some received roof insulation during the period covered by the data. There were few days with similar outdoor temperatures between the pre and post treatment periods, but July 2nd and July 16th were fairly similar with peak temperatures in the mid-90s and clear skies. Both also had similarly warm days preceding them (reducing the potential impact of thermal mass effects).

The figure below shows the temperature data for four houses where the data for each of these two days is overlapped. The dashed lines show the July 2nd data (representing the "pre-treatment" condition) and the solid lines show the July 16th data (post treatment). The bold lines show the 2nd floor bedroom indoor air temperatures while the lighter lines show the outdoor temperatures.

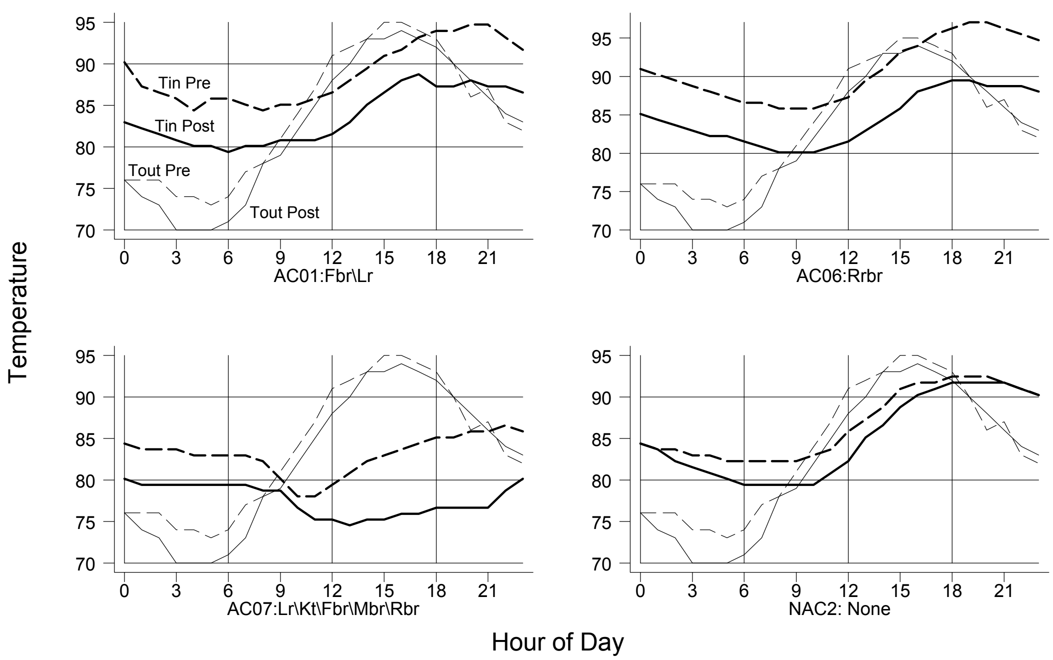

Figure 3. Matched day overlapped comparison of temperatures for four houses

Site NAC2 had no treatments between the two days and the temperature profiles of both days look similar with nearly identical peaks, although the pre-treatment day is a little warmer. Sites AC01 and AC06 show noticeably larger differences in 2nd floor temperatures between the two days, indicating the impacts of treatments. The difference between the days is clear throughout the 24 hour cycle. Site AC07 shows obvious air conditioning but also cooler indoor temperatures after treatment. It is not clear how much of this change may be due to the treatments or different air conditioning settings.

The similarity of sites AC06 and AC08 and the fact that AC06 was treated on July 10th while AC08 was treated July 16th allows for another graphical assessment of the treatment impacts. The figure below shows the second floor temperatures for both of these sites along with the outdoor temperatures (dotted line) from late June through July 19th. Site AC08 is the bolder line.

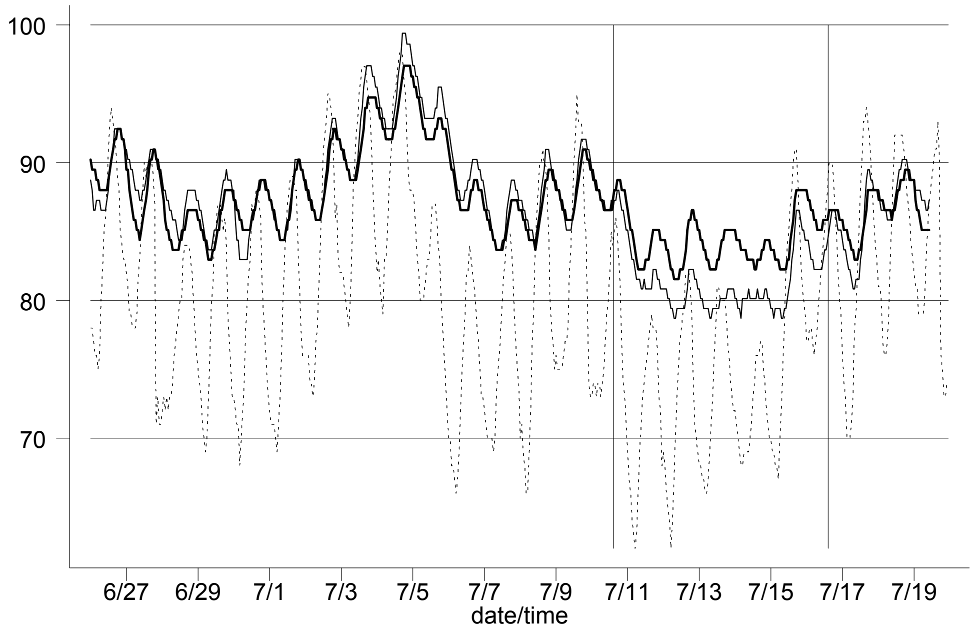

Figure 4. 2nd Floor Temperatures of houses AC06 and AC08 with 1 week gap between treatments

The figure shows that AC06 was a little hotter than AC08 until treatment (first vertical line), then was much cooler until AC08 was treated (second vertical line). Once they were both treated the original pattern re-emerged (although both are cooler than before). This figure shows a clear impact from the roof coating. Although the outdoor temperatures were cooler during the week of interest, potentially skewing results, the similarity in temperature patterns before and after both were treated provides convincing evidence of a noticeable treatment impact.

Figure 5 and Figure 6 show the 2nd floor and outdoor temperatures for houses with data in August, including four of the sites included in the prior graphs. Figure 5 shows the data for houses without front bedroom air conditioners and Figure 6 shows houses with front bedroom air conditioners.

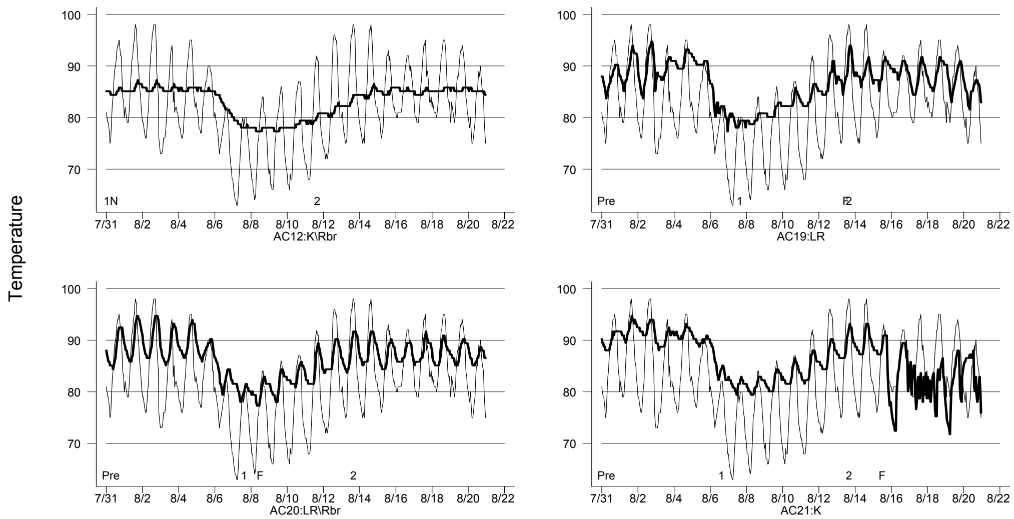

Figure 5. 2nd floor Temperature Profiles for houses without front bedroom air conditioners and with August data

Figure 5 shows that site AC12 continued to show flat temperatures consistent with having some unreported air conditioning. The second floor bedroom temperatures never exceeded the mid-80's even during the 10 day heat wave from August 11th through 20th. The other three sites all appear to have noticeably cooler temperatures after treatment with peak temperatures lower during the mid-August heat wave than during the early August heat wave. Site AC21 shows unusual temperature patterns beginning around August 16th with indoor temperatures dropping well below outdoor temperatures. This later data is suspect and was not used in the analysis.

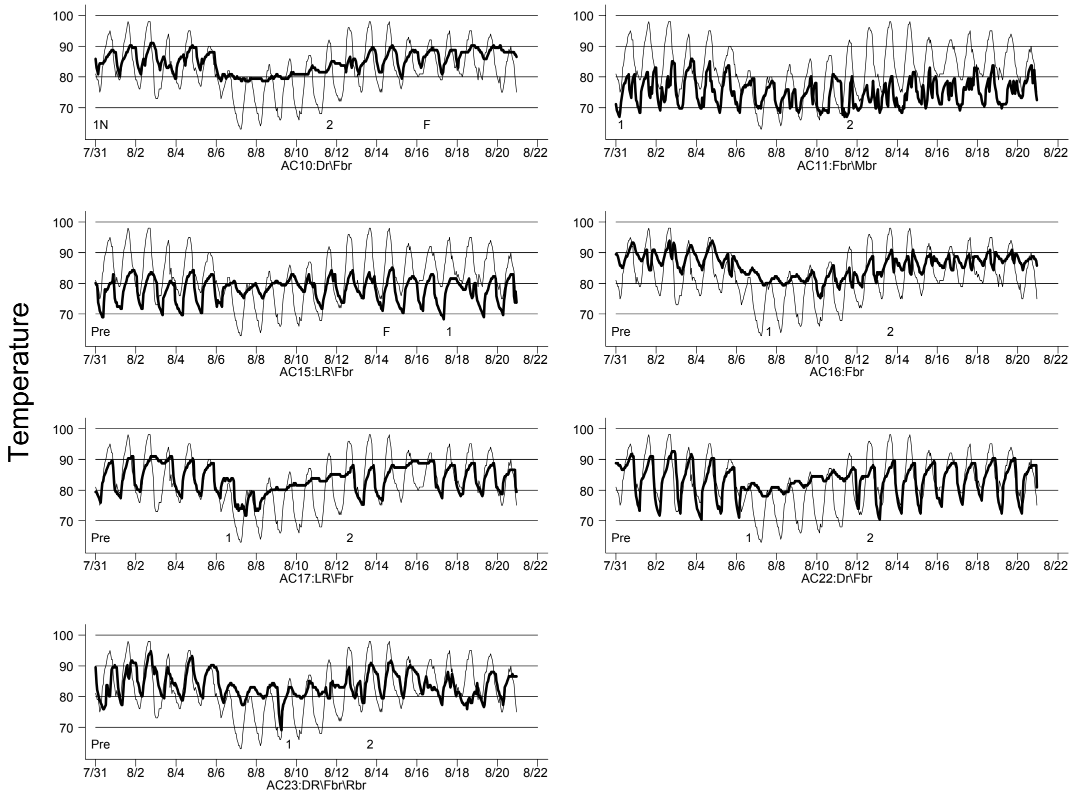

Figure 6. 2nd Floor Temperature Profiles for houses with front bedroom air conditioners and with August data

Figure 6 includes three sites from the earlier analysis (AC10, AC11, and AC15) with data consistent from July. The other four houses all show more moderate A/C usage as temperatures peak at about 90 F for all of them. These four houses all appear to exhibit some impacts from treatment as peak temperatures decline from the early August heat wave to the mid-August heat wave.

Daily Temperature Summaries

The time series plots of temperatures provide a solid overview of temperature patterns at each site and indicate potential air conditioning usage patterns as well as point toward potential treatment impacts. However, these plots do not allow for easy comparison of changes in temperature profiles due to treatments. One alternative approach involves summarizing each day's temperature profile and plotting indoor and outdoor conditions against each other.

Figure 7 and Figure 8 show the maximum daily indoor (2nd floor bedroom) temperature plotted against the maximum daily outdoor temperature with a line drawn to show equal temperatures. The graphs include all days hotter than 85 F. Circles are used for days before treatment and plus signs for days after treatment.

Figure 7 shows all houses with no air conditioning reported in the front bedroom. The maximum indoor and outdoor temperature track fairly closely for most houses. Site AC12 has noticeably cooler indoor temperatures, consistent with the earlier analysis that suggested there may some air conditioning there. The figure also shows that temperatures generally declined after treatment – the plus signs are generally below the circles for most houses at most temperatures.

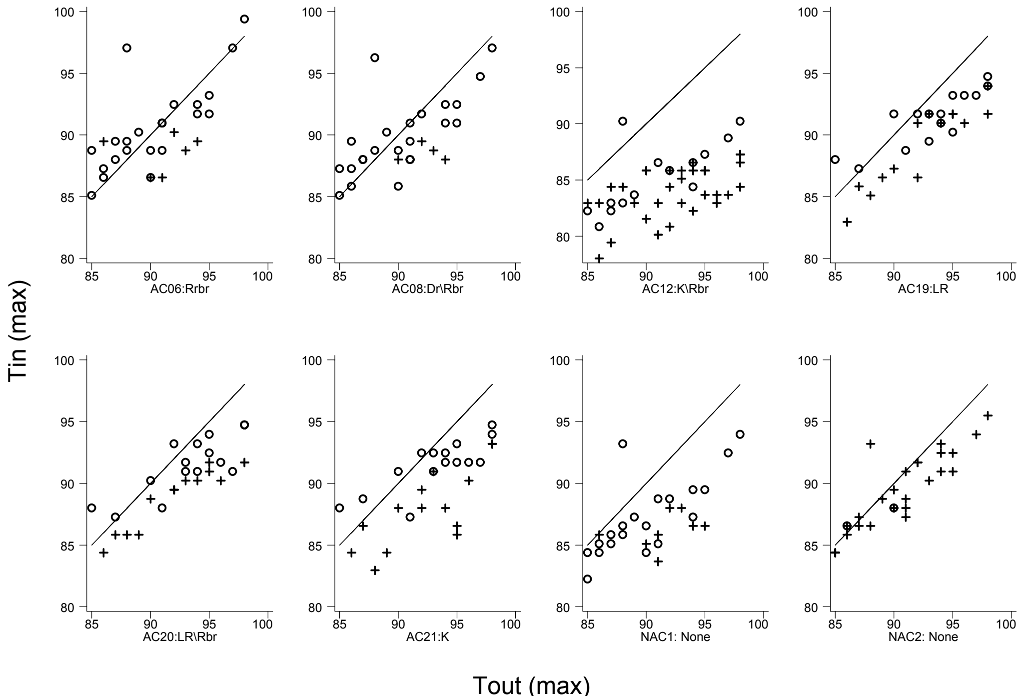

Figure 7. Maximum daily indoor and outdoor temperatures: houses without air conditioning in bedroom. Circles indicate pre-treatment days, plus signs are post treatments days.

Figure 8 shows the results for sites with air conditioning in the front bedroom. Most of these houses had considerably lower indoor temperatures due to air conditioning. Sites AC4, AC7, AC11, and AC15 again have the most obvious cooling – the indoor temperatures are relatively constant. Several of the other sites resemble the houses without cooling. Ac16, AC22 and AC23 all appear to show impacts from treatments.

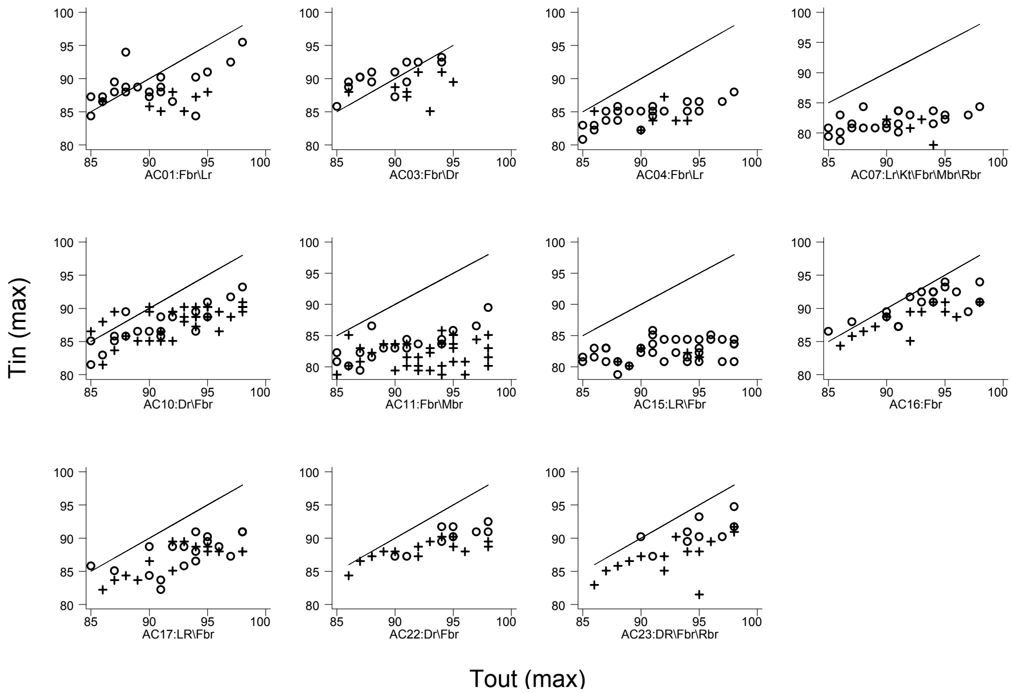

Figure 8. Maximum daily indoor and outdoor temperatures: houses with air conditioning in bedroom

Ceiling Temperatures

Figure 9 and Figure 10 show the same relationships between daily maximum temperatures except the indoor temperature is for the 2nd floor bedroom ceiling. As expected, the impact of treatments is more pronounced on these graphs since the program treatments directly affect heat gain through the ceiling and therefore only indirectly affect air temperatures. By focusing on the ceiling temperatures, the impact on air conditioned houses appears almost as clearly as among houses without bedroom air conditioning. This finding implies that the impact of program treatments may appear as indoor temperature reductions in houses without air conditioning in the bedrooms, but could appear as either temperature reductions or cooling load reductions in the air conditioned houses.

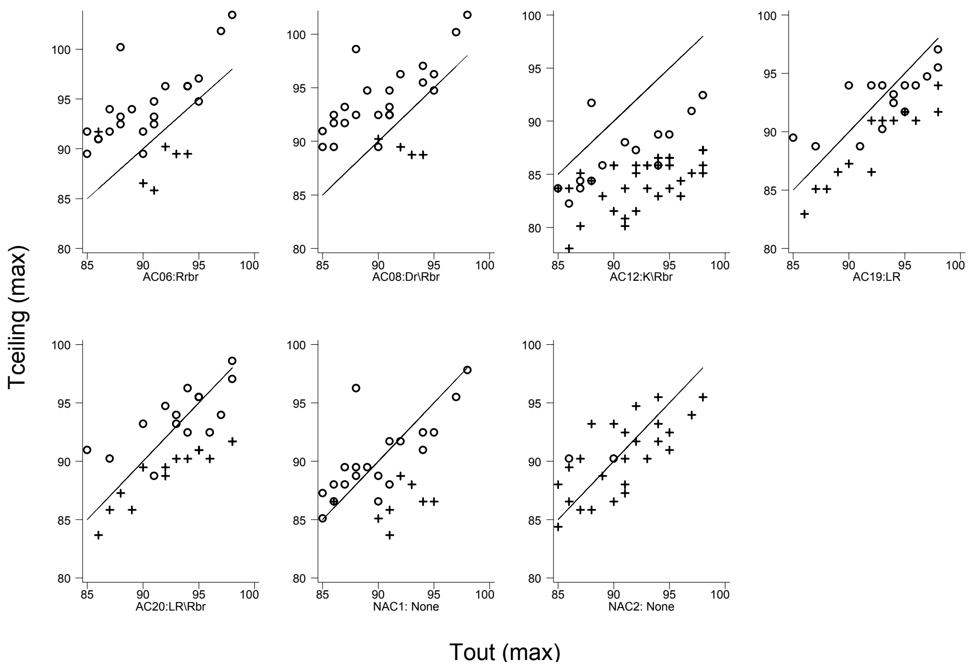

Figure 9. Maximum Daily Ceiling and Outdoor Temperatures: houses without air conditioning in bedroom.

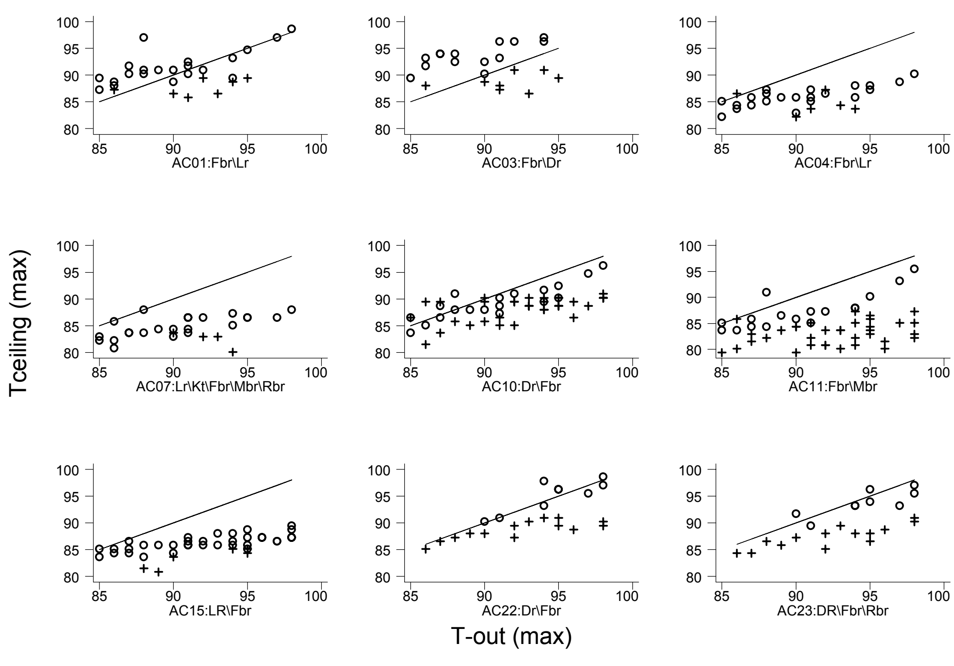

Figure 10. Maximum Daily Ceiling and Outdoor Temperatures: houses with air conditioning in bedroom

Another approach for assessing treatment impacts is to compare the ceiling and air temperatures in the 2nd floor bedrooms. The heat transfer from the roof to the house should be directly proportional to the difference in these temperatures – the area between the two curves provides an estimate of the overall heat transfer. If the treatments are fully effective at reducing heat gain from the roof, then the difference between the ceiling and air temperatures should drop dramatically from treatments. Figure 11 shows the daily maximum ceiling and air temperatures for the houses with July data and Figure 12 shows the August houses.

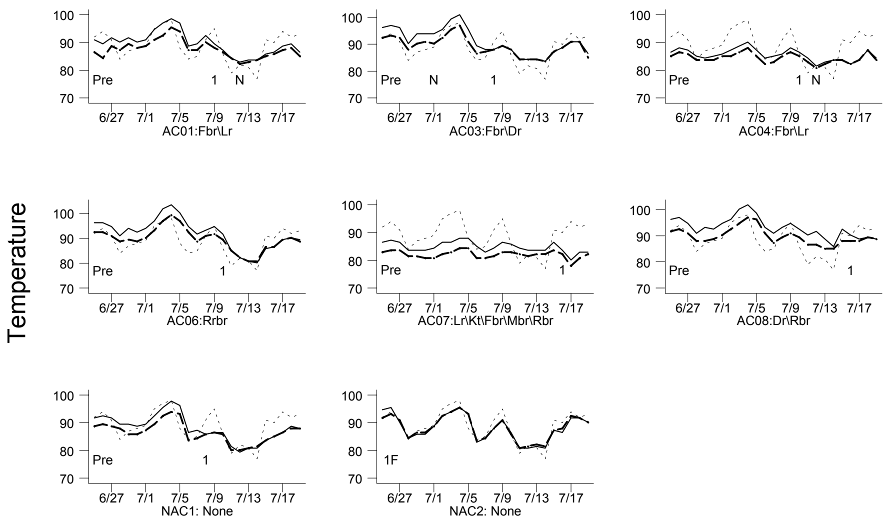

Figure 11. Maximum Daily Ceiling and air (dashed line) temperatures -- July houses (outside maximum temperatures shown as dotted line)

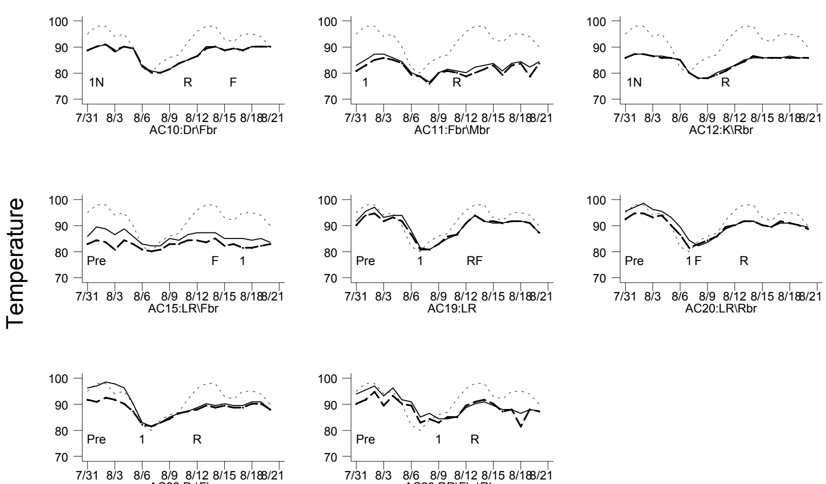

Figure 12. Maximum Daily Ceiling and air (dashed line) temperatures -- August houses (outside maximum temperatures shown as dotted line)

In most houses, the difference between the ceiling and air temperatures narrows or is even eliminated after treatments (e.g., AC03, AC06, AC20, AC22, AC23). Houses which had already been treated by the start of the data mostly showed ceiling and air temperatures that were indistinguishable (NAC2, AC10, AC12). This comparison clearly shows treatment impacts even on air conditioned houses. Of course, houses with heavy air conditioning usage (AC07, AC11, AC15) will still have a temperature difference between the ceiling and air due to normal conduction.

An alternative approach to this analysis is to plot the difference between the ceiling and air temperature in the 2nd floor bedroom over time. Figure 13 shows this for site AC06 with a vertical line showing when the roof was coated.

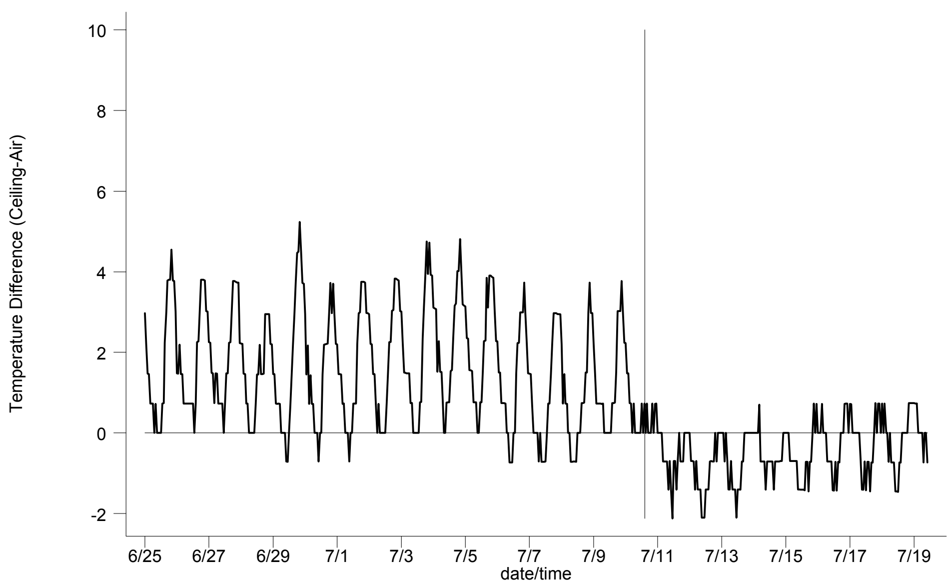

Figure 13. Temperature Difference between Ceiling and Air : site AC06

The figure shows a clear and immediate impact from the roof coating, confirming the prior conclusions that heat gain through the roof was essentially eliminated by the treatments.

First Floor Temperatures

We also examined the impact of Cool Home treatments on first floor temperatures. Most houses had air conditioners on the first floor which can obviously obscure any potential impacts. One house – site NAC1 -- had no air conditioning on either floor and also had data from before and after the roof coating. Figure 14 shows the temperature profile for NAC1.

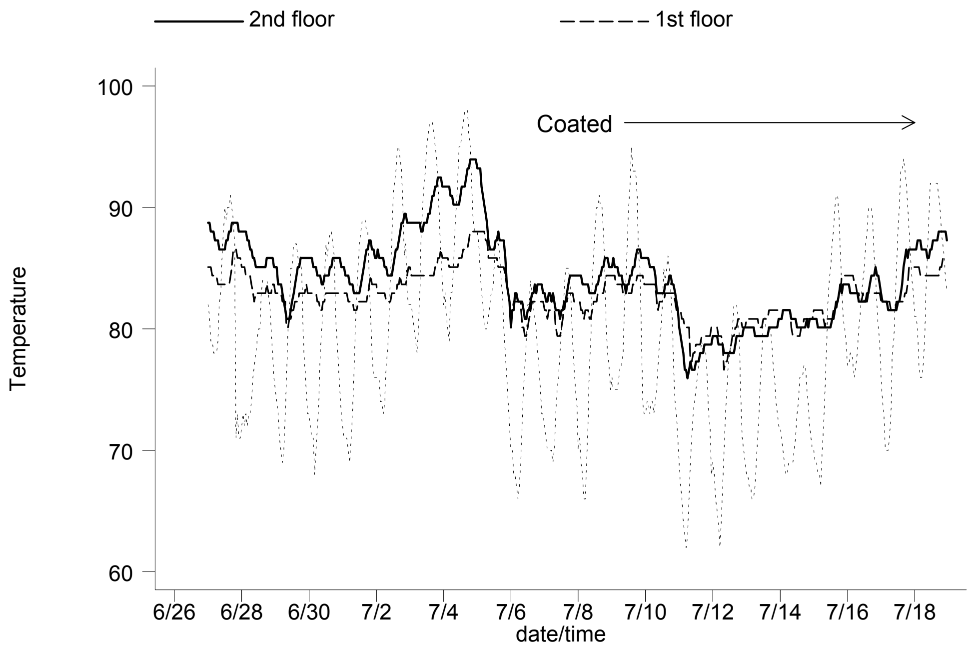

Figure 14. 1st and 2nd floor temperatures for site NAC1 (no air conditioning).

The figure shows that the second floor was much hotter than the first floor during hot days before the coating (July 8th) and then the two floors were quite similar after the roof coating. This finding is consistent with a substantial reduction in 2nd floor specific heat gain. When 1st floor temperature data were similar to what was presented in Table 1, we found no significant change in maximum temperatures. On average, the first floor was a half degree warmer after treatment. The data for site NAC1 shows a one degree increase.

Quantitative Assessment of Treatment Impacts

Although the graphs of the preceding section indicate that the treatments are affecting the indoor temperatures, they are a qualitative rather than quantitative assessment of treatment impacts. Statistical analysis of the temperature data for different treatment periods within and between sites is needed to provide a quantitative assessment of treatment impacts.

Examination of the preceding maximum temperature graphs led to the first approach used to statistically summarize the treatment impacts. The approach involved calculating the daily minimum, maximum, and average for each temperature at each site and for the corresponding outdoor temperature. Each day's indoor air and ceiling temperatures were subtracted from the corresponding outdoor temperature summary to measure how much cooler the indoors was compared to the outdoors. Next, all days with outdoor maximum temperatures cooler than 90 degrees, or with the prior day cooler than 90 degrees, were removed to focus the analysis on hot days and exclude the initial day of each heat wave. The temperature difference summaries (indoor/outdoor difference in minimum, maximum, and average temperatures) for the remaining hot days were then averaged for each site and each treatment status. The net impact of the treatments for each site was then calculated as the change in the in/out temperature difference between the pre-treatment period and the final post-treatment period. Table 1 shows the results of this analysis.

Table 1. Change in Indoor/Outdoor Temperature Differences after treatment

A/C in bedroom	Job	Exposure: shade	Change in Tin-Tout between pre and post (positive = cooler) Maximum Temperature Ceiling	Maximum Temperature Air	Average Temperature Ceiling	Average Temperature Air	Minimum Temperature Ceiling	Minimum Temperature Air
no A/C	AC06	W:total	6.3	2.7	4.2	2.3	2.6	1.7
no A/C	AC08	W:total	6.4	2.6	3.5	1.6	0.3	0
no A/C	AC12	S:total	3.8	2.3	2	1.1	2.5	2.1
no A/C	AC19	N:some	2.7	1	2.4	1.3	4.1	2.7
no A/C	AC20	S:no	4.2	1.8	2.6	1.1	2.2	1.3
no A/C	AC21	N:total		2.9		1.5		0.5
no A/C	NAC1	N:no	4.9	2	2.4	0.7	1.7	0.6
A/C	AC01	S:no	3.3	1	2.4	0.4	2.1	1.3
A/C	AC03	E:some	7.2	4.3	4.5	3.1	0.6	-1
A/C	AC10	N:some	3	1	0.7	-0.4	0	-0.7
A/C	AC16	E:no		2		1.5		1.7
A/C	AC17	W:total		0.7		-1		-1.2
A/C	AC22	W:some	5.3	1	2.9	0.4	3.1	1.8
A/C	AC04	S:total	1.6	0.1	1.7	1.1	2	1.3
A/C	AC07	E:total	3.7	2	2.3	1.4	-0.3	-1
A/C	AC11	E:no	6.6	3.6	5.7	4.3	5.1	2.8
A/C	AC15	S:total	0.5	-1.1	1.4	0.6	3.1	3.8
A/C	AC23	S:no	5.1	2.5	3	0.6	1.8	-0.1
Average Impacts:								
Houses without A/C in bedroom			4.7	2.2	2.9	1.4	2.2	1.3
Houses with A/C in bedroom			4.0	1.6	2.7	1.1	1.9	0.8
Overall			4.3	1.8	2.8	1.2	2.1	1.0

The table shows that, in 2nd floor bedrooms, the daily maximum ceiling temperature dropped by an average of 4.3 degrees due to program treatments and the maximum air (i.e. wall) temperature dropped by an average of 1.8 F after treatment. The impact were somewhat larger in houses without bedroom air conditioners – ceilings became about 4.7 F cooler and the bedroom air temperature dropped by about 2.2 F compared to outside. The impacts on air temperatures were only about half as large as the impact on ceiling temperatures. The impacts of the treatments on average and minimum temperatures were positive but smaller than the impact on maximum temperatures. Minimum temperatures declined by about half as much as maximum temperatures did.

When the analysis were re-run restricted to only the hottest days (tout max>=95 F), the impacts were slightly larger but the sample size smaller.

A similar examination of the difference between the ceiling and room air temperatures found that the average temperature difference declined from 2.4 to 1.0 F after treatment. If one eliminates three houses with heavy air conditioning usage, the decline was about 80% (from 2.0 F to 0.4 F), implying an 80% reduction in heat gain through the ceiling. A simple heat transfer calculation indicates that this change in temperature should reduce daily cooling loads by about 30,000 Btus during hot weather, or the equivalent of nearly 4 hours continuous runtime for a typical 8000 Btu/hr window air conditioner.

Regression analysis is another approach to statistically estimate the impact of program treatments on maximum indoor air and ceiling temperatures. The advantage of regression over the previous method of averages is that it can account for the relationship between outdoor temperatures and indoor/outdoor temperature differences as well as incorporate information on the prior day's maximum temperature. This approach should provide more reliable estimates in cases where these factors may differ between the pre and post periods. Table 2 shows the results from the regression analysis.

Table 2. Regression Estimates of Impacts on Maximum Temperatures *(italics denote numbers with large uncertainty)*

A/C in bedroom	Job	Exposure	Ceiling	Air
no A/C	AC06	W:total	7.3	3.6
no A/C	AC08	W:total	7.2	3.5
no A/C	AC12	S:total	4.8	3.1
no A/C	AC19	N:some	2.2	0.7
no A/C	AC20	S:no	4.5	2.0
no A/C	AC21	N:total		2.7
no A/C	NAC1	N:no		1.8
A/C	AC01	S:no	4.4	2.4
A/C	AC03	E:some	5.6	1.8
A/C	AC10	N:some	*3.3*	*1.3*
A/C	AC16	E:no		*2.3*
A/C	AC17	W:total		*0.5*
A/C	AC22	W:some	6.4	1.8
A/C	AC04	S:total	2.3	*1.0*
A/C	AC07	E:total	*3.9*	*2.2*
A/C	AC11	E:no	*6.5*	3.4
A/C	AC15	S:total	*1.5*	0.3
A/C	AC23	S:no	5.4	*2.5*
Average Impacts:				
Houses without A/C in bedroom			5.2	2.5
Houses with A/C in bedroom			4.4	1.8
Overall			4.7	2.1

The overall results are quite similar to the prior table – average impacts of 4.7 F on ceiling maximum temperatures and 2.1 F on air maximum temperatures (vs. 4.3 and 1.8). The similar findings tend to reinforced both results.

A third approach for estimating the program impacts involved using a single pooled regression model that includes the same factors as the site-specific model but also incorporates inter-site differences (e.g., exposure, shading, the presence of air conditioning, etc.). Several approach were explored for building such a model. Impact estimates were quite consistent across a variety of model approaches – the impact estimates were about 2.3F for maximum air temperatures in houses without A/C in the bedroom, 1.9 F for those with A/C, and 4.4 F impacts on ceiling temperatures for both houses with or without bedroom air conditioners. These findings are consistent with the prior two analyses.

Now that we have developed estimated temperature impacts of the treatments, the evaluation needs to examine how these temperature changes affect occupant health and safety as well as cooling loads (in houses with air conditioners). The former task can be assessed using existing models of heat stress and examining how these temperature changes should affect the ability of a person to lose heat to their surroundings. The latter task can be estimated using engineering models of heat transfer from the ceiling to the air and, to the extent that sufficient data are available, by analyzing electric usage data.