Improving Ventilation and Saving Energy: Final Report on Indoor Environmental Quality and Energy Monitoring in Sixteen Relocatable Classrooms

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Abstract

An improved HVAC system for portable classrooms was specified to address key problems in existing units. These included low energy efficiency, poor control of and provision for adequate ventilation, and excessive acoustic noise. Working with industry, a prototype improved heat pump air conditioner was developed to meet the specification. A one-year measurement-intensive field-test of ten of these IHPAC systems was conducted in occupied classrooms in two distinct California climates. These measurements are compared to those made in parallel in side by side portable classrooms equipped with standard 10 SEER heat pump air conditioner equipment. The IHPAC units were found to work as designed, providing predicted annual energy efficiency improvements of about 36% to 42% across California's climate zones, relative to 10 SEER units. Classroom ventilation was vastly improved as evidenced by far lower indoor minus outdoor CO_2 concentrations. The IHPAC units were found to provide ventilation that meets both California State energy and occupational codes and the ASHRAE minimum ventilation requirements; the classrooms equipped with the 10 SEER equipment universally did not meet these targets. The IHPAC system provided a major improvement in indoor acoustic conditions. HVAC system generated background noise was reduced in fan-only and fan and compressor modes, reducing the nose levels to better than the design objective of 45 dB(A), and acceptable for additional design points by the Collaborative on High Performance Schools. The IHPAC provided superior ventilation, with indoor minus outdoor CO_2 concentrations that showed that the Title 24 minimum ventilation requirement of 15 CFM per occupant was nearly always being met. The opposite was found in the classrooms utilizing the 10 SEER system, where the indoor minus outdoor CO_2 concentrations frequently exceeded levels that reflect inadequate ventilation. Improved ventilation conditions in the IHPAC lead to effective removal of volatile organic compounds and aldehydes, on average lowering the concentrations by 57% relative to the levels in the 10 SEER classrooms. The average IHPAC to 10 SEER formaldehyde ratio was about 67%, indicating only a 33% reduction of this compound in indoor air. The IHPAC thermal control system provided less variability in occupied classroom temperature than the 10 SEER thermostats. The average room temperatures in all seasons tended to be slightly lower in the IHPAC classrooms, often below the lower limit of the ASHRAE 55 thermal comfort band. State-wide and national energy modeling provided conservative estimates of potential energy savings by use of the IHPAC system that would provide payback a the range of time far lower than the lifetime of the equipment. Assuming electricity costs of \$0.15/kWh, the per-classroom range of savings is from about \$85 to \$195 per year in California, and about \$89 to \$250 per year in the U.S., depending upon the city. These models did not include the non-energy benefits to the classrooms including better air quality and acoustic conditions that could lead to improved health and learning in school. Market connection efforts that were part of the study give all indication that this has been a very successful project. The successes include the specification of the IHPAC equipment in the CHPS portable classroom standards, the release of a commercial product based on the standards that is now being installed in schools around the U.S., and the fact that a public utility company is currently considering the addition of the technology to its customer incentive program. These successes indicate that the IHPAC may reach its potential to improve ventilation and save energy in classrooms.

Introduction

This is the final report on the California Energy Commission's (CEC) Public Interest Energy Research (PIER) Program funded project "Improving Ventilation and Saving Energy," Contract Number 500-03-041. It is an update of the interim report submitted to CEC in Fall 2005 (Apte et al., 2005). The primary goals of the "Improving Ventilation and Saving Energy" (IVSE) project were to develop, evaluate, and demonstrate a very practical HVAC system for portable or relocatable classrooms (RCs) that consistently provides them with the current minimum ventilation standards, while saving energy, and reducing HVAC-related noise levels. The ultimate goal was to provide the specification of this system to the public domain, and stimulate increased use of advanced classroom HVAC in the market through interaction with key school facility stakeholders.

A number of studies (e.g., Seppanen et al. 1999, Wargocki et al. 2002; Erdmann et al. 2002) have investigated the relationship of ventilation rates to health outcomes (sick building syndrome symptoms, respiratory illnesses), absence rates, and perceived air quality; however, most studies have been performed in office buildings. Some studies have used indoor CO_2 concentrations as a surrogate for ventilation rate per occupant. A large majority of these studies have found a worsening of some health, absence, or perceived air quality outcomes at lower ventilation rates or higher CO_2 concentrations. Detrimental effects have been particularly clear when ventilation rates are reduced below 20 CFM per occupant and several studies have found benefits of increasing ventilation rates above 20 CFM per occupant. These studies indicate that ventilation rates have important effects on the health of occupants.

Although continuous ventilation is required in California classrooms under both state energy and occupational laws (CEC. 2001, CCR 1995,) and is a required component of ASHRAE Standard 62.1 (ASHRAE 2004), there is a need for an improved classroom ventilation system. This need is based, in part, on the considerable evidence, summarized in Daisey et al. (1998, 2003), indicating that ventilation rates in classrooms often do not meet the current ASHRAE minimum rate of 15 CFM per occupant (ASHRAE, 2004). While relatively few measurements of actual classroom ventilation rates are available, concentrations of CO_2 in classrooms often substantially exceeded 1000 ppm; implying ventilation rates less than 15 CFM per occupant, with several studies reporting peak concentrations exceeding 1500 ppm, and some concentrations exceeding 3000 ppm (Daisey et al 2003, Daisey and Angell 1998). In a recent statewide random survey of California RCs CO_2 concentrations exceeded 1000 ppm in about 40% of classrooms and concentrations exceeded 2000 ppm in approximately 10% of classrooms (CARB-DHS 2003). In a survey of 400 classrooms in Washington state and Idaho (Shendell et al. 2004), CO_2 concentrations measured in 45% of classrooms exceeded 1000 ppm, thus, a considerably larger fraction of steady state or peak CO_2 concentrations would have exceeded 1000 ppm.

Additional evidence of low classroom ventilation rates was obtained in a study in 14 California schools (Lagus Applied Technologies 1995). The measured mean minimum air exchange rate was 2.4 h^{-1}, with a range of 1.2 to 2.9 h^{-1}, while the air exchange rate corresponding to the current standard was estimated to be 3 h^{-1}.

Several statutes and standards address the provision of adequate ventilation in California classrooms. Continuous ventilation is required in California Classrooms under both state energy and occupational laws (CEC. 2001, CCR 1995) and is a required component of ASHRAE Standard 62.1 (ASHRAE 2004).

Anecdotally, we are aware that ventilation rates in classrooms are often low because teachers frequently operate classroom HVAC systems in the mode where the supply fan shuts off except when heating or cooling is required. Thus, outside air is supplied mechanically only during periods of heating or cooling and the time average rate of supply is often below standards. We also observe that teachers use this mode of HVAC system operation to avoid HVAC system-related noise. These anecdotal reports are supported by the findings from a recently completed survey of California RCs. Teachers in 60% of RCs reported that they sometimes turned off HVAC systems to reduce noise levels (CARB-CDHS 2003). Consequently, the available evidence indicates the importance of reducing HVAC noise in the development of improved classroom HVAC systems.

The RC HVAC industry has been incrementally addressing the classroom noise levels generated by the wall mount heat pump air conditioner (HPAC) that they produce. For example, in the late 1990s Bard Manufacturing Company developed a 12 SEER (Seasonal Energy Efficiency Ratio) “Quiet Climate” model to meet specifications from the Los Angeles Unified School District (LAUSD, 1998). This unit was designed to operate at indoor sound levels ≤50 dB(A) measured at a point 3m (10’) from the return grille and 1.5m high. This model is the current state of the art, but has a relatively small market penetration in California. Unfortunately, 50 dB(A) is not currently considered an adequate target for classroom sound levels. The Collaborative on High Performance Schools (CHPS) recommends unoccupied classroom levels to be at or below 45 dB(A) (CHPS 2002). Additionally, the Acoustical Society of America (ASA) provide a guideline for classrooms of 35 dB(A) (ASA 2002).

A great deal of energy is used to condition ventilation air in high occupancy spaces such as classrooms. Mudarri et al. (1996) used an energy simulation model and estimated that increasing school building ventilation rates by 10 CFM, from 5 to 15 CFM per occupant, would increase annual HVAC energy use by 15%, 31%, and 32% in Miami, Washington, DC, and Seattle, respectively. From these predictions, we can estimate that the energy to provide 15 CFM per student of ventilation is approximately 22%, 45%, and 45% of total classroom HVAC energy in these three climates, respectively. This finding indicates a clear energy and financial penalty from increasing ventilation to meet existing standards. Therefore, improved energy efficiency must be applied to offset the increased demand.

When we consider these factors together – the important effects of ventilation on people, the evidence of ventilation deficiencies in classrooms, and the energy used for ventilation, it is very clear that we need to develop and promote the use of highly energy efficient systems for providing classroom ventilation. To this end, an improved heat pump air conditioner (IHPAC) HVAC system was designed and fabricated. The prototype IHPAC was the product of improvement specifications to address indoor environmental quality (IEQ) and energy efficiency needs by LBNL, and design, in-house testing and refinement, and fabrication of a prototype design by Bard Manufacturing. The IHPAC was extensively tested in an RC test-bed facility at

LBNL for energy efficiency, control of ventilation, and acoustic noise output, and suitability as a retrofit or new construction replacement for RCs. The results of these extensive tests have been presented in detail in a previous report (Apte et al. 2005).

- The laboratory testing procedure involved installation and verification of the performance of an IHPAC system, and its comparison with a standard HVAC system having an efficiency of 10 SEER. Points of verification included checking that the physical characteristics of the IHPAC system are suitable for direct replacement of existing 10 SEER systems;
- quantitative demonstration of improved energy efficiency;
- reduced acoustic noise levels;
- quantitative demonstration of improved ventilation control; and
- verification that the system would meet temperature control demands necessary for the thermal comfort of the occupants.

Results indicated showed that the IHPAC met these goals. The IHPAC was found to be a direct bolt-on replacement for the 10 SEER system. Calculated energy efficiency improvements based on many days of classroom cooling or heating showed that the IHPAC system was about 44% more efficient during cooling and 38% more efficient during heating than the 10 SEER system. Noise reduction was dramatic, with measured A-weighed sound level for fan only operation conditions of 34.3 dB(A), a reduction of 19 dB(A) compared to the 10 SEER system. Similarly, the IHPAC stage-1 and stage-2 compressor plus fan sound levels were 40.8 dB(A) and 42.7 dB(A), reductions of 14 and 13 dB(A), respectively. Thus, in these tests the IHPAC was 20 to 35 times quieter than the 10 SEER systems depending upon the operation mode. The IHPAC system met the ventilation requirements and was able to provide consistent outside air supply throughout the study. Indoor CO_2 levels with simulated occupancy were maintained below 1000 ppm. Finally temperature settings were met and controlled accurately. The goals of the laboratory testing phase were met and the system was found to be acceptable and ready for further study in a field test of occupied RCs.

This report summarizes and evaluates the data from the field test of the IHPAC system. The objectives of the field study were to evaluate the energy, ventilation, and IEQ performance of the advanced HVAC system when deployed in occupied classrooms and to perform a highly visible demonstration of the system. Although highlights of study methods are presented here, a detailed field study design and methods description has been reported (Apte et al. 2004) and should be referred to for complete information on how the field study was conducted.

During this field study some parameters ware measured in real-time (continuously or every 1 to 30 minutes) and periodic measurements (once per season) are made for other parameters. Parameters measured in real time include indoor and outdoor temperature and humidity, HVAC power, and indoor and outdoor carbon dioxide concentrations. Parameters measured periodically include: concentrations of formaldehyde and other volatile organic compounds, particle concentrations, noise levels, and ozone concentrations.

The objectives of the data evaluation include quantifying how the advanced HVAC system influences: a) ventilation rates; b) pollutant concentrations; c) noise levels; d) HVAC operation periods; e) HVAC energy use; and f) thermal comfort.

Methods

Field Study Plan

The IHPAC system was installed in six relocatable classrooms, called intervention classrooms. Six matched control classrooms were also selected. The control classrooms were matched with intervention classrooms by location (school), grade level, manufacturer, and classroom age. Each intervention RC was located exactly next door to a control RC. In addition to the six RC pairs, an additional four RCs were equipped with an IHPAC at the same school sites, but were studied less intensively. Instrumentation systems were installed in each intervention and control classroom and HVAC energy performance and IEQ were monitored over an entire school year. The benefits of the advanced HVAC system have been quantified by comparing the measured data from the intervention and control classrooms. The field study monitored the RCs for over 12 months, and site visits for detailed IEQ monitoring were completed in four seasons.

School Recruitment

Criteria for school selection were based upon climate, and geography. Northern and Southern California locations were selected for broader representation of the state. The San Joaquin Valley was selected for cold winter and hot summers, and the San Bernardino Valley was selected for the high cooling demand and long cooling season. Schools were selected and recruited for this study in early 2004. Recruitment of participant schools was accomplished through two mechanisms. In the case of the Modesto City Schools in Northern California, we contacted the Facilities Manager directly, as LBNL had previously conducted research in the district and had a working relationship with them. In the case of San Bernardino, Geary Pacific Corp., the California Distributor of Bard HVAC equipment provided a list of potential school districts in the Southern CA region to LBNL. Contact letters were sent to a number of school district facilities managers in the region and site visits were conducted at those districts that expressed interest in participating. The Fontana Unified School District was found to meet the needs of the study and was therefore selected. Principals from two schools in each district were contacted with the assistance of their facilities managers, and were found to be willing to host the research in their schools.

RCs in each school were assessed for their potential to be studied as a set where some would be used as controls and others would receive the HVAC system upgrade with the advanced systems. Each school had to have a group of RCs, preferably sited in a row, equipped with 10 SEER Bard HVAC systems, and in at least pairs with the same year of manufacture. It was preferred that the RCs were at most 10 years old. Additionally if they had a known or suspected IAQ problem they would not be acceptable.

Improved HPAC system installation and RC HVAC commissioning

Ten IHPAC systems were shipped from Bard Corporation's factory to Northern and Southern CA branches of Geary Pacific Corp. Geary Pacific installed, with the assistance of local HVAC contractors, the HVAC systems and associated ducting, registers, and controls in all ten study RCs. Geary Pacific also commissioned the advanced systems and re-commissioned the existing HVAC systems in the matched control RCs. Commissioning included setting of the outdoor air supply rates at 465 CFM (equivalent to 15 CFM per occupant), replaced air filters, balanced supply registers, and verified proper functioning of controls.

The IHPAC systems were equipped with standard 2 inch pleated panel filters (MERV rating 7, ASHRAE 52.1 efficiency 25-30%, see ASHRAE 1992). The 10 SEER systems were equipped with the standard 1 inch filter typically supplied with these units (ASHRAE 52.1 arrestance 70-75%, MERV rating 1-4, efficiency <20%). New filters were installed at the beginning of the study and replaced every 30 days.

HVAC Control Systems

The HVAC systems in the Control RCs were left for the teachers to operate using the existing standard thermostat coupled with an existing standard twist-type four-hour shutoff timer. The operation of this thermostat is entirely under the control of the teachers, and sometimes the school custodians at the beginning or end of the day. The thermostat has an automatic mode where it heats or cools according to setpoint, providing ventilation and air circulation only when thermal conditioning is required. An additional manual setting on the thermostat allows the teacher to turn on the fan independently if desired, allowing for continuous ventilation. However, as discussed above, this option is seldom used consistently due to the additional noise produced when the air supply fan is operating. The expectation in leaving them “as-is” is that the thermostats in the Control RCs would be used in the typical fashion during the study, and that they would follow their school district policy for HVAC operation.

In the RCs equipped with the IHPAC systems, an automatic “smart controller” was provided. Bard Manufacturing developed this controller for the IHPAC system as part of this project. It was designed to relieve the responsibility of the teachers of the majority of HVAC operation tasks. Additionally, it decouples the ventilation and thermal aspects of control through the use of an internal infrared motion-detector-type occupancy sensor that triggers ventilation whenever occupants are detected. The teacher’s control interface is limited to a simple temperature setting adjustment, using up-arrow and down-arrow buttons to provide a locked indoor temperature range (field settable by a technician, and set to ±4.0ºF (2.5ºC) in this study) in order to accommodate individual comfort differences. The occupancy sensor logic is set to wait 30 minutes after the last observed motion in the RC before setting back the temperature and shutting down the ventilation. It is also desensitized to very short (i.e., one-minute) detection of motion to avoid unneeded operation, but triggers HVAC operation as soon as a valid occupancy is detected. Finally, the system is designed to learn the classroom occupancy schedule over a moving two-week period, and then start anticipating occupancy by pre-conditioning the RC to the settings learned from the teacher’s temperature control use patterns. Pre-conditioning also includes a pre-occupancy ventilation purge of three air changes (roughly one hour) as required by California Title 24. An additional benefit of this control system is that it has a digital electronic interface configured to operate on a LonWorks (www.echelon.com) network, allowing remote access for monitoring and control of all of the thermostat and HVAC functions.

Instrumentation and Monitoring

The instrumentation used in this field study is shown in Table 1. Real-time data were stored as 6-minute averages or totals. Real-time data included total RMS power consumption and indoor and outdoor temperature, RH, and CO2 concentrations. Total RMS power consumption was measured on each HVAC system using WattNode™ (Continental Control Systems, Boulder CO, www.wattnode.com) power meters. Indoor and outdoor temperature, RH, and CO_2 concentrations were measured for each RC continuously. Indoor and outdoor particle, aldehydes, VOCs, and ozone concentrations in the RCs were monitored once a season during site visits. Classroom acoustic noise was measured during occupied and unoccupied periods with the HVAC operating during the seasonal site visits in each RC.

Indoor and outdoor temperature and RH were monitored primarily using the sensors in the PureChoice Nose™ (PureChoice Inc., Lakeview, MN). This device is connected to an i.Lon 100 network, and was accessible on the Internet by the researchers 24 hours a day.

CO_2 was measured using two different systems: the Fuji ZPF-9 and the PureChoice Nose™ CO_2 sensor. The Fuji ZPF-9 has been used by LBNL for many years as a standard method in buildings. In this study a PureChoice Nose™ CO_2 sensor was also installed in each RC. The sensors differ in stated accuracy, and the Fuji unit samples with a pump, while the PureChoice sensor samples using gas diffusion. The PureChoice sensor was factory-calibrated and expected to maintain accuracy specifications for five years. The Fuji units was calibrated at least once a season during site visits and an automatic calibration check system was run *in situ* once a week. Both systems were connected to the i.Lon 100 network and were accessible on the Internet by the researchers 24 hours a day.

Site visits to the schools occurred once per season (May 2005, early September 2005, late November 2005; and February 2006) in order to check and calibrate instrumentation, to characterize indoor and outdoor concentrations of particles, VOCs, aldehydes, and ozone, and to conduct acoustical measurements. Classroom ventilation rates were measured during unoccupied periods using CO_2 decays. Real-time data from the particle, sound level meter, and thermal comfort (TC) carts were downloaded onto a laptop computer for subsequent analysis. CO_2 decay data was monitored using the existing monitors installed in each RC. Similarly, the VOC, aldehyde, and ozone sampling media were transported to LBNL for subsequent laboratory analysis.

Measurements of air supply and ventilation

Outside air supply flowrates and supply register flowrates were measured using an active flow hood method (Walker et al. 2001) developed at LBNL. The same process was applied to measure the outside air intake flow and the return flow. Outside air supply rates (outside air is about 30% of the total supply air in this recirculating system) was set to 15 CFM per occupant, or 465 CFM for a class of 30 students and one teacher. The three supply registers were balanced to split the total supply flow equally (about 500 CFM per register).

RC air exchange rates have been measured using a tracer decay method. CO_2 decays were be measured with the installed CO_2 monitors, and the air exchange rate was calculated after subtracting the outdoor CO_2 concentration. During seasonal site visits, additional CO_2 decays with the HVAC system ventilation fans on were conducted. This was achieved by injecting CO_2 from a cylinder into the unoccupied rooms until a concentration of approximately 2000 ppm was reached. After allowing the CO_2 to decay to background levels, the air exchange rate was calculated as the negative slope of the natural logarithm of the indoor minus outdoor tracer concentration during the tracer decay (ASHRAE 2005).

Energy Modeling

Classroom energy modeling was conducted in order to assess the energy savings potential of the IHPAC system. Monitored HVAC energy consumption in the sixteen classrooms, as well as indoor and outdoor temperature and humidity measurements provide the basis for calibration of the portable classroom energy model. The model was fashioned after the previous work of Rainer et al (2003) using DOE-2 version 2.1E (Buhl et al 1993). The fine details of this model are beyond the scope of this report, however a DOE-2 input file is available upon request. All RCs and their operating schedules modeled were identical with the exception of the HVAC system – either the 10 SEER or IHPAC. Classrooms of the two system types were always located side by side in the same row of classrooms, so energy loads from environmental conditions were very well matched.

The 1-minute averaged data collected in the field from all of the classrooms were averaged up to 1-hour for modeling purposes since DOE-2 operates at this time step. For the 10 SEER classrooms the average hourly indoor temperatures collected from the indoor Nose sensors during occupied school hours were used as setpoint values. In the case of the IHPAC classrooms the Viconics thermostat temperatures available via the LonWorks network were used for the setpoint value as these were exactly the temperatures that the thermostat used for control. These setpoints were scheduled into the DOE-2 run deck to simulate loads as close as possible.

Weather files for DOE-2 input were developed for both climate zones. Measured hourly average outdoor temperature and RH were used. Solar data in RAW form (unpacked DOE-2 weather data file format) for monitoring network sites closest to the Modesto and Fontana schools were purchased from Western Regional Climate Center of the Desert Research Institute and converted to the DOE-2 input format and merged into the data files.

Energy performance data for the 10 SEER and IHPAC units used in the DOE-2 models were provided by Bard Manufacturing. These data are published in Bard's specification sheets and include energy cooling and heating capacities, energy efficiency ratios, and part load curves (Bard Mfg 2006, 2007).

Once assembled, the DOE-2 model was run for each of the ten IHVAC and six 10 SEER units in the field. Due to DOE-2 schedule capacity constraints, the models were run four times; once per season for about 6 weeks of each period. Hourly energy consumption predictions for each 6-week period of each season for each classroom were inspected. As discussed below, the results of the modeling were varied. Some periods of model-to-measured comparisons show very close correspondence, while other periods have poor correlation.

Two parameters appeared to have the greatest influence on whether the model and measured data would agree – solar data and occupancy schedule. Visual model output inspection was ultimately used as confirmation that the model's simulation accuracy was adequate in order to consider it sufficiently calibrated for California climate zone and national energy savings estimates.

Results

Carbon Dioxide Concentrations

Indoor CO_2 concentrations in the intervention and control RCs during the study, are presented in Tables 2 and 3, for Northern and Southern California, respectively. Plots of indoor CO_2 concentration distributions by season for all intervention and control RCs are provided in the Appendix (Figs A-1 to A-4). The annual average schoolday indoor-outdoor CO_2 concentrations, across all intervention and control classrooms, were 250±100 ppm and 660±330 ppm, respectively. Likewise, the average outdoor CO_2 concentration was 370±20 ppm. Indoor annual averages in the Northern California classrooms were 220±90 ppm and 520±450 ppm for intervention and controls, respectively. In Southern California RCs the annual average concentrations were 280±110 ppm and 630±370 ppm for intervention and controls, respectively

In Northern California the intervention classrooms' schoolday average indoor-outdoor CO_2 concentrations ranged from a low of about 120±120 ppm to a high of 340±240 ppm. The lowest averages were observed during the Winter 2005 without exception while the highest classroom averages mostly occurred during Fall 2005. The control classroom indoor-outdoor CO_2 concentrations ranged from a low of about 240±320 ppm to a high of 1400±680 ppm. Again, the lowest seasonal concentrations occurred during Winter 2005.

In Southern California the intervention classrooms' schoolday average indoor-outdoor CO_2 concentrations ranged from a low of about 120±110 ppm to a high of 560±570 ppm. No observable seasonal trend was identified in intervention classroom CO_2 classrooms. The control classroom indoor-outdoor CO_2 concentrations ranged from a low of about 140±230 ppm to a high of 1400±110 ppm. The lowest seasonal concentrations occurred during Summer 2005.

The maximum 99th percentile seasonal indoor-outdoor CO_2 concentrations in intervention classrooms were 950 ppm (classroom 24) and 3000 ppm (classroom 13) in Northern and Southern California, respectively. Similarly, the 99th percentile concentration differences for control classrooms were 3700 ppm and 4300 ppm for Northern and Southern California classrooms.

Measured Ventilation Rates

Tables 4 - 6 present measured outside airflows, supply airflows, and ventilation rates for the classrooms for spring, summer, and fall visits. Flow rates as found, and after adjustment where needed, are provided. Table 4 shows the 10 SEER HVAC system data. Unadjusted outside air supply rates as found in the spring visit to Northern CA RCs 21, 23, and 26 ranged from 128 to 260 CFM. These were adjusted to the highest setting achievable for the units, with rates of 230 and 275 CFM. This was below the target of 480 CFM. The Southern CA classrooms 14, 16, and 36 had outside air supply rates initially ranging from 256 to 377 CFM during the spring visit. These were adjusted to achieve the target. Only classroom 36 had the ability to achieve the setting, while rooms 14 and 16 rates were low.

With the exception of classrooms 21 and 14, the outdoor air supply rates between seasonal visits was reasonably stable. The rates in room 21 dropped significantly from 242 CFM in the spring to about 100 CFM in the fall and about 150 CFM in the winter. Similarly the spring rate of 428 CFM in classroom 14 degraded to below 100 CFM in the following summer and fall.

Total supply flows measured during the spring visit for the 10 SEER classrooms (Table 4) as measured as the sum of supply register flows (S1+S2) ranged from below 700 to almost 1200 CFM, with Room 16 having the lowest fan output. This can be compared with the rated total supply flow for the 4 ton 10 SEER unit of 1550 CFM (with wet coil at 0.2" H_2O static pressure, Bard 2006). The supply register flows in the 10 SEER rooms were reasonably well balanced, with room 26 having the greatest imbalance, a relative flow difference of about 20% between the two registers.

Measured air exchange rates in the classrooms were conducted with outside air fan on during a CO_2 decay during an unoccupied period with door and windows closed. For purposes of comparison, a room with volume of 9120 ft^3 (24' by 40' by 9.5' high) and an outside air supply rate of 480 CFM would have an air exchange rate of about 3.2 h^{-1}. As seen in Table 4, measured air exchange rates in the 10 SEER classrooms ranged from a low or 1.2 h^{-1} to a high of 4.0 h^{-1}. Across seasons the average air exchange rates 1.6±0.6 h^{-1} to 3.7±0.4 h^{-1}. The northern CA classrooms had lower air exchange rates than those in the south, but the difference was only marginally significant ($p = 0.06$, Students t test).

The IHPAC classroom ventilation rate measurement data are shown in Tables 5 (Northern CA) and 6 (Southern CA). As can be seen from the data, after initial adjustment to close to 480 CFM during the spring visits the outside air settings varied little across the seasons, with only a few exceptions. The flow rate drift between seasons observed in northern CA units that did need adjustment was nearly always downward, with a maximum drift of about 90 CFM between spring and summer measurements. Similar drift patterns were seen in a few southern CA units across seasons (Table 6), about equally split between downward and upward changes. The greatest upward change was seen in Room 13 where the rates had dropped and were adjusted in the summer, and then increased and had to be lowered in the fall, with the stage 2 setting having increased by 128 CFM. This was atypical of the units, whose rate changes ranged from about -80 CFM to +80 CFM.

Register balance among the three supply diffusers were reasonably stable and consistent across season. The Tables clearly show the increasing total supply rate from fan only, to Stage 1 to Stage 2 compressor operation, while the outside air remained relatively constant. The measured return rates also indicate this ramped supply rate.

Again, the target air exchange rate was 3.2 h^{-1}. The classroom air exchange rate for Northern CA averaged across seasons ranged from 2.5±0.1 h^{-1} to 3.6±0.4 h^{-1} (average = 3.0±0.4), and for Southern CA ranged from 2.4±1.0 h^{-1} to 4.0±0.1 h^{-1}(average = 3.3±0.6). The northern and southern classrooms air exchange rates were not different statistically ($p>0.05$).

Acoustic Levels

Sound pressure (noise) levels were measured in each classroom, unoccupied, in at least two seasons. Tables 7 and 8 present noise levels at the standard distance of 10 feet normal to the center of the return plenum grille and 5 feet above the floor with classroom lights on. Tables 9 and 10 contain the same data background adjusted to a 25 dB(A) for better comparisons between

HVAC units. As shown in Table 7, average of the three season measured unadjusted noise levels in 10 SEER classrooms ranged from 40.2±2.3 to 52.4±3.2 dB(A) in fan only mode, while the range was 51.3±1.6 to 55.3 dB(A) when both fan and compressor was running. As seen in Table 8, the similar ranges for the IHPAC were 38.2±0.6 to 40.7±1.1 dB(A), 41.1±3.2 to 46.8±2.1 dB(A), and 44.0 to 48.2±1.8 dB(A) for fan only, fan and stage 1 compressor, and fan and stage 2 compressor operation, respectively. In the both 10 SEER and IHPAC classrooms no systematic trend of changing sound pressure output of the systems appeared across the seasonal measurements. Variability in measured sound levels across the seasons was small, indicating that the noise output was stable within the school year of the study.

After normalization of the sound pressure levels in the classrooms to a 25 dB(A) background the levels dropped somewhat in all cases. As seen in Table 9, the highest average of season levels were 52.3±3.1 dB(A) and 55.2±0.7 dB(A) for 10 SEER fan only and fan and compressor, respectively. Likewise, as shown in Table 10, the highest levels for the IHPAC were 39.6±0.7 dB(A), 46.8±2.1 dB(A), and 48.2 dB(A) for fan only, fan and stage 1 compressor, and fan and stage 2 compressor operation, respectively. Again, no systematic trend is observed in the noise output of the HVAC systems.

Figures A-5-to A-7 (see Appendix) provide additional information on the acoustics of the HVAC systems, showing octave band sound pressure level spectra from 63 Hz to 8 kHz during the spring, summer, and fall season field visits measured at the standard position. These plots also provide noise criteria (NC) level curves for direct interpretation of the NC in the classrooms (ASHRAE 2005). Figures A-8 to A-10 (see Appendix) show the noise levels in different classroom locations starting from the standard position normal to and 10 feet from the return plenum, at a 45-degree angle and 10 feet from the return, and at 20 feet and 30 feet from the return. Figures A-8 to A-10 show the HVAC system noise levels under the different operating conditions, fan only and fan and compressor modes.

VOC and Aldehyde Concentrations

VOC and aldehydes samples were collected in the classrooms during each site visit (see Methods report, Apte et al. 2004). The GC-MS was calibrated for a wide range of compounds typical of indoor environments. Concentration data for IHAPC and 10 SEER classrooms, averaged across the two school districts, both by season and across the three seasons' measurements are presented in the sections below. A subset of compounds of particular interest due to their odorous or toxic nature has been extracted from the entire VOC dataset for the purpose of comparison of indoor conditions in the two classroom types.

Table 11 lists a set of compounds that have low odor thresholds (Devos et al. 1989, and AIHA 1989) and/or are listed as chronic reproductive toxin or carcinogens by the State of California's Proposition 65 (State of California 1986), and/or are listed by the California Environmental Protection Agency for their chronic toxicity (OEHHA 2005), or are listed by the U.S. Environmental Protection Agency as Hazardous Air Pollutants (USEPA 2005). These chemicals are representative of portable classrooms. Due to their relevance to classroom occupants, these compounds were focused on in this study.

VOC Concentrations

Tables 12 - 14 present results of measured indoor and outdoor VOC concentrations in the spring, summer, fall monitoring visits, respectively, aggregated separately across the IHPAC and 10 SEER classrooms. Table 15 presents the three measurement period average of these data, again for the IHPAC and 10 SEER rooms. Figure 1 shows the relative average concentrations of the selected list of compounds in the IHPAC and 10 SEER classrooms, and outdoors. Note that the GC-MS analysis of a few of the compounds yielded slightly negative concentrations, as shown in the tables and figures. These should be interpreted as zero values. Figure 2 shows the ratio of average indoor IHPAC to 10 SEER VOC concentrations. The ratios range from zero to 0.86 with an average of 0.43, suggesting that on average, concentrations of odorous and toxic VOCs in the IHPAC classrooms were less than half of those in the 10 SEER classrooms.

Aldehyde Concentrations

Tables 12 - 14 present results of measured indoor and outdoor formaldehyde and acetaldehyde concentrations in the spring, summer, fall monitoring visits, respectively, aggregated separately across the IHPAC and 10 SEER classrooms. Table 15 presents the average of these data, again for the IHPAC and 10 SEER rooms. Across all rooms and all year, average concentrations of formaldehyde were 16±7.9 and 24±6.5 $\mu g\ m^{-3}$ for the IHPAC and 10 SEER classrooms, respectively. Similarly, average concentrations of acetaldehyde were 7.8±4.3 and 12±5.2 $\mu g\ m^{-3}$. The maximum concentrations of these compounds were 38 $\mu g\ m^{-3}$ and 35 $\mu g\ m^{-3}$, and 16 $\mu g\ m^{-3}$ and 21 $\mu g\ m^{-3}$ for the IHPAC and 10 SEER rooms, for formaldehyde and acetaldehyde, respectively. From Figure 2, the average concentrations of both acetaldehyde and formaldehyde in the IHAPC classrooms were about 65% of those in the 10 SEER classrooms.

Particle Matter Concentrations

Particle concentrations are presented as schoolday averages of the real-time data collected by the optical particle counters (see Table 1). Tables 16 - 19 present the schoolday average, standard deviation, first percentile, and 99th percentile size-resolved and bin total PM mass concentrations for each classroom and outdoors and each season's field sampling campaign. A few classroom-sampling periods were missed over the study duration due to instrument failure. Particle mass was calculated assuming a density of 1 g cm^{-3}. $PM_{2.5}$ concentrations are approximate, being the sum of the lower five particle size bins. Figure 3 summarizes the average approximate $PM_{2.5}$ concentrations and their range for each classroom and outdoors.

A comparison of the 10 SEER and IHPAC average $PM_{2.5}$ data for paired side-by side classrooms indicates no evidence that concentrations of particle matter were influenced by the type of HVAC system present, the concentrations in the two types of classrooms not being statistically different (Student's paired two sample for means t-test, p=0.81). The schoolday average (± standard deviation) $PM_{2.5}$ concentrations across all 10 SEER and IHPAC classrooms and seasons were 13.7±6.3 $\mu g\ m^{--3}$ and 15±9.1 $\mu g\ m^{--3}$, respectively. Likewise, the outdoor average concentration was 22±18 $\mu g\ m^{-3}$, slightly higher than those indoors. Particle concentration data may be reviewed in greater detail in Tables 16=19.

Particle mass concentrations were highest in the 2.0 µm and 5.0 µm size bins as expected. The ratio of the sum particle mass in the 0.3 µm to 2.0 µm bins (approximate $PM_{2.5)}$ to the sum mass concentration of all six bins is an indicator of the relative fine and course fractions of particle matter in the classrooms, or in the outdoor air. The ratios across seasons by HVAC groupings for the 10 SEER and IHPAC classrooms were 0.32±0.06 and 0.32±0.09, respectively. Similarly, the ratio for outdoor air averaged across all sites was 0.46±0.07. The size ratios by classroom types were virtually identical, whereas that of the outdoor air was different (statistically significant, Student's t-test, p=0.01).

Thermal Comfort

Thermal comfort (TC) measurements in occupied classrooms according to ASHRAE Standard 55 (ASHRAE, 1992, 1995) were accomplished during each field measurement visit using the LBNL thermal comfort carts. Although only two TC carts were available, an attempt was made to collect data in as many classrooms as possible during a morning and afternoon period. This involved moving the carts between classrooms at recess and lunch breaks, often moving the carts from one school in a study district to the other. Logistics notwithstanding, much TC data were collected. Figures 4 - 6 report AM and PM measurement periods in the classrooms, including averaged temperature and relative humidity and the percent of time that, according to ASHRAE Standard 55, that TC would be acceptable. This latter variable is reported in the case where measured air velocity was included in the model, and that where it was excluded. Further details of these measurements may be found in the Appendix, Table A-1.

As shown in Figure 4, TC cart data show that springtime indoor average AM temperatures ranged from about 21.1 ºC to 24.7 ºC and 21.0 ºC to 22.1 ºC for the 10 SEER and IHPAC classrooms, respectively. Similarly, afternoon average temperatures ranged from 22.8 ºC to 23.4ºC (10 SEER) and 20.8 ºC to 22.5 ºC (IHPAC). Relative humidity ranged from about 50.5% RH to 58% across both 10 SEER and IHPAC classrooms. Given the measured springtime thermal conditions in the classrooms acceptable thermal comfort by the ASHRAE definition was often unmet in either 10 SEER or IHPAC. The 10 SEER classrooms in Southern California, 14, 16, and 36, and IHPAC classroom 35, had acceptability 67 to 100% of the afternoon time period (model excluding air velocity). Classroom 36 also met the TC acceptability criterion in the AM period.

Summer TC cart data (Figure 5) show that average AM temperatures ranged from 21.5 ºC to 25.3 ºC and 20.2 ºC to 21.4 ºC in the 10 SEER and IHPAC classrooms, respectively. Afternoon average temperatures ranged from 23.2 ºC to 26.7 ºC and 20.0 º to 24.9 ºC in these respective classroom types. Average indoor relative humidity levels ranged from about 39% up to 67%. ASHRAE Standard 55 TC was much more often acceptable in the 10 SEER classrooms, however the large portion of schoolday TC conditions did not meet the standard's criteria.

Fall TC cart data (Figure 6) show that average AM temperatures ranged from 16.2 ºC to 22.3 ºC and 17.8 ºC to 20.1 ºC in the 10 SEER and IHPAC classrooms, respectively. Afternoon average temperatures ranged from 22.0 ºC to 23.6 ºC and 20.7 º to 23.0 ºC in these respective classroom types. Average indoor relative humidity levels ranged from about 34% up to 62%. ASHRAE Standard 55 TC was almost never acceptable in any of the classrooms.

In addition to TC cart measurements, temperature and relative humidity data were collected in real time during the entire study period from January 2005 on. Indoor and outdoor schoolday hour statistics from these data are provided in Tables 20 and 21. Average temperature and RH data are graphed for easy interpretation in Figures 7-10.

As seen in Figure 7, average northern California classroom indoor temperatures in the 10 SEER and IHPAC were quite different. Spring and Summer 10 SEER temperatures were about 2.5 ºF warmer than in the IHPAC, on average. Winter and fall average temperatures were 1-2 ºF lower in the 10 SEER classrooms. In all seasons, the variability in average indoor temperatures was much greater in the 10 SEER classrooms.

As shown in Figure 8, Southern California 10 SEER classrooms were about 2 to 4 ºF warmer on average in the spring, summer, and fall and just slightly cooler in the winter. As in the North, the 10 SEER average classroom temperatures were more variable.

Northern California indoor RH (Figure 9) in the winter and spring were higher by 3 to 6 percent in the 10 SEER classrooms, and lower by about 5 percent in the summer. Average RH in the fall was approximately the same in classrooms of both HVAC types. In southern California average indoor RH (Figure 10) was always lower in the 10 SEER classrooms with a difference of as much as about 8 percent in the summer. As with temperatures, the variability in average RH levels was greater in the 10 SEER classrooms.

Energy Consumption

Daily HVAC energy consumption statistics for Northern and Southern California classrooms are presented in Table 22. Figures 11-15 are box and whisker plots that show the distributions of daily HVAC energy consumption for IHPAC and 10 SEER systems during the winter 2004, and spring, summer, fall, and winter 2005, respectively. These plots show the median, first and third quartile, and minimum and maximum measured daily energy consumption.

In Northern California, measured daily average electric energy consumption was about 2.7±1.1 kWh and 3.4±0.6 kWh for the 10 SEER and IHPAC systems, respectively. Similarly, average daily Southern California energy consumption across all seasons was about 3.0 kWh and 3.4 kWh for the 10 SEER and IHPAC systems, respectively.

Northern California Fall, spring, summer, and Winter 10 SEER daily energy consumption were about 2.3±0.7, 2.5±1.2, 4.8±3.3, and 1.8±0.2 kWh, respectively. Southern California Fall, spring, summer, and Winter 10 SEER daily energy consumption were about 2.7±1.1, 2.7±1.0, 6.6±3.2, and 1.2±0.5 kWh, respectively. Similarly, Northern California Fall, spring, summer, and Winter IHPAC daily energy consumption were about 2.7±0.7, 3.2±0.7, 5.6±2.2, and 2.7±0.3 kWh, respectively. Southern California Fall, spring, summer, and Winter IHPAC daily energy consumption were about 3.2±0.9, 3.2±0.8, 6.2±1.8, and 1.8±0.3 kWh, respectively.

Finally, across both climate zones the year average daily average energy consumption was 2.9±0.9 kWh and 3.4±0.7 kWh for the 10 SEER and IHPAC systems, respectively. The fall, spring, summer, and Winter 10 SEER daily energy consumption averages were about 2.9±0.9, 2.6±1.0, 5.7±3.0, and 1.5±0.4 kWh, respectively. Lastly. Fall, spring, summer, and Winter IHPAC daily energy consumption averages were about 2.9±0.7, 3.2±0.7, 5.9±1.9, and 2.2±0.5 kWh, respectively.

HVAC Component Operation Modes

Tables 23 and 24 present, for each classroom, data on the average percent of time that HVAC systems operated in various component modes: off, supply fan only, and compressor plus fan operation. “School hours” in the Tables refer to standard schedule hours of Monday-Friday from 7:30 AM to 3:00 PM. Operation of the 10 SEER systems was triggered by thermostat setting and a 4-hour twist timer; if the system was not activated, HVAC operation would not occur. The IHPAC was operated by a more complicated system that automatically provided a one-hour pre-occupancy ventilation purge, and pre-occupancy conditioning that anticipated the classroom schedule, and had an occupancy override that turned on the system supply fan on sensing arrival of occupants. The occupancy sensor guaranteed ventilation as long as occupants were detected and provided a 15-minute time-to-shut-off when the classroom was vacated. Monitored energy use patterns showed distinct IHPAC system off-times during recess and lunch hour periods.

The 10 SEER systems have only one compressor mode while the IHPAC compressor has two stages. These detailed data are summarized in Tables 25 and 26. On average, across the entire school year, the 10 SEER systems were turned off during school day hours 77% and 53% of the time in Northern and Southern California, respectively. In comparison, the IHPAC system was turned off 25% and 24% of the time, respectively, during the same time periods. 10 SEER system fans were turned off most frequently during the winter and least frequently in the summer in both climate zones. Interestingly, the opposite was observed for the IHPAC systems, where the fan was turned off most frequently in the summer and least in the winter.

As seen from Table 25, 10 SEER compressor use frequency was greatest during the summer in both Northern (34%) and Southern (41%), and the least in the winter (north: 9%; south 4%). IHPAC stage 1 compressor use varied little in either climate zone, with an average of 30%±22 in the north and 19%±3% in the south. Compressor stage 2 varied more with greatest use in the summer (north: 22%; south 31%) and winter (north: 4%; south 2%).

Energy Modeling

DOE-2 Model Calibration

Figures 16 and 17 show selected weekly sequences of measured hourly average indoor temperature and hourly HVAC energy use. DOE-2 predicted indoor temperatures and energy use for the same time periods for 10 SEER classrooms (Figure 16) and IHPAC classrooms (Figure 17) is plotted for comparison. The data shown are typical weeks of HVAC operation chosen from each season during the study, although not all predicted days agree as well as those shown. The degree to which measured data and modeled results depend upon the accuracy of correspondence between the true and modeled occupancy and operation schedules, and upon the degree to which the solar radiation data used for the DOE-2 models agree with the true hourly total and horizontal solar radiation incident on the classrooms.

As can be seen in both Figures16 and 17, the basic shape, and trend, and magnitude of modeled 10 SEER and IHPAC energy load in each season is relatively good correspondence with the measured data. The thermostat setting estimate that is derived from measured data drives predicted indoor temperature during occupied hours. During unoccupied hours the temperature is allowed to swing based on thermal balance driven by external loads. The predicted indoor temperature does not track the measured values consistently during unoccupied hours.

As discussed in the Methods Section, the purpose of the DOE-2 – measured data comparisons is to assess the calibration of the model; i.e., degree to which the DOE-2 building model and HVAC parameters correctly predict energy use. With the models calibrated, it is possible to run them for different climate zones.

DOE-2 model results – California Climate Zones

Table 27 presents the predicted annual energy use of the 10 SEER and IHPAC equipped classrooms across all sixteen California climate zones (CEC 2004). The table has the results broken out by heating, cooling, and fan consumption components. It provides model results for continuous ventilation during classroom occupancy and for both systems as well as intermittent ventilation on compressor cycling for the 10 SEER systems. Annual predicted heating energy demand ranged from 126 (CZ 7) to 1727 (CZ 16) kWh for the 10 SEER classrooms and between 60 (CZ 7) to 1127 (CZ 16) kWh for the IHPAC classrooms. Annual cooling energy ranged from 17 (CZ 1) to 1258 (CZ 15) kWh in 10 SEER classrooms vs. 23 (CZ 1) to 787 (CZ 15) kWh in IHPAC rooms. Predicted fan energy ranged from 973 (CZ 7) to 1593 (CZ 15) kWh for the 10 SEER classrooms and 748 (CZ 1) to 1005 (CZ 14) kWh for the IHPAC classrooms. Figure 18 compares energy consumption for the 10 SEER and IHPAC classrooms for Oakland (CZ 3), Burbank (CZ 9), and Sacramento (CZ 12) using continuous ventilation.

Using the 10 SEER unit with continuous operation during occupancy as the reference, total annual energy savings per classroom using the IHPAC system in the 16 climates zones range from about 570 to 1300 kWh, average 880±220 kWh. On average this is a 39%±2% energy saving, ranging from 36% to 42%. Assuming electricity costs of $0.15/kWh, the range of savings is from about $85 to $195 per year per IHPAC system (Figure 19).

An estimated net incremental cost of $1150 per IHPAC unit relative to the 10 SEER product was provided by Bard (Tiernan 2006) based on the relative unit list prices minus the incremental cost of the R410A refrigerant used in the IHPAC. Simple payback estimates for the California climate zones were calculated by dividing annual energy savings into the net incremental cost. Figure 20 shows the sixteen climate zones, energy cost savings and simple payback. At the $0.15/kWh cost of electricity, simple payback times (shown in parentheses in Figure 20) range from six years in CZ 16 to 13 years in CZ 7.

The 10 SEER classrooms operated with intermittent ventilation (Table 27) show lower fan energy use, as expected. For the classroom models used, the heating and cooling component energy benefits of intermittent fan use based on load were not large, and in some cases, due most likely to "economizer" effects, were negative.

DOE-2 model results – U.S. Cities

Table 28 compares component and total annual energy consumption for classrooms using the 10 SEER and IHPAC systems for 37 major cities in the United States. Again, the table has the results broken out by heating, cooling, and fan consumption components. It provides model results for continuous ventilation during classroom occupancy and for both systems. Annual predicted heating energy demand ranged from 28 (Miami) to 7272 (Anchorage) kWh and 13 (Miami) to 6481 (Anchorage) kWh for the 10 SEER and IHPAC classrooms, respectively. Likewise, annual cooling energy ranged from 18 (Anchorage) to 1467 (Miami) kWh in 10 SEER classrooms vs. 11 (Anchorage) to 871 (Miami) kWh in IHPAC rooms. Predicted fan energy ranged from 1006 (San Diego) to 1868 (Anchorage) kWh and 629 (San Diego) to 1163 (Anchorage) kWh for these different HVAC systems.

Total annual energy savings per classroom using the IHPAC system in the 37 Cities range from about 593 to 1667 kWh, average 1100±220 kWh. On average this is a 34%±6% energy saving, ranging from 16% to 44%. Assuming electricity costs of $0.15/kWh, the range of savings is from about $89 to $250 per year per classroom, depending upon the city.

Comparison of Nose CO_2 and Fuji CO_2 Data

Carbon dioxide measurements were made contemporaneously using both PureChoice™ Nose and the Fuji ZPF-9 sensors in thirteen of the sixteen classrooms in the study. Table 29 presents the results of least-squares linear regression of Nose and Fuji measurements collected from three one-week periods following Fuji calibrations conducted during Spring, Summer, and Fall field visits. The regression model is Nose (ppm) = Slope * Fuji (ppm) + Intercept. Figure 21 shows the paired data for all thirteen-sensor pairs. The “Shared” column in the table refers to whether the sampling line for a particular Fuji paired with that room’s Nose was multiplexed with another room or outdoors site. Multiplexed sampling lines switched between up to 3 sites on a six-minute sample cycle – the first three minutes of each locations data were dropped to accommodate instrument stabilization.

With the exception of one sensor pair (Room 25, using a shared Fuji sensor) the correlation coefficient (R^2) was greater than 0.95. The regression slope (m) was greater than unity in 8 of the pairs with three having $m \leq 1.10$; five of these had $m \leq 1.05$. Five sensor pairs had slopes less than unity, and all but one of these had $m \geq 0.95$. Intercepts were all positive, ranging from 13 ppm to 119 ppm.

Discussion

As discussed earlier, the objectives of the data evaluation were to quantify how the advanced HVAC system influences:

- Ventilation rates;
- Pollutant concentrations;
- Noise levels;
- HVAC operation periods;
- HVAC energy use; and
- Thermal comfort.

Ventilation, CO_2, and HVAC Operation Periods

Development of a system that would reliably provide adequate ventilation was a key goal of this project. As discussed above, only one of the six 10 SEER systems under test could not be adjusted to provide the 465 CFM (15 CFM per occupant * 31 occupants) of outside ventilation air required by state code and recommended in ASHRAE Standard 62.1. The IHPAC was found to be fully field-adjustable in the required ventilation supply range. However, the flow rate settings were observed to drift from their intentional setting over a period of months. Typically the drift was in the upward direction, which is the fail-safe direction in terms of meeting minimum ventilation requirements.

Air exchange rates measured by CO_2 decay during ventilation periods corroborate the relatively low ventilation provided by the classrooms using the 10 SEER system relative to the IHPAC. This is not particularly surprising since the HVAC fan provides the only significant ventilation in the classrooms; the windows were kept closed and infiltration through the portable classroom shell is relatively low.

Indoor minus outdoor (delta) CO_2 concentrations during occupied hours are a good indicator of how well occupant bioeffluents are being removed through ventilation. At 15 CFM per occupant, delta CO_2 reaches a steady-state concentration of about 700 ppm (ASHRAE, 2004). If observed concentrations are at or in excess of this level, and the concentration has not yet reached steady state, the ventilation rate must be less than 15 CFM per occupant. For example, if the school day average delta CO_2 concentration is >700 ppm, steady state values, if they were ever achieved would be higher since the average includes sub-steady-state concentrations.

Elevated CO_2 concentrations are a function of both inadequate supply of outside air and inadequate use of the outside air supply fan. As discussed previously, a number of reasons exist for low use of the outside air supply fan; of these, system noise and thermostat/control design are key. Teachers may decide to forgo space conditioning in order to avoid the mechanical noise levels created by the HVAC system. The thermostatic link to ventilation in the standard operating design of the 10 SEER system ensures lower than continuous ventilation except when conditioning demands are so great that the compressor remains on continuously.

In the case of the 10 SEER classrooms in this study, four of the six classrooms studied had delta CO_2 averages close to or in excess of 700 ppm for entirety of the study. In contrast, none of the IHPAC units had all-study average delta CO_2 concentrations near 700 ppm – the highest average was 410 ppm. Half of the yearlong 99th percentile delta CO_2 concentrations in the 10 SEER classrooms were well above 3000 ppm, and all of them were greater than double the 700-ppm target. In the IHPAC classrooms, 30% of the 99th percentile whole year values never exceeded 700 ppm, and 80% were below 850 ppm all but 1% of the time. Two of the IHPAC units, classrooms 13 and 35, in the Southern California SD reached 1600 ppm 1% of the time. In the case of room 13 this is due to 99th percentile levels of 3000 ppm and 1500 ppm, during the spring ’05 and summer ’05, respectively. In classroom 35 the spring and summer top 1% delta CO_2 concentrations were both 1700 ppm. Since both of these classrooms were capable of providing adequate ventilation for 31 occupants and the controller was designed to turn provide the ventilation during occupancy, and since both had very low average delta CO_2 concentrations, it is likely that the problem occurred due to a system malfunction that was corrected. In all IHPAC cases the peak CO_2 problems stopped occurring after summer ’05, probably due to correction of a brownout condition due to poor power distribution at the school.

The very high 99th percentile delta CO_2 values across seasons in the 10 SEER classrooms indicate that chronic peak levels in the thousands of ppb were occurring. The highest 99th percentile delta CO_2 levels, 4300 ppm, were observed in the Southern California SD in the winter season. Excluding summer, these peak values were regularly above 2000 to 3000 ppm.

The 10 SEER and IHPAC operation mode data show clearly why the IHPAC provided lower delta CO_2 concentrations throughout the year. The percentage of time that the fan or fan + compressor modes were activated were substantially lower with the 10 SEER than with the IHPAC. This was because the occupancy sensor triggered the ventilation fan in the IHPAC smart control system whenever the occupants were present. In the 10 SEER classrooms the teacher had to make a conscious decision to turn on the ventilation fan, or had to rely on the thermal cycling of the HVAC system to provide ventilation.

The above discussion provides evidence that the IHPAC systems in use provided the ventilation to the classrooms, as designed. It also corroborates earlier studies in portable classrooms where inappropriate ventilation control scheme coupled with the noise-related disincentive to use the system leads to excessive CO_2 buildup and poor overall ventilation. The fact that some excessive CO_2 peaks were still evident in some of the IHPAC classrooms is evidence that the system was not infallible, but the problems that came up were remedied by system adjustments.

Pollutant Concentrations

VOCs and Aldehydes

The gas phase compounds identified in the classrooms are typical of those seen in modular classroom construction (Hodgson et al, 2004). The measured results follow the logic that increased ventilation provides improved indoor air quality; the measured compounds were all substantially lower in the IHPAC classrooms. Formaldehyde is likely the compound that has received greatest concern in portable classrooms; as a registered Toxic Air Contaminant, an irritant and carcinogen, low concentrations are of importance. The formaldehyde Chronic Reference Exposure Level (REL) set by the California EPA is 3 µg m^{-3} (Cal/EPA 2003). Given the repeated daily schedule of students and teachers over many years, the chronic REL is an appropriate comparison to measured concentrations. However the value of 3 µg m^{-3} is very difficult to achieve and ambient levels may often be at this level. The acute REL for formaldehyde (Cal/EPA 1999) is 94 µg m^{-3} averaged over and 1-hour period. An intermediate 8-hour Acute REL level of 33 µg m$^{-3,}$ based on the acute REL 1-hr value has been published in a guideline by Cal EPA (Broadwin 2000, CalEPA/ARB 2004, Lam 2004).

If the intermediate acute 1-hour REL of 33 µg m^{-3} is used as a comparative value, average formaldehyde concentrations in the both the 10 SEER and IHPAC classrooms would be considered acceptable. However, this level was exceeded in at least one classroom with each type of HVAC system at least once.

It is interesting that the ratio of IHPAC to 10 SEER average formaldehyde concentrations was about 0.67 compared to the average across all of the VOCs discussed where the average was 0.43. Using ventilation for removal of formaldehyde from indoor emissions is not as effective as it is for many VOCs. This is due to the mechanism of natural diffusion of formaldehyde from materials. The rate of diffusion out of the materials is governed by Fick’s Law, which states that it is proportional to the concentration gradient at the surface of the material. With higher amounts of ventilation, the formaldehyde in the materials diffuses at a greater mass transfer rate, increasing the amount of the gas that is released into the air. This factor reduces the effectiveness of ventilation at formaldehyde removal. Source control and reduction as well as ventilation are needed to ensure that formaldehyde levels are as low as possible in classrooms. This can best be accomplished through careful material selection.

Acetaldehyde levels follow a similar pattern to formaldehyde in the classrooms studied. On average across the year of study the IHPAC classroom acetaldehyde concentrations were lower than the chronic REL (Cal/EPA 2003) of 9 $\mu g\ m^{-3}$, while the 10 SEER average concentrations exceeded that value. In the fall the IHPAC average also exceeded the chronic REL. Again, the chronic REL is rather restrictive for this compound and may be virtually impossible to meet on a consistent basis. Overall, the increased amount of ventilation provided by the IHPAC did lead to lower levels than those in the 10 SEER classrooms.

Octanal and pentanal, two carbonyl compounds with low odor thresholds (7 $\mu g\ m^{-3\ \text{and}}$ 2 $\mu g\ m^{3}$, respectively) were observed in the classrooms sometimes above the odor threshold. The year-long average 10 SEER classroom average pentanal concentrations were at the odor threshold, whereas the IHPAC average was many time lower (0.16 $\mu g\ m^{-3}$). Nonetheless, classroom types had some measurements of these concentrations above the odor threshold.

In general, VOCs are ubiquitous in the portable classroom environment, but were found to be generally lower when the IHPAC ventilation was provided.

$PM_{2.5}$

As discussed above, the HVAC system type did not affect PM2.5 concentrations. The IHPAC systems used in the classrooms, despite the upgrade to 2” pleated filters, did not employ particulate filters with sufficient efficiency to improve particle removal rates. Outdoor $PM_{2.5}$ concentrations were higher than those indoors, so dilution by additional ventilation air would not be expected to reduce the particle matter load in the classrooms. Although the indoor $PM_{2.5}$ concentrations observed in the classrooms in this study were not of great concern, this is not always the case (Daisey et al. 2003). Development of an improved filtration capability in the IHPAC would be of value in many classroom situations, particularly where the outside particle concentrations are of concern.

Since more outside air volume was provided to the IHPAC classrooms relative to the 10 SEER classrooms, more particle mass from outdoor air was entrained into these HVAC systems. If the two system types had the filters with the same particle removal efficiency it would stand to reason that more PM from outdoors would enter the IHPAC classrooms and they would have higher indoor PM concentrations. Since concentrations were relatively the same in the two classroom types, the higher efficiency of the 2” pleated particle filters in the IHPAC system was likely responsible for removal of the additional PM mass provided due to additional ventilation.

Acoustic Levels

An evolution of sound level standards for classroom background noise levels has occurred over the past few years. For example:

1. Collaborative for High Performance Schools (CHPS) – Various CHPS points are granted for 45, 40 and 35 dB(A) levels.

2. Los Angeles Unified School District (LAUSD 1998) requited a maximum of 50 dB(A) at 10 feet in front of the HVAC unit. LAUSD has since adopted CHPS standards.

3. ANSI/ASA S12.60-2002:– ASA has set a maximum background level in classrooms of 35 dB(A), a technological challenge to achieve at low cost points, but possible when extremely low background classroom levels are essential, for example when teaching the hearing impaired.

The reduction of acoustic noise emitted from the wall mount classroom HVAC system achieved in the IHPAC is one of the major achievements of this project. Noise plays an important role in the operation of the portable classroom as a learning environment. Teachers must be able to bring noise levels under control in their classrooms in order to be heard and to maximize the attention of the students. When voices must be raised over a high background noise level, an environment is created where the room occupants must compete to be heard, leading to an upward spiral of speech amplitude. Teachers often opt to turn off an offending ventilation system if doing so improves the acoustic environment in the classroom. The consequences of this action are poor ventilation, indoor air quality, and thermal control, with possible outcomes including increased transmission of respiratory infections, increased exposure to toxic air contaminants, increased absenteeism, etc.

The fan-only sound pressure level range of 36 to 40 dB(A) in the IHPAC classrooms is a substantial improvement compared to the 38 to 52 dB(A) range in the 10 SEER classrooms. Across all of the IHPAC units and three measurement sessions, the average background sound pressure level was 38±1.4 dB(A). Since under the Title 24 requirement for continuous ventilation implies that the fan must be on always during occupied hours, the fan only operation can make up a large part if total daily noise exposure. With the exclusion of classroom 24 the fans were operated about 38%±14% of the time without the HVAC compressor activated.

During Stage 1 operation of the IHPAC compressor the noise levels ranged from 41 to 47 dB (averaged across the three seasons of measurements. The average measured background noise level for this mode was 44±2 dB(A). Across the seasons and all IHPAC classrooms the HVAC system was in Stage 1 mode for 24%±16% of the schoolday hours.

The IHPAC system was in the Stage 2 mode for only 13%±6% of schoolday hours. The average measured background noise level for this mode of operation across IHPAC classrooms was 46±1.5 dB(A).

Thus, the IHPAC met the background sound pressure level goal of 45 dB(A) in both Fan only an Stage 1 modes. In Stage 2 mode, the system was on average slightly higher. However, on average this mode was only in use 13% of the time. If the noise level is normalized by the amount of HVAC operating time, the average sound pressure level experienced in the classroom is about 41 dB(A).

Thermal Comfort, Indoor Temperature and Relative Humidity

As discussed above, measurements of thermal environmental parameters seldom showed that the ASHRAE 55-defined thermal comfort level was rarely met in classrooms using either HVAC system. This is similar to the findings in another portable classroom study where TC parameters were measured (Apte et al. 2003). TC, as ASHRAE defines it has a narrow band of acceptable relative humidity and temperature. It is unclear that Standard 55 is relevant to elementary school students; children's metabolism and activity levels, and the frequency of changing of activities differ from those of adults; they also wear different levels and styles of clothing.

The acceptable ranges of operative temperature and relative humidity for the cooling season, based on ASHRAE Standard 55 (1992, 1995a), are 22.5ºC to 26.0ºC and 30% to 60% RH, respectively. Likewise, for the heating season the ranges are 20.0ºC to 23.5ºC and 30% to 60% RH, respectively.

In general, the indoor humidity levels measured in both types of classrooms were within the acceptable ranges during the TC cart measurements across all three seasons where the carts were used. Most often, when the TC criteria were unmet it was due to classroom temperature. It appears that the thermostat setpoint selected by the teachers in the IHPAC rooms tended to be slightly lower than those used in the 10 SEER classrooms. This combined with the much tighter thermal control provided by the IHPAC control system acted to keep the room temperature below ASHRAE 55 temperature bands. The relevance of this to actual student and teacher thermal comfort is uncertain.

Energy Consumption

As expected, due to the increased use of outside air ventilation by the IHPAC classrooms, measured daily energy consumption was with one exception (discussed below) greater than for the 10 SEER classrooms. Interpretation of this fact must be weighed against the fact that the State of California requires continuous ventilation that is supplied by the IHPAC by law (CEC 2001, CCR 1995). Thus, the appropriate comparison between the energy consumption of the 10 SEER and the IHPAC systems must be based on an equivalency of conditioned outside air delivered to the classroom. Since the 10 SEER classrooms studied were not in compliance with this requirement, for all of the reasons discussed above, it is necessary to use a modeling approach to explore the energy benefits of the IHPAC.

The one exception, where the IHPAC used less daily energy than the 10 SEER system, was during the summer in the Southern California schools. In this case the 10 SEER consumption was 6.6±3.2 kWh per school day while the IHPAC consumed 6.2±1.8 per day. The reason for this is that outdoor temperatures in the Southern climate zone were sufficiently extreme that HVAC was a necessity. Additionally, the cooling demand was sufficient to have high 10 SEER compressor use; consequently, more ventilation and therefore more outside air thermal conditioning was provided. In this case, the cost of that extra outside air conditioning is seen in higher daily energy consumption. This observation is evident from the delta CO_2 data for the summer time period in the Southern California school district (Table 3) that typically had the lowest average and 99th percentile values during this period.

Energy Modeling

Calibration of the HVAC systems energy performance using DOE-2 proved to be very difficult. In retrospect, more detailed measurements of local weather conditions including wind speed and horizontal and total insolation would have been very useful. As it was, the closest available weather station data was not from locations sufficiently close to provide the temporal detail needed for hourly energy modeling. In addition, although daily attendance records were used in energy modeling, uncertainty in occupancy numbers and activities was problematic when trying to close energy load balances. A third problem was programming the appropriate hourly thermostat set points for the 10 SEER classrooms. Since the setting values were not monitored it was necessary to use hourly indoor temperature measurements to infer the thermostat setting.

Nonetheless, it was possible to identify sufficient numbers of days where modeling agreement with both measured indoor temperature and energy consumption data to show that the compressor and fan performance curves used in the models were correct.

Once the system calibrations were complete, application of the DOE-2 models to the typical meteorological conditions by climate zone in California was straightforward. The results of comparisons between the 10 SEER system with the assumption of continuous ventilation and the IHPAC show favorable energy savings of about 36% to 42% across California's climate zones.

Payback periods, even with a conservative modeled electricity cost of \$0.15/kWh, are reasonable but not exceptionally short. As expected, the climate zones with more extreme temperatures provide the fastest payback. Interestingly, the fast growing geographic regions of the State are inland with more extreme seasonal temperatures including the Central Valley (CZ 12, 13), the San Bernardino Valley and Riverside County (CZ 14) have the lowest payback periods of six to seven years. With rising cost of energy the payback period may drop to a few years in some climate zones.

Market Connections

The content of this report has been largely technical. However, a major goal of the project was to work towards bringing the energy and indoor environmental benefits of the improved HVAC technology to the market. The design of this study that hinged on collaboration with an industrial partner, Bard Manufacturing Co., and a marketing partner, Geary Pacific Supply Corporation, proved to be a successful model. From the beginning, management at these companies saw the benefit of combining a self-funded product development project with a technical specification being developed through CEC-PIER funded research despite the fact that the end product specification would be publicly available. A benefit to them was that their product would be rigorously tested with a degree of measurement and scientific scrutiny not typically applied to HVAC system development. This collaboration led to the manufacture of the ten IHPAC systems that were studied in this project.

The risk to the companies involved was fairly high because technical success would not necessarily translate into a marketing success. The HVAC market and the School Facilities market are both traditionally rather conservative and slow to adopt new technology. Thus, a product must have a compelling advantage to attract market share. In the case of this project, these advantages were increased energy efficiency, improved acoustical characteristics, and improved classroom air quality. Potential benefits included lower energy costs, and improved health and learning conditions for the classroom occupants.

The specification for the IHPAC system is not manufacturer specific, but is available through the Collaborative in High Performance Schools (CHPS 2006). This specification was developed and written at LBNL as part of this project and will now presumably used by all HVAC manufacturers with an interest in producing wall mount unitary HVAC systems for RCs.

A stakeholders workshop was held in Sacramento CA on March 9, 2007 to identify a means to promote the benefits of the IHPAC specification and to find support for development of a public utility product incentive to schools who purchase products meeting the specification. The meeting was well attended by stakeholders from the HVAC industry, School Facilities industry, major California school districts, California Energy Commission, California Air Resources Board, California Department of Health Services, Cal EPA, three California public utilities. One follow-up telephone conference was held about a month later. The outcome of this meeting was twofold. First, stakeholder awareness of the potential for saving energy and simultaneously improving the quality of the portable classroom environment was raised. Second, the public utilities went away with interest in developing a product incentive package for the school portable classroom market.

To date, no incentive package has been brought to the market. However, Pacific Gas and Electric has continued to work on the package development, and together with the California Public Utilities Commission is currently assessing the energy and non-energy benefits to the Company and ratepayers (Flood, 2008).

Finally, Bard Manufacturing and Geary Pacific Supply now markets the IHPAC as their premium portable classroom HVAC system under the product name Quiet Climate 2 (Bard 2007), and are now having major production runs of the IHPAC product, supplying their system to large school districts in California and in the Southeastern part of the U.S. (Derks, 2008)

Conclusions

An improved HVAC system for portable classrooms was specified to address key problems in existing units. These included low energy efficiency, poor control of and provision for adequate ventilation, and excessive acoustic noise. Working with industry, a prototype improved heat pump air conditioner was manufactured to meet the specification developed by this project. In this report we have presented the results of a year of field-testing of ten of these IHPAC systems in occupied classrooms in two distinct California climates that were manufactured in a limited production run. These results are compared to those of parallel measurements in side by side portable classrooms equipped with standard 10 SEER heat pump air conditioner equipment.

The IHPAC units were found to work as designed, providing predicted annual energy efficiency improvements of about 36% to 42% across California's climate zones, relative to 10 SEER units. Classroom ventilation was vastly improved as evidenced by far lower indoor minus outdoor CO_2 concentrations. The IHPAC units were found to provide ventilation that meets both California State energy and occupational codes and the ASHRAE minimum ventilation requirements; the classrooms equipped with the 10 SEER equipment universally did not meet these targets.

The IHPAC system provided a major improvement in indoor acoustic conditions. HVAC system generated background noise was reduced in fan only and fan and compressor modes, reducing the nose levels to better than the design objective of 45 dB(A), and acceptable for additional design points by the Collaborative on High Performance Schools.

The IHPAC provided superior ventilation, with indoor minus outdoor CO_2 concentrations that showed that the Title 24 minimum ventilation requirement of 15 CFM per occupant was nearly always being met. The opposite was found in the classrooms utilizing the 10 SEER system, were the indoor minus outdoor CO_2 concentrations frequently exceeded levels that reflect inadequate ventilation.

The improved ventilation conditions in the IHPAC lead to effective removal of volatile organic compounds and aldehydes, on average lowering the concentrations by 57% relative to the levels in the 10 SEER classrooms. The average IHPAC to 10 SEER formaldehyde ratio was about 67%, indicating only a 33% reduction of this compound in indoor air. Use of ventilation for formaldehyde removal is not as effective as it is for many VOCs because of the diffusion mechanisms that cause the compound to be emitted from composite wood products. This underscores the importance of choosing low formaldehyde emitting materials for use in classroom environments.

Indoor particulate matter concentrations in the classrooms were not changed by the IHPAC system relative to the 10 SEER systems. This was not surprising since the filtration supplied by both systems were relatively similar. Average ambient PM concentrations were higher than indoor levels during the study, suggesting that filtration and other particle removal mechanisms were at work. The fact that increased volume of outside air supplied to the IHPAC classrooms did not lead to higher particle levels indoors suggests that the 2” pleated filters used in the IHPAC provided some additional particle removal benefit not afforded by the 1” standard filters typically provided for the relocatable classrooms.

The IHPAC thermal control system provided less variability in occupied classroom temperature than the 10 SEER thermostats. This is not surprising since the conditions were controlled by occupancy sensor rather than manually by a teacher. The average room temperatures tended to be slightly lower in the IHPAC classrooms, often below the lower limit of the ASHRAE 55 thermal comfort band. Calculated thermal comfort values indicate that neither 10 SEER or IHPAC classrooms provided conditions technically considered comfortable, and those in the IHPAC were slightly satisfying. However, the value of this observation is unclear – the control systems in both classroom types provided latitude in temperature control that would have allowed higher or lower temperatures suggesting that the ASHRAE 55 definition may not be appropriate for the classroom situation.

State-wide and national energy modeling provided conservative estimates of potential energy savings by use of the IHPAC system that would provide payback a the range of time far lower than the lifetime of the equipment. These models did not include the non-energy benefits to the classrooms including better air quality and acoustic conditions that could lead to improved health and learning in school.

The market connection efforts that were part of the study give all indication that this has been a very successful project. The successes include the specification of the IHPAC equipment in the CHPS standards, the release of a commercial product based on the standards that is now being installed in schools around the U.S., and the fact that a public utility company is currently considering the addition of the technology to its customer incentive program. These successes indicate that the IHPAC may reach its potential to improve ventilation and save energy in classrooms.

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Tables

Table 1. The field study instrumentation

Parameters Measured	Instrument	Calibration method	Data collection rate/ acquisition method
Air temperature	Onset Instrument, HOBO-Pro Series Temp Ext © loggers with a resolution of 0.02 ^{o}C and rated accuracy of ±0.2 ^{o}C	NIST-traceable RTD system with 0.02 ^{o}C rated accuracy	Real-time, internal data logger – download monthly
Relative humidity	Onset Instrument HOBO® Temperature, RH © with rated accuracy of ±3% RH	Use of salt solutions to produce air with various reference values of humidity	Real-time, internal data logger – download monthly
Carbon dioxide concentration	California Analytical Instruments infrared analyzer, ZPF-9, 0-3000 ppm range	Cylinders of primary standard calibration gases	Real-time – data logged to i.Lon 100 web server, acquired continuously
Air Temperature, Relative Humidity, Carbon Dioxide (CO_2)	PureChoice Nose ™. Temperature (resolution 0.1 ^{o}C, rated accuracy ±0.5 ^{o}C), RH (resolution 1% RH, rated accuracy larger of ±10% or ±5% RH), CO_2 range 0-5000 ppm (resolution 10 ppm, accuracy greater of ±5% or 100 ppm).	NIST-traceable calibrations	Real-time – data logged to i.Lon 100 web server, acquired continuously
Ventilation rate	Tracer gas decay during unoccupied time using sulfur hexafluoride (SF_6), or carbon dioxide tracer gas. Tracers monitored using infrared analyzers	Cylinders of primary standard calibration gases	Measured once a season per RC during site visits. Real-time data collected on laptop computer
Particle concentration, size distribution	Optical particle counter (OPC) with 6 channels for particle number size distribution (# m-3), with size bins 0.3, 0.5, 0.7, 1, 2 and 5 µm (Met One, Model 237B)	Factory calibration, and intercomparison with other aerosol instrumentation at LBNL	Measured once a season per RC during site visits. Real-time data collected on laptop computer
Aldehyde concentrations	7-hour aldehyde samples collected onto treated silica-gel cartridges (WAT047205, Waters Corp.) with sample flow rate of 0.15 L/min. Analysis by high performance liquid chromatography with UV detection following ASTM standard method D-5197-97 (ASTM, 1997b).	Sorbent tubes spiked with known quantity of aldehydes	Samples collected once a season per RC during site visits. Analyzed at LBNL post sampling.
VOC concentrations	7-hour VOC gas samples collected onto Tenax-TA™ sorbent tubes (CP-16251; Varian Inc.) modified by substituting a 15-mm section of Carbosieve S-III 60/80 mesh (10184, Supelco Inc.) at the outlet end. Sample flow rate will be 0.005 l/min. VOC samples analyzed by thermal desorption-gas chromatography/mass spectrometry generally following U.S. EPA Method TO-1 (U.S. EPA, 1984)	Sorbent tubes spiked with known quantity of VOCs	Samples collected once a season per RC during site visits. Analyzed at LBNL post sampling.
Ozone concentrations	7-hour indoor and outdoor ozone passive samplers (Ogawa 3300) with Ion Chromatography (IC) analysis by IML Inc., Sheridan WY.	Nitrite to nitrate chemistry. Nitrate standards used to calibrate IC.	Samples collected once a season per RC during site visits. Analyzed at IML post sampling.
Sound levels	Sound spectrum meter for ~6 to 20 Hz spectrum such as the Bruel and Kjaer model 2260	Factory calibration	Measured once a season/RC during site visits, collected on laptop computer
Power Monitoring	WattNode™ datalogging line power monitor measures true RMS power and energy consumption– logged continuously. Current measured with inductive current transducers simultaneously with line voltage. Accuracy of the WattNode™ is ± 0.5% of reading over operating range.	Factory Calibration	Real-time – data logged to i.Lon 100 web server, acquired continuously
Thermal Comfort	LBNL Thermal Comfort Cart. ASHRAE Standard 55-2004. Measures air temperature, mean radiant temperature, relative humidity, and air velocity.	Factory Calibration and Calibration checks using NIST-traceable methods	Integrated datalogger downloaded after collection

Table 2. CO_2 Concentrations in Northern California Classrooms.[1]

			Delta CO_2 (ppm)			Outdoor CO_2 (ppm)		
Site	Room	Season	Avg (Stdev)	1st %	99th %	Avg (Stdev)	1st %	99th %
N1	21	All	300 (440)	0	2200	360 (50)	330	440
		Spring '05	570 (740)	0	2700	370 (90)	340	470
		Summer '05	280 (400)	0	2400	350 (40)	330	380
		Fall '05	260 (330)	0	1400	370 (20)	340	450
		Winter '05	240 (320)	0	1300	370 (40)	350	410
	22	All	240 (210)	-10	690			
		Winter '04	230 (200)	-10	650			
		Spring '05	150 (130)	-10	380			
		Summer '05	260 (200)	-10	650			
		Fall '05	340 (240)	0	760			
		Winter '05	180 (210)	0	640			
	23	All	1000 (870)	0	3300	360 (110)	310	420
		Winter '04	1100 (800)	0	2600	350 (110)	320	390
		Spring '05	1000 (670)	0	2500	360 (140)	330	380
		Summer '05	890 (670)	-10	2400	340 (90)	290	350
		Fall '05	1300 (960)	10	3400	370 (30)	330	430
		Winter '05	810 (1100)	0	3700	390 (160)	350	410
	24	All	290 (230)	0	830	350 (30)	320	420
		Spring '05	300 (200)	-10	670	350 (40)	330	360
		Summer '05	280 (240)	-10	950	340 (30)	320	350
		Fall '05	330 (210)	10	710	360 (40)	340	420
		Winter '05	250 (240)	0	700	360 (30)	340	390
N2	25	All	120 (130)	0	430			
		Winter '04	210 (160)	0	550			
		Spring '05	120 (120)	0	380			
		Summer '05	42 (78)	0	300			
		Fall '05	150 (130)	10	470			
		Winter '05	120 (120)	0	470			
	26	All	760 (760)	0	2400	350 (70)	320	420
		Winter '04	1400 (680)	10	2500	390 (120)	350	420
		Spring '05	810 (760)	0	2500	350 (10)	330	380
		Summer '05	190 (390)	-10	1700	330 (30)	320	360
		Fall '05	960 (670)	30	2400	340 (110)	330	360
		Winter '05	770 (760)	0	2300	360 (10)	340	370

[1] Rooms 22, 24, and 25 were intervention classrooms and Rooms 21, 23, and 26 were control classrooms.

Table 3. CO_2 Concentrations in Southern California Classrooms[1].

			Delta CO_2 (ppm)			Outdoor CO_2 (ppm)		
Site	**Room**	**Season**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**
S1	35	All	240 (360)	-20	1600			
		Winter '04	320 (250)	-10	820			
		Spring '05	490 (530)	-10	1700			
		Summer '05	180 (350)	-20	1700			
		Fall '05	110 (130)	-10	440			
		Winter '05	90 (110)	0	380			
	36	All	240 (400)	-20	1900	380 (50)	340	480
		Winter '04	240 (350)	-10	2000	380 (30)	350	440
		Spring '05	360 (490)	-30	2000	380 (70)	350	600
		Summer '05	190 (380)	-20	1900	370 (20)	340	460
		Fall '05	230 (440)	-20	2100	380 (80)	340	450
		Winter '05	140 (230)	-10	1100	370 (20)	340	460
	37	All	150 (170)	-30	660	380 (110)	260	810
		Winter '04	99 (140)	-30	480	290 (20)	260	340
		Spring '05	200 (180)	-10	730	340 (20)	300	370
		Summer '05	91 (140)	-50	550	510 (150)	350	880
		Fall '05	170 (180)	-10	700	360 (30)	330	410
		Winter '05	140 (160)	-10	630	360 (20)	330	380
S2	13	All	410 (370)	-20	1600			
		Winter '04	560 (570)	-20	3000			
		Spring '05	480 (360)	-10	1500			
		Summer '05	340 (260)	-10	820			
		Fall '05	320 (240)	-20	810			
		Winter '05	290 (300)	0	920			
	14	All	970 (890)	0	3800	430 (90)	350	670
		Winter '04	1400 (1100)	30	4300	480 (180)	360	810
		Spring '05	850 (710)	10	3400	420 (60)	360	570
		Summer '05	650 (630)	0	2600	420 (50)	350	520
		Fall '05	1300 (840)	10	3100	440 (40)	370	550
		Winter '05	990 (1100)	0	3900	420 (70)	340	580
	15	All	320 (250)	-10	830	390 (40)	340	510
		Winter '04	250 (270)	-10	830	460 (30)	410	530
		Spring '05	350 (250)	-10	840	380 (30)	340	430
		Summer '05	310 (220)	0	850	370 (30)	340	400
		Fall '05	380 (230)	0	840	360 (10)	340	400
		Winter '05	320 (260)	0	790	350 (10)	330	390
	16	All	690 (740)	0	3500	380 (70)	340	440
		Winter '04	1100 (990)	10	4300	410 (50)	370	710
		Spring '05	700 (710)	10	3300	380 (100)	350	410
		Summer '05	460 (380)	0	1800	370 (40)	340	390
		Fall '05	780 (830)	0	3300	360 (10)	340	410
		Winter '05	24 (19)	10	62	370 (10)	340	400

[1] Rooms 35, 37, 13, and 15 were intervention classrooms and Rooms 36, 14, and 16 were control classrooms.

Table 4. Outside Air Supply and Air Exchange Rates for Northern and Southern California 10 SEER HVAC systems[1].

			Flow Rates (CFM) and Air Exchange Rates (h^{-1})								
			Spring 2005			Summer 2005			Fall 2005		
School	Room	Location	Fan (Adj)	Comp (Adj)	ACH (h^{-1})	Fan (Adj)	Comp (Adj)	ACH (h^{-1})	Fan (Adj)	Comp (Adj)	ACH (h^{-1})
N1	21	Outside		242	2.2	100	99	1.2	147	148	1.3
		S1				692	673		692	697	
		S2				681	687		664	627	
		Return		1218		1364	1320		1275	1320	
	23	Outside		260 (275)	2.0	221	221	2.1	213	215	1.8
		S1				675	678		633	636	
		S2				644	675		573	617	
		Return		1218		1169	1218		1106	1148	
N2	26	Outside		128 (230)	2.7	221	265	2.2	213	182	2.1
		S1		678		765	751		707	723	
		S2		404		492	511		487	479	
		Return		1256 (1148)		1138	1169		1117	1138	
S1	14	Outside		428	2.7	55	83		76	99	3.1
		S1		570		502	491		572	536	
		S2		591		523	527		606	607	
		Return		1010		1041	1106		1169	1198	
	16	Outside		256 (328)	2.3	256	310		289	342	2.2
		S1		329		300	309		339	345	
		S2		324		287	298		307	306	
		Return		686		514	586		562	636	
S2	36	Outside		377 (514)	3.4	560	485		514	574	4.0
		S1		555		499	505		585	533	
		S2		576		520	517		630	543	
		Return		1419		725	826		826	933	

[1] “Fan” refers to measured airflow rates with fan only, “Comp” refers to measured airflow rates with fan and compressor on. “Adj” refers to measurement after adjustment of flow rates. “ACH” refers to air exchange rates measured with fan on.

Table 5. Outside Air Supply and Air Exchange Rates for Northern California IHPAC Systems[1].

			Flow Rates (CFM) and Air Exchange Rates (h^{-1})											
			Spring 2005				Summer 2005				Fall 2005			
School	Room	Location	Fan (Adj)	Stg1 (Adj)	Stg2 (Adj)	ACH (h^{-1})	Fan (Adj)	Stg1 (Adj)	Stg2 (Adj)	ACH (h^{-1})	Fan (Adj)	Stg1 (Adj)	Stg2 (Adj)	ACH (h^{-1})
N1	20	Outside					476	448	509	2.5	461	450	460	2.4
		S1					287	334	442		297	332	452	
		S2					278	339	462		302	336	463	
		S3					256	296	403		259	302	409	
		Return					483	1041	1320		446	883	1218	
	22	Outside	483	497	487	3.3	456	428	384 (452)	2.3	406 (497)	336 (497)	390 (467)	2.6
		S1					288	340	400		300	318	427	
		S2					295	331	442		310	318	427	
		S3					295	328	419		287	311	421	
		Return	530	262	1148		534	1074	1218		511	879	1198	
	24	Outside	476	476	504	2.7	517 (465)	450	474	3.9	450	426 (481)	440 (463)	3.0
		S1					304	330	433		304	344	441	
		S2					260	281	381		275	300	383	
		S3					262	304	364		253	279	374	
		Return	476	970	1237		465	983	1208		497	933	1256	
N2	25	Outside	487 (476)	994 (479)	418 (494)	3.3	414 (494)	393 (472)	408 (481)	2.9		446	450	2.8
		S1	271	313	405		275	332	411		275	317	415	
		S2	311	350	453		295	345	437		287	347	451	
		S3	269	304	398		264	308	375		261	309	391	
		Return	476 (469)	994 (958)	1218 (1189)		375	549	1169		461	1006	1237	
	27	Outside	483 (479)	402 (487)	434 (479)		485	424 (463)	430 (461)	3.9	448	444	474	3.3
		S1	325	385	481		319	360	464		314	402	478	
		S2	257	327	371		254	285	400		262	318	419	
		S3	268	326	405		258	300	389		252	327	404	
		Return	500 (487)	1148 (1063)	1431 (1346)		479	1018	1247		321	1074	1329	

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[1] "Fan" refers to measured airflow rates with fan only, "Stg1" and "Stg2" refer to measured airflow rates with fan and compressor on in stage 1 and stage 2, respectively. "Adj" refers to measurement after adjustment of flow rates. "ACH" refers to air exchange rates measured with fan on.

Table 6. Outside Air Supply and Air Exchange Rates for Southern California IHPACs[1].

			Flow Rates (CFM) and Air Exchange Rates (h^{-1})											
			Spring 2005				Summer 2005				Fall 2005			
School	Room	Location	Fan (Adj)	Stg1 (Adj)	Stg2 (Adj)	ACH (h^{-1})	Fan (Adj)	Stg1 (Adj)	Stg2 (Adj)	ACH (h^{-1})	Fan (Adj)	Stg1 (Adj)	Stg2 (Adj)	ACH (h^{-1})
S1	13	Outside	481	492	538 (476)	2.8	436 (496)	416 (487)	416 (490)		553 (464)	572 (500)	644 (495)	3.0
		S1	339	345	472		305	334	439		304	341	451	
		S2	268	281	364		230	258	389		230	266	343	
		S3	293	318	412		265	295	391		278	293	384	
		Return	740	1041	1329		639	970	1198		617	828	1138	
	15	Outside	546 (485)	500	535 (485)	3.2	428 (478)	454	444 (474)		465	465	516 (490)	3.2
		S1	268	278	389		246	267	361		249	306	369	
		S2	299	310	428		264	302	411		281	315	424	
		S3	278	304	410		249	278	371		257	305	375	
		Return	752	1063	1381		664	994	1247		634	958	1256	
	17	Outside	487	465	477	3.8	469	490	487		540 (536)	444	448	3.5
		S1	339	387	502		248	277	363					
		S2	358	389	505		232	265	348					
		S3	321	373	476		209	226	298					
		Return	720	1046	1355		676	1006	1293					
S2	35	Outside	556 (494)	490	541 (476)	1.7	472	460	436 (476)		504	534 (507)	559 (476)	3.1
		S1	252	281	380		233	265	333		236	265	329	
		S2	246	284	359		233	265	348		231	272	346	
		S3	313	339	452		299	337	454		289	344	443	
		Return	624	1006	1289		652	1018	1284		652	1018	1256	
	37	Outside	514	502	513	4.2	487	455	472		511	479	494	4.0
		S1	249	275	366		216	254	317					
		S2	284	313	400		254	298	395					
		S3	329	356	463		298	321	437					
		Return	584	1029	1265		543	970	1198					

[1] "Fan" refers to measured airflow rates with fan only, "Stg1" and "Stg2" refer to measured airflow rates with fan and compressor on in stage 1 and stage 2, respectively. "Adj" refers to measurement after adjustment of flow rates. "ACH" refers to air exchange rates measured with fan on.

Table 7. Acoustic noise levels (dB(A)) in unoccupied northern and southern California 10 SEER classrooms measured centered on and 10 feet from return grille and 5 feet high.

		A-Weighted noise levels (dB(A))							
		Spring		**Summer**		**Fall**		**Average (Stdev)**	
School	**Room**	**Fan**	**Fan+Comp.**	**Fan**	**Fan+Comp.**	**Fan**	**Fan+Comp.**	**Fan**	**Fan+Comp.**
N1	21	51.5	52.6	-	-	50.7	52.5	51.1 (0.6)	52.5 (0.1)
	23	-	-	52.5	53.4	50.6	51.1	51.6 (1.3)	52.3 (1.6)
N2	26	54.6	56.6	-	-	50.2	52.7	52.4 (3.2)	54.6 (2.7)
S1	14	46.3	53.1	46.8	49.9	48.0	51.1	47.0 (0.9)	51.3 (1.6)
	16	42.8	54.9	38.4	54.8	39.4	56.1	40.2 (2.3)	55.3 (0.7)
S2	36	46.9	52.9	44.5	55.6	46.6	54.1	46.0 (1.3)	54.2 (1.4)

Table 8. Acoustic noise levels (dB(A)) in unoccupied northern and southern California IHPAC classrooms measured centered on and 10 feet from return grille and 5 feet high.

		A-Weighted noise levels (dB(A))											
		Spring			**Summer**			**Fall**			**Average (Stdev)**		
School	**Room**	**Fan**	**Fan + Stage1**	**Fan + Stage2**	**Fan**	**Fan + Stage1**	**Fan + Stage2**	**Fan**	**Fan + Stage1**	**Fan + Stage2**	**Fan**	**Fan + Stage1**	**Fan + Stage2**
N1	20	40.5	45.5	-	-	-	-	41.0	43.9	44.0	40.8 (0.3)	44.7 (1.1)	44.0 (-)
	22	39.9	-	-		-	-	41.5	45.7	47.7	40.7 (1.1)	45.7 (-)	47.7 (-)
	24	-	-	-	37.0	41.8	44.1	39.7	42.5	45.2	38.3 (1.9)	42.1 (0.5)	44.7 (0.8)
N2	25	39.7	42.5	46.4	40.8	43.4		39.9	43.0	45.4	40.1 (0.6)	43.0 (0.4)	45.9 (0.7)
	27	-	-	-	-	-	-	39.8	43.9	45.8	39.8 (-)	43.9 (-)	45.8 (-)
S1	13	38.4	43.6	48.6	37.6	42.2	47.2	38.6	37.6	45.6	38.2 (0.6)	41.1 (3.2)	47.1 (1.5)
	15	38.6	43.5	46.8	38.3	44.5	47.0	38.7	47.2	48.3	38.5 (0.2)	45.1 (1.9)	47.4 (0.8)
	17	40.6	45.4	47.5	-	-	-	-	-	-	40.6 (-)	45.4 (-)	47.5 (-)
S2	35	39.5	48.4	49.0	42.6	47.6	49.5	38.4	44.5	46.2	40.2 (2.2)	46.8 (2.1)	48.2 (1.8)
	37	40.0	46.6	51.8	37.7	41.1	44.7	37.3	44.5	45.2	38.3 (1.5)	44.1 (2.8)	47.2 (3.9)

Table 9. Acoustic noise levels (dB(A)) in unoccupied northern and southern California 10 SEER classrooms measured centered on and 10 feet from return grille and 5 feet high with background adjusted to 25 dB(A)..

		A-Weighted noise levels (dB(A))							
		Spring		Summer		Fall		Average (Stdev)	
School	Room	Fan	Fan+Comp.	Fan	Fan+Comp.	Fan	Fan+Comp.	Fan	Fan+Comp.
N1	21	51.4	52.5	-	-	50.3	52.3	50.9 (0.8)	52.4 (0.2)
	23	-	-	52.4	53.3	50.5	51.0	51.5 (1.4)	52.2 (1.6)
N2	26	54.5	56.5	-	-	50.1	52.7	52.3 (3.1)	54.6 (2.7)
S1	14	46.1	53.1	46.6	49.8	47.7	50.9	46.8 (0.8)	51.3 (1.7)
	16	41.3	54.8	36.5	54.8	37.0	56.1	38.3 (2.6)	55.2 (0.7)
S2	36	46.4	52.8	43.8	55.6	46.5	54.1	45.6 (1.5)	54.2 (1.4)

Table 10. Acoustic noise levels (dB(A)) in unoccupied northern and southern California IHPAC classrooms measured centered on and 10 feet from return grille and 5 feet high with background adjusted to 25 dB(A).

		A-Weighted noise levels (dB(A))											
		Spring			Summer			Fall			Average (Stdev)		
School	Room	Fan	Fan + Stage1	Fan + Stage2	Fan	Fan + Stage1	Fan + Stage2	Fan	Fan + Stage1	Fan + Stage2	Fan	Fan + Stage1	Fan + Stage2
N1	20	39.1	45.1	-	-	-	-	40.1	43.5	43.6	39.6 (0.7)	44.3 (1.2)	43.6 (-)
	22	37.5	-	-	-	-	-	39.4	45.1	47.2	38.4 (1.3)	45.1 (-)	47.2 (-)
	24	-	-	-	34.8	41.2	43.7	37.9	41.6	44.8	36.3 (2.2)	-	44.3 (0.8)
N2	25	36.0	40.9	45.9	32.9	40.8	-	37.9	42.1	44.9	35.6 (2.5)	41.3 (0.7)	45.4 (0.7)
	27	-	-	-	-	-	-	39.4	43.7	45.7	39.4 (-)	43.7 (-)	45.7 (-)
S1	13	38.0	43.5	48.6	35.5	41.6	47.0	38.2	37.0	45.5	37.2 (1.5)	40.7 (3.4)	47.0 (1.6)
	15	38.0	43.3	46.7	36.7	44.1	46.8	37.9	47.1	48.2	37.5 (0.7)	45.1 (1.9)	47.4 (0.8)
	17	37.8	44.7	47.0	-	-	-	-	-	-	-	45.4 (-)	47.5 (-)
S2	35	38.8	48.3	48.9	38.9	46.8	49.0	38.1	44.4	46.2	38.6 (0.4)	46.8 (2.1)	48.2 (1.8)
	37	39.9	46.6	51.7	37.1	40.8	44.6	36.9	44.4	45.1	38.0 (1.7)	44.1 (2.8)	47.2 (3.9)

Table 11. Selected toxic and odorous volatile organic compounds, their odor thresholds and chronic toxicity for the State of California's Proposition 65, CalEPA's Toxic Air Contaminant, and USEPA's Hazardous Air Pollutant listings.

Compound	Class	Odor Threshold (µg m^{-3})^1	Prop 65 List^2	CalEPA Chronic^3	Cal EPA Chronic REL (µg m^{-3})^3	EPA Chronic HAPs^4
Ethylene glycol	Alcohol	25000		+	400	+
Phenol	Alcohol	423		+	200	+
1,2,4-Trimethylbenzene	Aromatic	736				
Naphthalene	Aromatic	200		+	9	+
Toluene	Aromatic	5830	+	+	300	+
m-Xylene	Aromatic	1430		+	700	+
1,4-Dichlorobenzene	Halo-Carbon	730	+			
Dichloromethane	Halo-Carbon	96000	+	+	400	
Tetrachloroethene	Halo-Carbon	3900				+
2-Butanone	Ketone	23000				+
2-Propanone	Ketone	33000				
4-Methyl-2-pentanone	Ketone	3600				+
1-Methyl-2-pyrrolidinone	Nitro-cmp		+			
Caprolactam	Nitro-cmp					+^{5}
d-Limonene	Terpene	2430				
Octanal	Aldehyde	7				
Pentanal	Aldehyde	2				
Acetaldehyde	Aldehyde	335	+	+	9	+
Formaldehyde	Aldehyde	1070	+	+	3	+

+ Signifies listing of compound in relevant document

[1] Odor thresholds from Devos et al. 1990, AIHA 1989.

[2] Proposition 65 list of air contaminants known to cause cancer or reproductive toxicity from State of California (1986)

[3] Chronic Reference Exposure Level list 2005, (OEHHA, 2005)

[4] US EPA Hazardous Air Pollutant list USEPA (2005)

[5] Listed as a toxic air contaminant with no current concentration limit

Table 12 VOC Concentrations (μg m^{-3}) for All Schools.

	Spring 2005						
	IHPAC			10 SEER			Outside Air
Compound	**Avg (Stdev)**	**Min**	**Max**	**Avg (Stdev)**	**Min**	**Max**	**Avg (Stdev)**
1-Butanol	4.4 (6.2)	0.53	15	4.2 (2.1)	1.4	6.6	0.5(0.0)
2-(2-Butoxyethoxy)ethanol	13 (13)	4.0	35	19 (14)	4.5	38	0.0(0.0)
2-Butoxyethanol	4.8 (3.4)	1.4	11	57 (58)	10.0	170	0.6(0.1)
2-Ethyl-1-hexanol	1.2 (0.69)	0.53	2.4	2.4 (1.0)	1.4	3.6	1.6(0.0)
2-Propanol	15 (20)	1.3	44	25 (48)	1.3	120	1.6(0.4)
BHT	0.39 (0.18)	0.26	0.66	1.4 (1.5)	0.26	4.1	0.4(0.0)
DPGME[1]	4.5 (4.4)	1.6	10	13 (18)	1.5	40	0.0(0.0)
Ethanol	5.5 (7.5)	0.0	190	9.5 (8.5)	27	240	8.8(10)
Ethylene glycol	13 (1.0)	12	14				
Phenol	2.1 (1.4)	0.39	4.2	6.0 (8.0)	1.6	22	7.1(4.5)
Propylene glycol	17 (8.9)	10	29	21 (21)	2.7	55	0.0(0.0)
Benzaldehyde	2.0 (1.3)	0.40	3.8	3.5 (1.1)	2.2	4.9	27(18)
Hexanal	4.1 (2.4)	2.0	8.7	11 (5.2)	2.9	18	0.4(0.6)
Octanal	2.4 (1.2)	1.1	4.5	4.9 (2.2)	3.1	7.9	1.0(1.2)
Pentanal	1.4 (1.1)	0.27	3.3	3.5 (1.9)	1.3	6.0	0.2(0.3)
n-Decane	0.28 (0.01)	0.27	0.29	0.55 (0.17)	0.26	0.67	0.3(0.0)
n-Dodecane	0.41 (0.25)	0.26	0.70	2.7 (2.6)	0.68	5.6	0.2(0.0)
n-Nonane	0.27 (0.01)	0.25	0.29	0.35 (0.10)	0.26	0.47	0.4(0.1)
n-Undecane	0.43 (0.21)	0.25	0.68	1.0 (0.84)	0.26	2.2	0.3(0.0)
1,2,4-Trimethylbenzene	0.36 (0.20)	0.26	0.77	0.64 (0.40)	0.27	1.4	0.2(0.2)
m-Xylene	1.3 (0.79)	0.64	2.8	2.1 (0.49)	1.5	2.7	1.0(0.6)
Naphthalene	0.27 (0.01)	0.26	0.29	0.33 (0.15)	0.26	0.63	0.3(0.0)
Toluene	3.4 (1.8)	1.2	6.0	6.5 (4.8)	2.0	16	2.5(1.8)
Butyl acetate	5.8 (6.3)	0.90	16	43 (97)	0.92	240	0.7(0.3)
TMPD-DIB[1]	3.7 (2.5)	1.5	8.0	5.0 (1.3)	2.9	6.6	0.3(0.0)
TMPD-MIB[1]	5.1 (2.2)	3.3	9.2	9.9 (5.3)	3.9	18	0.0(0.0)
1,4-Dichlorobenzene	1.6 (1.9)	0.39	5.5	5.9 (6.3)	0.27	17	0.3(0.0)
Dichloromethane	1.9 (1.1)	1.2	3.6	2.8 (2.0)	1.3	6.1	1.5(0.4)
Tetrachloroethene	0.27 (0.01)	0.26	0.29	0.62 (0.72)	0.25	2.1	0.3(0.1)
2-Butanone	1.2 (0.54)	0.51	1.8	1.7 (0.48)	1.2	2.2	1.2(0.7)
2-Propanone	5.7 (7.5)	0.0	15	9.4 (11)	-1.9	28	-1.8(2.1)
4-Methyl-2-pentanone	1.3 (1.1)	1.0	29	7.4 (17)	0.67	430	1.1(0.7)
Acetophenone	1.4 (1.3)	-0.17	3.0	2.1 (1.6)	0.59	4.7	21(16)
Benzothiazole	0.63 (0.47)	0.0	1.3	1.2 (0.40)	0.77	2.0	0.1(0.2)
D5 Siloxane	2.2 (1.3)	7.1	38	2.9 (2.8)	7.6	60	0.6(0.6)
1-Methyl-2-pyrrolidinone	0.28 (0.01)	0.27	0.29	3.5 (6.7)	0.26	16	0.0(0.0)
Caprolactam	1.5 (1.4)	0.53	4.1	1.7 (0.97)	0.54	2.9	0.0(0.0)
d-Limonene	5.6 (10)	0.81	26	9.3 (12)	0.77	34	0.0(0.0)
Acetaldehyde	4.4 (2.6)	1.1	9.1	9.3 (5.3)	5.0	16	2.1(1.3)
Formaldehyde	16 (11)	7.4	38	22 (5.7)	15	28	2.0(0.8)

[1] TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate;
TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol diisobutyrate
DPGE = Dipropylene glycol monomethyl ether

Table 13. Summer sampling VOC Concentrations (μg m^{-3}) for All Schools.

	Summer 2005						
	IHPAC			10 SEER			Outside Air
Compound	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg.(Stdev)
1-Butanol	2.6 (2.0)	0.57	6.2	5.9 (3.1)	3.1	12	
2-(2-Butoxyethoxy)ethanol	4.2 (0.16)	4.0	4.4	7.5 (4.2)	4.2	13	
2-Butoxyethanol	7.0 (5.7)	2.6	17	24 (24)	4.1	67	1.2(0.5)
2-Ethyl-1-hexanol	0.86 (0.49)	0.57	1.8	2.1 (1.0)	0.56	3.4	0.6(0.0)
2-Propanol	1.4 (1.6)	0.0	4.0	14 (19)	0.0	48	0.5(0.8)
BHT	0.47 (0.48)	0.26	1.5	0.70 (0.56)	0.28	1.7	0.3(---)
DPGME	4.1 (4.6)	1.6	13	7.4 (14)	1.6	36	
Ethanol	1.3 (0.45)	6.4	19	54 (91)	11	2300	6(7.3)
Ethylene glycol							
Phenol	3.3 (2.3)	0.0	6.3	5.9 (3.0)	3.1	9.7	4.0(2.3)
Propylene glycol				4.5 (3.0)	2.7	8.0	
Benzaldehyde	5.0 (2.9)	2.2	8.7	6.9 (2.2)	3.8	9.7	17(8.6)
Hexanal	2.4 (4.2)	-1.5	7.7	7.9 (7.5)	-2.4	16	-1.0(2.1)
Octanal	1.7 (0.33)	1.2	2.0	3.8 (2.8)	0.20	8.2	1.6(0.9)
Pentanal	0.00 (0.93)	-0.85	1.3	1.5 (1.3)	-0.83	2.8	-0.4(0.8)
n-Decane	-0.61 (0.60)	-1.2	0.01	0.33 (0.98)	-1.2	1.5	-0.5(0.6)
n-Dodecane	0.12 (0.51)	-0.52	0.60	3.4 (3.0)	0.63	8.2	1.0(1.3)
n-Nonane	0.62 (0.36)	0.28	1.1	0.60 (0.29)	0.27	1.0	0.4(0.1)
n-Undecane	0.52 (0.22)	0.28	0.82	2.0 (1.9)	0.75	5.8	0.7(---)
1,2,4-Trimethylbenzene	1.0 (0.78)	0.28	1.8	1.2 (0.71)	0.28	2.1	1.2(0.8)
m-Xylene	3.8 (2.9)	0.87	6.6	4.2 (2.5)	1.5	7.7	4.2(3.4)
Naphthalene	0.0 (0.0)	0.0	0.0	0.45 (0.90)	0.0	2.3	0.0(---)
Toluene	11 (8.4)	1.7	20	16 (7.3)	5.8	23	29(32)
Butyl acetate	8.1 (13)	0.83	33	1.5 (0.92)	0.78	3.2	0.6(0.3)
TMPD-DIB[1]	3.6 (3.6)	2.0	11	6.1 (2.8)	2.9	9.7	0.1(0.2)
TMPD-MIB[1]	2.7 (0.78)	1.6	4.0	5.5 (4.3)	1.9	12	0.6(0.0)
1,4-Dichlorobenzene	0.88 (0.28)	0.57	1.3	3.0 (4.6)	0.28	12	0.3(0.0)
Dichloromethane	-2.8 (2.6)	-5.0	0.0	-2.4 (2.7)	-5.0	0.0	-3.4(2.9)
Tetrachloroethene	0.44 (0.24)	0.28	0.77	0.78 (0.63)	0.27	1.7	0.5(0.3)
2-Butanone	3.3 (3.0)	0.57	6.1	3.2 (2.6)	0.57	6.7	2.9(2.0)
2-Propanone	-4.6 (9.4)	-19	4.6	16 (32)	-15	56	1.0(12)
4-Methyl-2-pentanone	15 (26)	0.80	68	1.8 (1.9)	0.80	5.7	0.6(0.3)
Acetophenone	1.2 (0.37)	0.69	1.8	2.5 (1.1)	1.0	3.9	10.5(5.2)
Benzothiazole	0.79 (0.69)	0.0	1.9	1.8 (1.1)	1.0	3.2	)
D5 Siloxane	5.2 (3.6)	12	115	3.7 (3.8)	3.8	110	1.7(1.5)
1-Methyl-2-pyrrolidinone	0.28 (0.01)	0.26	0.29	2.7 (5.7)	0.27	14	
Caprolactam	1.1 (0.83)	0.53	2.5	1.5 (0.79)	0.57	2.4	
d-Limonene	2.1 (2.1)	0.79	6.0	12 (19)	0.97	49	0.3(0.0)
Acetaldehyde	7.9 (3.2)	4.9	12	13 (4.8)	7.5	19	7.3(2.6)
Formaldehyde	18 (7.7)	10	27	26 (5.0)	21	33	7.4(4.3)

[1] TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate;
TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol diisobutyrate

Table 14. Fall Sampling VOC Concentrations (μg m^{-3}) for All Schools.

	Fall 2005						
	IHPAC			10 SEER			Outside Air
Compound	Avg (Stdev)	Min	Max	Avg (Stdev)	Min	Max	Avg.(Stdev)
1-Butanol	2.6 (3.8)	0.56	10	4.9 (7.7)	0.59	20	
2-(2-Butoxyethoxy)ethanol	4.4 (0.09)	4.3	4.5	7.3 (3.6)	4.0	10	
2-Butoxyethanol	22 (43)	2.2	110	16 (10)	2.2	33	0.6(0.0)
2-Ethyl-1-hexanol	0.77 (0.32)	0.57	1.4	2.3 (0.93)	0.59	3.4	0.6(0.0)
2-Propanol	9.1 (13)	1.4	35	20 (34)	3.2	89	1.5(0.0)
BHT	0.52 (0.25)	0.29	0.88	0.98 (0.80)	0.29	2.4	0.3(---)
DPGME	4.4 (6.4)	1.7	17	14 (21)	1.6	54	
Ethanol	6.4 (5.7)	27	160	9.8 (4.9)	27	160	11(3.6)
Ethylene glycol							
Phenol	2.3 (1.4)	0.59	4.1	4.7 (1.8)	2.3	6.9	4.6(1.6)
Propylene glycol				16 (13)	6.5	25	
Benzaldehyde	4.2 (1.3)	2.7	6.0	6.5 (1.4)	5.0	8.2	19(6.2)
Hexanal	0.25 (4.6)	-3.9	6.9	9.1 (8.3)	-5.2	17	-2.1(2.8)
Octanal	0.69 (1.1)	-1.1	1.7	2.5 (2.1)	-1.2	4.9	-0.1(1.0)
Pentanal	-0.90 (1.1)	-1.9	0.30	1.1 (1.7)	-2.0	2.5	-1.3(1.1)
n-Decane	-0.86 (0.27)	-1.1	-0.42	0.25 (0.68)	-0.77	1.1	-1.1(0.0)
n-Dodecane	1.3 (1.2)	0.28	3.1	1.9 (1.9)	0.44	5.1	0.0(0.4)
n-Nonane	0.41 (0.10)	0.29	0.54	0.63 (0.22)	0.30	0.87	0.2(0.2)
n-Undecane	0.86 (0.42)	0.43	1.5	1.5 (0.97)	0.46	3.3	0.3(---)
1,2,4-Trimethylbenzene	1.3 (0.55)	0.67	1.9	2.7 (1.1)	1.7	4.6	0.9(0.4)
m-Xylene	6.5 (3.6)	2.0	10	12 (8.2)	4.9	26	4.6(2.9)
Naphthalene	0.29 (0.00)	0.28	0.29	0.44 (0.24)	0.28	0.85	0.3(---)
Toluene	13 (5.0)	6.0	18	25 (12)	13	46	9.4(3.7)
Butyl acetate	6.2 (7.7)	0.74	19	7.9 (6.7)	1.3	18	0.6(0.3)
TMPD-DIB[1]	3.0 (2.2)	1.9	7.4	6.0 (4.9)	2.1	15	0.3(0.0)
TMPD-MIB[1]	3.3 (1.6)	1.7	5.5	6.2 (3.9)	1.8	12	0.6(0.0)
1,4-Dichlorobenzene	1.1 (1.0)	0.28	2.5	2.1 (1.9)	0.28	5.7	0.3(0.0)
Dichloromethane	0.26 (0.65)	0.0	1.6	0.28 (0.69)	0.0	1.7	0.0(0.0)
Tetrachloroethene	0.34 (0.17)	0.16	0.66	0.43 (0.31)	0.0	0.88	0.3(0.2)
2-Butanone	1.3 (0.42)	0.59	1.6	1.7 (0.28)	1.3	2.2	1.5(0.2)
2-Propanone	6.9 (14)	-7.2	27	18 (16)	-7.5	32	-1.6(10)
4-Methyl-2-pentanone	17 (18)	0.28	39	11 (9.9)	0.89	22	0.3(0.0)
Acetophenone	0.76 (1.3)	-1.3	2.6	2.2 (1.9)	0.23	5.3	13.2(5.9)
Benzothiazole	0.46 (0.26)	0.29	0.82	1.2 (0.36)	0.61	1.7	0.3(0.0)
D5 Siloxane	6.4 (5.5)	9.8	140	12 (10)	4.5	290	1.9(1.0)
1-Methyl-2-pyrrolidinone	0.28 (0.01)	0.27	0.29	3.6 (5.6)	0.27	10	
Caprolactam	0.76 (0.44)	0.57	1.7	0.92 (0.55)	0.53	1.8	
d-Limonene	8.6 (15)	1.6	40	38 (81)	1.2	200	0.3(0.0)
Acetaldehyde	11 (4.4)	5.5	16	14 (5.1)	8.1	21	7.3(3.1)
Formaldehyde	13 (2.9)	9.2	16	24 (8.4)	11	35	3.2(1.8)

[1] TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate;
TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol diisobutyrate

Table 15. VOC Concentrations (μg m^{-3}) averaged across three seasons, two climate zones, and four schools.

	All Measurements						
	IHPAC			**10 SEER**			**Outside Air**
Max	**Avg (Stdev)**	**Min**	**Max**	**Avg (Stdev)**	**Min**	**Max**	**Avg (Stdev)**
1-Butanol	3.2 (4.0)	0.53	15	5.0 (4.7)	0.59	20	1.0(0.6)
2-(2-Butoxyethoxy)ethanol	7.1 (7.9)	4.0	35	11 (9.1)	4.0	38	4.3(---)
2-Butoxyethanol	11 (25)	1.4	110	32 (39)	2.2	170	0.8(0.4)
2-Ethyl-1-hexanol	0.94 (0.53)	0.53	2.4	2.3 (0.93)	0.56	3.6	0.8(0.5)
2-Propanol	9.0 (14)	0.0	44	20 (34)	0.0	120	1.1(0.7)
BHT	0.46 (0.31)	0.26	1.5	1.0 (1.0)	0.26	4.1	0.3(0.0)
DPGME	4.3 (4.9)	1.6	17	12 (17)	1.5	54	
Ethanol	4.3 (5.6)	0.0	190	26 (57)	11	2300	8.9(6.8)
Ethylene glycol	13 (1.0)	12	14				
Phenol	2.6 (1.7)	0.0	6.3	5.5 (4.7)	1.6	22	5.3(3.1)
Propylene glycol	17 (8.9)	10	29	15 (17)	2.7	55	
Benzaldehyde	3.7 (2.3)	0.40	8.7	5.6 (2.2)	2.2	9.7	22(12)
Hexanal	2.3 (4.0)	-3.9	8.7	9.5 (6.9)	-5.2	18	-0.9(2.1)
Octanal	1.6 (1.1)	-1.1	4.5	3.7 (2.4)	-1.2	8.2	0.8(1.2)
Pentanal	0.16 (1.4)	-1.9	3.3	2.0 (1.9)	-2.0	6.0	-0.6(1.0)
n-Decane	-0.53 (0.58)	-1.2	0.29	0.37 (0.68)	-1.2	1.5	-0.6(0.6)
n-Dodecane	0.61 (0.92)	-0.52	3.1	2.7 (2.4)	0.44	8.2	0.4(0.9)
n-Nonane	0.43 (0.24)	0.25	1.1	0.55 (0.24)	0.26	1.0	0.3(0.2)
n-Undecane	0.62 (0.35)	0.25	1.5	1.5 (1.3)	0.26	5.8	0.4(0.2)
1,2,4-Trimethylbenzene	0.89 (0.67)	0.26	1.9	1.5 (1.2)	0.27	4.6	0.8(0.6)
m-Xylene	3.9 (3.3)	0.64	10	6.2 (6.5)	1.5	26	3.2(2.8)
Naphthalene	0.19 (0.14)	0.0	0.29	0.41 (0.51)	0.0	2.3	0.2(0.1)
Toluene	9.1 (6.9)	1.2	20	16 (11)	2.0	46	12(18)
Butyl acetate	6.7 (8.8)	0.74	33	17 (56)	0.78	240	0.6(0.3)
TMPD-DIB[1]	3.4 (2.7)	1.5	11	5.7 (3.2)	2.1	15	0.2(0.1)
TMPD-MIB[1]	3.7 (1.9)	1.6	9.2	7.2 (4.7)	1.8	18	0.6(0.0)
1,4-Dichlorobenzene	1.2 (1.3)	0.28	5.5	3.7 (4.7)	0.27	17	0.3(0.0)
Dichloromethane	-0.34 (2.5)	-5.0	3.6	0.22 (2.9)	-5.0	6.1	-0.6(2.5)
Tetrachloroethene	0.36 (0.18)	0.16	0.77	0.61 (0.56)	0.0	2.1	0.3(0.2)
2-Butanone	1.9 (2.0)	0.51	6.1	2.2 (1.6)	0.57	6.7	1.8(1.2)
2-Propanone	2.2 (11)	-19	27	14 (19)	-15	56	-1.0(7.8)
4-Methyl-2-pentanone	15 (19)	0.28	68	30 (100)	0.67	430	0.7(0.5)
Acetophenone	1.1 (1.1)	-1.3	3.0	2.3 (1.5)	0.23	5.3	15(11)
Benzothiazole	0.63 (0.49)	0.0	1.9	1.4 (0.72)	0.61	3.2	0.1(0.1)
D5 Siloxane	46 (41)	7.1	142	67 (78)	3.8	290	1.4(1.1)
1-Methyl-2-pyrrolidinone	0.28 (0.01)	0.26	0.29	3.2 (5.6)	0.26	16	
Caprolactam	1.1 (0.95)	0.53	4.1	1.4 (0.82)	0.53	2.9	
d-Limonene	5.4 (10)	0.79	40	20 (47)	0.77	200	0.2(0.1)
Acetaldehyde	7.8 (4.3)	1.1	16	12 (5.2)	5.0	21	5.4(3.4)
Formaldehyde	16 (7.9)	7.4	38	24 (6.5)	11	35	3.9(3.2)

[1] TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate;
TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol diisobutyrate

Table 16. Particle Mass Concentrations (μg/m^3) for School N1

		21 10 SEER			22 IHPAC			23 10 SEER			24 IHPAC			Outdoor		
Season	**Size (μm)**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**
Spring	0.3	0.14 (0.04)	0.09	0.29	0.2 (0.09)	0.07	0.37	0.22 (0.12)	0.08	0.57	0.14 (0.07)	0.05	0.31	0.36 (0.32)	0.06	1.5
	0.5	0.05 (0.02)	0.03	0.12	0.08 (0.03)	0.04	0.13	0.17 (0.09)	0.05	0.42	0.05 (0.02)	0.02	0.10	0.09 (0.08)	0.02	0.34
	0.7	0.05 (0.02)	0.02	0.12	0.08 (0.03)	0.03	0.15	0.17 (0.11)	0.05	0.59	0.04 (0.02)	0.01	0.084	0.07 (0.05)	0.01	0.23
	1.0	0.33 (0.16)	0.16	0.77	0.52 (0.26)	0.14	1.3	1.8 (1.3)	0.44	7.4	0.38 (0.32)	0.08	0.99	0.28 (0.19)	0.06	0.86
	2.0	1.9 (0.9)	0.54	3.9	4.5 (3.0)	0.71	14	16 (14)	2.4	74	2.8 (4.1)	0.26	8.8	2.8 (1.6)	0.78	7.6
	5.0	4.1 (3.1)	0.13	13	16 (13)	0.25	54	61 (51)	2.4	270	32 (320)	0.88	59	4.5 (4.7)	1.0	23
	Sum	6.5 (4.0)	1.3	17	21 (16)	1.4	69	79 (65)	5.7	360	36 (320)	1.5	69	8.2 (5.6)	2.7	29
	PM2.5	2.5			5.4			18			3.4			3.6		
Fall AM	0.3				0.82 (0.36)	0.39	1.7	0.85 (0.31)	0.35	1.3				1.8 (0.85)	0.67	3.2
	0.5				0.44 (0.31)	0.15	1.3	0.21 (0.08)	0.07	0.35				0.47 (0.32)	0.13	1.3
	0.7				0.39 (0.41)	0.09	1.6	0.16 (0.07)	0.04	0.29				0.34 (0.17)	0.11	0.78
	1.0				5.3 (6.4)	0.59	24	1.3 (0.75)	0.24	3.0				1.4 (0.59)	0.53	3.2
	2.0				54 (71)	2.2	280	8.0 (6.4)	0.56	26				6.5 (4.6)	2.4	25
	5.0				160 (180)	3.3	730	39 (39)	0.90	160				17 (17)	3.4	82
	Sum				220 (250)	7.6	1000	50 (47)	2.5	190				28 (22)	9.5	110
	PM2.5				61			11						11		
Fall PM	0.3							0.67 (0.21)	0.39	1.2						
	0.5							0.23 (0.09)	0.09	0.37						
	0.7							0.26 (0.12)	0.07	0.52						
	1.0							1.9 (1.1)	0.28	4.3						
	2.0							19 (13)	0.98	48						
	5.0							67 (48)	0.27	160						
	Sum							90 (62)	2.2	210						
	PM2.5							22.06								
Winter	0.3				1.1 (0.26)	0.54	1.5	1.1 (0.27)	0.71	2.0	1.1 (0.36)	0.42	1.7	3.2 (0.64)	2.1	4.1
	0.5				0.54 (0.25)	0.16	1.3	0.56 (0.18)	0.24	1.0	0.47 (0.19)	0.13	0.9	1.5 (0.35)	0.81	2.3
	0.7				0.29 (0.27)	0.05	1.3	0.35 (0.15)	0.10	0.74	0.27 (0.11)	0.08	0.58	1.1 (0.40)	0.53	2.2
	1.0				2.7 (3.8)	0.23	18	2.5 (1.3)	0.33	5.6	0.99 (0.37)	0.27	1.8	2.8 (1.1)	1.5	5.6
	2.0				24 (38)	0.68	180	16 (11)	0.71	47	6.6 (3.7)	1.3	15	13 (5.4)	8.0	33
	5.0				75 (89)	1.1	400	55 (43)	0.68	180	26 (24)	1.8	72	23 (22)	8.2	120
	Sum				100 (130)	3.0	600	76 (56)	3.0	230	35 (28)	5.1	91	45 (27)	26	160
	PM2.5				29			21			9.4			22		

Table 17. Binned and summed particle mass concentrations (μg/m^3) for School S1

		13 IHPAC			14 10 SEER			15 IHPAC			16 10 SEER			Outdoor		
Season	**Size (μm)**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**
Spring	0.3	3.1 (0.25)	0.27	3.3	1.8 (0.70)	0.99	3.0	3.0 (0.39)	1.9	3.7	3.4 (0.35)	2.2	3.9	4.2 (0.2)	3.8	4.6
	0.5	1.7 (0.30)	0.14	2.1	0.69 (0.39)	0.31	1.6	2.9 (1.0)	1.3	4.2	1.6 (0.62)	0.54	2.5	7.3 (0.43)	6.5	8.2
	0.7	0.47 (0.09)	0.04	0.57	0.27 (0.10)	0.13	0.44	1.0 (0.45)	0.35	1.7	0.61 (0.23)	0.20	0.93	6.0 (0.67)	5.0	7.3
	1.0	1.6 (0.32)	0.12	2.0	1.9 (1.1)	0.58	4.7	2.7 (1.0)	0.93	4.4	2.7 (0.88)	1.0	4.4	13 (1.7)	10	16
	2.0	3.7 (2.3)	0.16	5.1	11 (8.7)	0.74	32	6.8 (3.5)	0.7	16	5.9 (3.1)	1.7	14	47 (6.6)	35	61
	5.0	17 (20)	0.44	20	39 (28)	1.3	110	23 (20)	0.0	91	22 (16)	1.8	69	15 (28)	1.9	98
	Sum	28 (22)	1.2	33	55 (37)	6.9	150	40 (24)	5.5	110	36 (19)	12	93	93 (32)	66	190
	PM2.5	11			16			16			14			78		
Fall	0.3	3.1 (0.84)	1.7	4.1	2.7 (0.97)	1.1	4.0	2.9 (0.66)	1.6	3.8				5.7 (1.3)	3.1	7.0
	0.5	1.9 (0.99)	0.5	3.5	1.4 (0.76)	0.37	3.4	1.7 (0.72)	0.49	2.9				4.5 (2.0)	1.2	7.6
	0.7	0.76 (0.37)	0.2	1.5	0.88 (0.5)	0.26	2.1	0.69 (0.24)	0.25	1.1				2.2 (1.1)	0.62	4.3
	1.0	2.0 (0.81)	0.58	3.9	3.1 (1.9)	0.96	6.8	2.6 (0.73)	1.2	4.7				4.7 (1.6)	2.1	8.2
	2.0	10 (8.4)	1.2	38	16 (10)	0.89	38	10 (7.8)	1.2	38				30 (6.4)	16	43
	5.0	32 (34)	0.0	150	40 (26)	0.31	110	38 (39)	0.0	180				35 (32)	10	140
	Sum	50 (43)	6.7	200	64 (38)	5.8	160	56 (46)	9.5	230				82 (36)	40	200
	PM2.5	18			24			18						47		
Winter	0.3	2.1 (0.47)	1.3	3.1	1.2 (0.6)	0.56	2.6	1.5 (0.40)	0.68	2.2	0.99 (0.36)	0.41	1.8	2.7 (0.54)	1.8	3.7
	0.5	1.9 (0.54)	0.89	2.8	0.83 (0.37)	0.49	1.9	1.6 (0.61)	0.23	2.4	0.71 (0.44)	0.083	1.6	2.5 (0.64)	1.5	3.5
	0.7	1.5 (0.65)	0.45	2.4	0.46 (0.16)	0.22	0.91	1.0 (0.53)	0.08	1.8	0.36 (0.16)	0.046	0.73	0.88 (0.31)	0.43	1.4
	1.0	2.8 (1.1)	1.0	4.8	3.1 (1.5)	0.50	6.0	2.6 (1.2)	0.31	4.8	2.0 (0.9)	0.22	3.8	3.2 (0.96)	1.3	5.0
	2.0	17 (9.0)	5.1	46	17 (12)	0.38	43	6.5 (5.1)	0.46	24	10 (6.4)	0.62	25	7.6 (5.0)	2.6	23
	5.0	35 (31)	0.78	140	66 (52)	0.00	230	23 (31)	0.0	140	28 (20)	0.77	92	42 (52)	10	280
	Sum	60 (41)	11	200	89 (64)	2.5	270	36 (37)	1.8	180	43 (27)	2.5	120	59 (57)	19	320
	PM2.5	25			23			13			14			17		

Table 18. Binned and summed particle mass concentrations (μg/m^3) for School N2

		25 IHPAC			26 10 SEER			Outdoor		
Season	**Size (μm)**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**
Spring	0.3	0.18 (0.10)	0.05	0.37	0.21 (0.086)	0.067	0.3	0.21 (0.12)	0.071	0.42
	0.5	0.09 (0.05)	0.022	0.19	0.15 (0.087)	0.018	0.27	0.037 (0.018)	0.015	0.088
	0.7	0.06 (0.034)	0.012	0.15	0.16 (0.11)	0.014	0.31	0.03 (0.014)	0.013	0.075
	1.0	0.63 (0.41)	0.083	1.7	1.7 (1.2)	0.093	3.5	0.17 (0.076)	0.068	0.41
	2.0	5.9 (4.4)	0.37	17	8.6 (6.4)	0.22	20	0.93 (0.4)	0.32	2.2
	5.0	29 (25)	0.13	94	33 (27)	0.13	95	3.0 (1.9)	0.13	9.4
	Sum	36 (30)	0.84	110	44 (35)	0.67	120	4.4 (2.3)	0.79	12
	PM2.5	6.9			11			1.4		
Fall	0.3	0.80 (0.27)	0.38	1.3	0.73 (0.16)	0.45	1.1	1.6 (0.62)	0.74	2.5
	0.5	0.19 (0.05)	0.09	0.28	0.21 (0.06)	0.12	0.35	0.35 (0.15)	0.17	0.71
	0.7	0.14 (0.05)	0.05	0.24	0.15 (0.07)	0.06	0.29	0.24 (0.05)	0.16	0.37
	1.0	1.0 (0.54)	0.28	2.3	1.4 (0.82)	0.30	2.9	0.92 (0.17)	0.69	1.4
	2.0	6.0 (4.7)	0.6	18	11 (8.1)	0.85	26	8.2 (2.4)	5.8	17
	5.0	20 (19)	0.0	68	39 (32)	0.79	100	15 (8.5)	3.4	46
	Sum	28 (24)	1.8	90	52 (41)	3.3	130	26 (11)	14	66
	PM2.5	8.1			13			11		
Winter	0.3	1.7 (0.43)	1.1	2.4				2.9 (0.74)	1.6	3.9
	0.5	0.79 (0.23)	0.37	1.3				1.5 (0.40)	0.89	2.4
	0.7	0.38 (0.11)	0.16	0.56				0.98 (0.32)	0.48	1.6
	1.0	1.4 (0.35)	0.65	2.4				2.8 (0.86)	1.4	4.3
	2.0	4.4 (3.1)	0.94	13				5.8 (0.84)	3.9	7.8
	5.0	15 (14)	0.38	59				15 (4.4)	7.9	30
	Sum	24 (17)	4.6	77				29 (5.2)	21	45
	PM2.5	8.7						14		

Table 19. Binned and summed particle mass concentrations (µg/m^3) for School S2

		35 IHPAC			36 10 SEER			Outdoor		
Season	**Size (µm)**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**
Spring	0.3	2.0 (0.77)	0.96	3.3	1.9 (0.96)	0.8	3.8			
	0.5	1.2 (0.86)	0.35	3.0	0.92 (0.58)	0.43	2.4			
	0.7	0.55 (0.36)	0.19	1.3	0.51 (0.22)	0.20	1.0			
	1.0	2.3 (1.3)	0.69	5.3	2.4 (1.6)	0.44	5.0			
	2.0	7.6 (7.2)	0.63	35	17 (14)	0.51	41			
	5.0	19 (25)	0.0	140	38 (39)	0.13	130			
	Sum	33 (32)	4.4	180	61 (53)	4.7	180			
	PM2.5	14			23					
Fall	0.3							3.9 (1.3)	0.48	4.9
	0.5							3.3 (2.0)	0.05	5.4
	0.7							1.4 (0.9)	0.02	2.7
	1.0							4.9 (2.8)	0.18	8.5
	2.0							10 (5.4)	1.0	20
	5.0							32 (22)	6.6	93
	Sum							56 (29)	8.8	130
	PM2.5							24		
Winter	0.3	1.6 (0.34)	1.0	2.3	1.3 (0.34)	0.43	1.9	2.6 (0.38)	2.0	3.4
	0.5	1.3 (0.54)	0.36	2.2	1.0 (0.46)	0.14	1.7	1.9 (0.28)	1.3	2.4
	0.7	0.54 (0.25)	0.16	0.97	0.46 (0.23)	0.07	0.79	1.1 (0.22)	0.64	1.6
	1.0	1.6 (0.63)	0.53	2.7	0.83 (0.34)	0.27	1.3	2.7 (0.5)	1.6	3.9
	2.0	3.8 (2.3)	0.64	9.3	3.5 (2.7)	0.45	9.0	4.6 (1.6)	2.5	10
	5.0	10 (11)	0.23	37	13 (15)	0.0	34	14 (12)	4.0	61
	Sum	19 (14)	3.2	54	20 (18)	4.1	47	27 (13)	14	82
	PM2.5	8.8			7.1			13		

Table 20. School day hours Indoor and Outdoor Temperatures in Northern California Classrooms.

			Temperature (°F)			RH (%)		
Site	**Room**	**Season**	**Avg (Stdev)**	**1st %**	**99th %**	**Avg (Stdev)**	**1st %**	**99th %**
N1	20	All	71.0 (4.9)	57.4	84.0	46.7 (10.1)	25.7	69.7
	IHPAC	Winter	70.4 (5.3)	55.6	84.5	44.1 (10.4)	24.3	73.6
		Spring	71.0 (4.0)	62.7	83.4	47.0 (10.3)	26.4	69.7
		Summer	73.3 (4.8)	66.3	85.2	53.6 (7.6)	37.5	70.1
		Fall	69.8 (4.7)	57.6	79.3	44.3 (8.6)	25.9	64.6
	21	All	72.1 (7.6)	51.9	93.1	48.3 (9.6)	27.7	73.6
	10 SEER	Winter	69.3 (7.2)	48.8	82.8	51.8 (11.3)	26.6	77.6
		Spring	74.5 (5.1)	63.3	86.9	47.6 (7.8)	31.9	65.6
		Summer	78.3 (7.6)	66.0	96.8	44.4 (7.7)	30.1	59.8
		Fall	68.8 (5.8)	55.7	82.7	47.5 (8.5)	25.5	73.2
	22	All	70.9 (4.0)	59.0	82.5	48.2 (10.0)	26.4	69.1
	IHPAC	Winter	70.5 (4.9)	58.0	82.3	45.4 (9.6)	25.5	68.5
		Spring	72.1 (3.4)	66.0	82.9	45.4 (10.0)	24.7	69.5
		Summer	71.3 (3.7)	66.5	84.0	56.7 (6.5)	40.2	70.7
		Fall	70.1 (3.1)	61.9	77.1	47.5 (9.2)	28.1	67.9
	23	All	71.3 (5.7)	53.4	84.6	53.5 (7.3)	32.1	68.5
	10 SEER	Winter	71.0 (7.1)	49.1	81.1	54.6 (8.2)	31.3	70.9
		Spring	71.7 (4.3)	62.7	80.1	53.5 (6.9)	34.5	65.6
		Summer	71.4 (5.3)	63.6	89.0	55.1 (6.0)	34.4	64.2
		Fall	71.4 (5.1)	57.1	81.3	51.0 (6.8)	30.0	67.1
	24	All	71.0 (3.8)	62.3	81.8	49.2 (9.0)	28.5	68.5
	IHPAC	Winter	69.4 (3.5)	59.5	77.0	48.8 (9.9)	27.0	69.1
		Spring	71.2 (3.1)	63.4	79.6	48.6 (9.1)	28.1	68.7
		Summer	72.9 (4.1)	66.1	83.6	54.4 (6.5)	38.8	66.6
		Fall	71.3 (3.7)	63.2	79.1	46.0 (7.8)	29.4	63.8
	Outdoor	All	67.2 (13.5)	41.3	98.7	55.6 (18.1)	23.7	92.5
		Winter	58.4 (8.5)	40.6	78.7	66.2 (17.1)	27.4	94.6
		Spring	69.8 (9.9)	50.3	94.1	49.5 (14.1)	24.0	83.3
		Summer	82.8 (10.1)	59.5	102.8	42.6 (11.9)	22.1	73.9
		Fall	63.7 (12.3)	39.2	93.4	57.6 (17.7)	23.6	91.8
N2	25	All	72.8 (5.8)	63.3	96.0	45.6 (9.2)	26.3	67.5
	IHPAC	Winter	70.7 (3.4)	62.4	81.2	45.4 (9.5)	25.3	67.9
		Spring	71.3 (3.8)	64.2	82.5	46.6 (9.3)	27.6	68.2
		Summer	78.5 (8.8)	63.4	100.9	44.8 (9.5)	26.5	65.7
		Fall	72.1 (2.9)	64.7	78.8	45.7 (8.3)	28.6	66.8
	26	All	71.7 (12.6)	32.0	94.8	44.9 (14.4)	0.0	65.6
	10 SEER	Winter	68.3 (11.7)	32.0	88.5	48.7 (15.2)	0.0	66.2
		Spring	73.4 (6.2)	58.3	88.7	48.3 (7.7)	31.0	63.6
		Summer	80.4 (9.2)	61.3	97.7	41.2 (8.7)	28.0	64.4
		Fall	67.2 (16.7)	32.0	84.2	38.3 (19.2)	0.0	59.8
	27	All	71.4 (6.0)	60.6	92.3	45.4 (10.2)	25.2	69.6
	IHPAC	Winter	70.0 (4.3)	59.2	80.8	44.2 (10.2)	23.7	67.5
		Spring	69.8 (4.2)	61.0	81.2	46.7 (10.4)	26.9	71.6
		Summer	75.8 (8.9)	60.2	97.3	46.1 (10.0)	29.0	68.3
		Fall	71.0 (3.8)	62.7	81.2	45.4 (9.8)	24.2	66.7
	Outdoor	All	68.3 (13.7)	43.2	100.4	54.1 (22.0)	20.9	99.5
		Winter	58.9 (8.5)	41.6	80.8	67.1 (23.8)	25.1	163.8
		Spring	70.0 (10.2)	50.2	94.6	47.3 (15.3)	21.5	86.0
		Summer	83.7 (10.5)	60.5	105.1	39.3 (12.3)	19.0	73.5
		Fall	66.4 (12.2)	41.7	95.2	55.1 (19.8)	21.0	96.1

Table 21. Schoolday Hours Indoor and Outdoor Temperatures in Southern California Classrooms.

			Temperature (°F)			RH (%)		
Site	Room	Season	Avg (Stdev)	1st %	99th %	Avg (Stdev)	1st %	99th %
S1	13 IHPAC	All	72.4 (3.9)	61.4	83.4	44.8 (12.6)	18.6	66.5
		Winter	71.5 (4.2)	60.0	79.2	39.2 (11.9)	16.8	65.2
		Spring	72.3 (2.9)	64.6	80.6	49.2 (9.4)	23.2	65.1
		Summer	74.1 (4.6)	67.5	92.3	54.4 (6.6)	34.5	69.3
		Fall	72.2 (3.0)	63.7	78.8	39.1 (13.7)	18.3	64.9
	14 10 SEER	All	74.1 (6.2)	54.4	86.0	46.4 (9.6)	23.1	63.8
		Winter	71.4 (8.1)	53.1	85.1	43.6 (9.5)	21.5	62.4
		Spring	75.1 (4.1)	63.1	83.9	48.2 (7.0)	28.8	62.8
		Summer	76.7 (3.6)	70.1	89.6	52.5 (7.3)	36.7	65.7
		Fall	74.4 (5.2)	58.6	84.7	42.7 (10.5)	21.9	62.0
	15 IHPAC	All	72.5 (4.1)	61.9	84.8	46.4 (218.8)	18.6	65.1
		Winter	71.4 (4.7)	57.8	80.1	45.0 (376.9)	18.0	59.1
		Spring	72.5 (3.0)	65.7	79.9	47.6 (10.1)	21.7	65.0
		Summer	74.5 (4.4)	68.2	90.5	54.6 (6.3)	37.3	67.3
		Fall	72.2 (2.8)	64.5	79.2	39.0 (13.3)	18.7	63.5
	16 10 SEER	All	74.2 (6.5)	54.5	91.7	40.3 (9.6)	17.7	58.8
		Winter	71.9 (8.6)	53.2	98.7	36.8 (10.4)	15.8	56.9
		Spring	75.2 (4.7)	61.5	84.4	43.5 (7.4)	26.1	59.3
		Summer	77.1 (3.1)	69.9	89.1	45.1 (6.4)	34.0	60.9
		Fall	74.0 (5.2)	57.2	82.6	37.8 (9.9)	18.3	56.3
	17 IHPAC	All	73.6 (4.2)	61.9	87.7	43.9 (12.3)	20.2	65.1
		Winter	72.4 (4.1)	59.7	80.7	37.5 (11.0)	19.3	60.5
		Spring	73.0 (2.9)	68.0	81.4	48.5 (10.7)	20.2	66.3
		Summer	76.1 (5.1)	68.7	93.7	52.9 (6.1)	34.5	65.2
		Fall	73.2 (3.0)	64.9	82.0	39.1 (12.9)	21.0	66.2
	Outdoor	All	72.1 (15.9)	32.0	103.7	36.3 (22.3)	0.0	87.4
		Winter	66.0 (9.0)	49.9	90.5	38.7 (25.5)	1.6	92.6
		Spring	73.6 (9.9)	55.6	96.2	42.8 (17.6)	10.7	80.6
		Summer	87.7 (10.4)	64.1	106.6	36.5 (15.1)	10.0	75.0
		Fall	64.4 (21.6)	32.0	101.2	25.8 (23.6)	0.0	81.8
S2	35 IHPAC	All	71.8 (5.1)	56.7	84.3	44.3 (12.9)	15.9	67.9
		Winter	70.5 (5.8)	53.3	80.2	38.3 (11.3)	14.5	60.7
		Spring	72.3 (3.9)	59.6	81.1	48.7 (10.2)	20.6	67.7
		Summer	74.2 (4.7)	66.2	86.0	53.7 (7.7)	34.5	70.1
		Fall	70.8 (4.3)	59.2	80.9	39.7 (14.8)	16.3	68.6
	36 10 SEER	All	73.1 (8.3)	51.5	92.4	40.2 (11.5)	16.2	64.7
		Winter	69.3 (8.9)	49.8	88.2	37.7 (11.5)	15.3	56.2
		Spring	73.8 (7.1)	51.9	89.2	42.2 (9.7)	19.0	58.9
		Summer	79.7 (5.6)	69.8	97.3	44.6 (9.1)	27.8	64.6
		Fall	71.9 (6.3)	55.2	84.1	37.5 (13.4)	15.0	69.1
	37 IHPAC	All	71.7 (5.5)	56.0	85.2	45.5 (12.5)	17.8	68.3
		Winter	69.5 (5.6)	54.8	80.6	40.6 (12.1)	16.1	64.1
		Spring	70.7 (4.7)	56.4	81.8	49.6 (10.7)	22.7	67.9
		Summer	75.6 (4.7)	67.2	86.7	52.3 (8.2)	32.3	72.6
		Fall	72.1 (4.3)	60.6	82.7	41.8 (13.7)	17.8	68.9
	Outdoor	All	76.2 (14.4)	51.7	108.6	38.7 (18.6)	10.8	83.9
		Winter	65.8 (8.0)	50.7	86.5	44.0 (20.6)	9.8	88.6
		Spring	78.1 (11.3)	56.6	102.3	39.0 (15.2)	13.8	77.0
		Summer	93.8 (11.0)	66.0	113.0	32.3 (12.9)	12.1	71.1
		Fall	73.7 (10.7)	52.6	99.8	36.0 (20.5)	10.8	81.5

Table 22. Northern and Southern California schools daily energy consumption statistics by classroom.

Energy Consumption (Watt-Hours)											
Site	Room	Season	Avg (Stdev)	1st %	99th %	Site	Room	Season	Avg (Stdev)	1st %	99th %
N1	20	All	2730 (1900)	12.0	7790	S1	13	All	3880 (3360)	3.00	12100
	IHPAC	Winter	2560 (1230)	0.00	5740		IHPAC	Winter	1640 (1220)	0.00	5600
		Spring	2510 (2060)	16.9	8790			Spring	3640 (2250)	18.4	10800
		Summer	4280 (2220)	19.1	8810			Summer	7770 (3740)	0.00	13800
		Fall	1680 (1160)	12.0	6190			Fall	3680 (2750)	8.00	10900
	21	All	1860 (1690)	62.2	6180		14	All	4090 (4640)	18.0	18300
	10 SEER	Winter	1610 (1300)	68.0	5300		10 SEER	Winter	904 (1420)	18.0	4710
		Spring	1670 (1640)	31.0	7040			Spring	3850 (3090)	1.60	12600
		Summer	2890 (2060)	61.5	6320			Summer	9500 (5340)	19.4	20100
		Fall	1420 (1470)	65.1	5210			Fall	3860 (3570)	19.0	14200
	IHPAC	All	4160 (3020)	91.3	12500		15	All	3970 (4500)	2.00	11600
	22	Winter	2870 (1460)	52.6	7050		IHPAC	Winter	2150 (5750)	0.00	6130
		Spring	3240 (1780)	91.3	8250			Spring	3850 (2710)	18.6	12100
		Summer	7830 (3840)	183	14400			Summer	7240 (3350)	36.5	12000
		Fall	3490 (1860)	99.0	8220			Fall	3630 (2790)	3.00	11600
	23	All	3910 (3600)	71.7	13800		16	All	2830 (3420)	0.00	13300
	10 SEER	Winter	1670 (1210)	77.0	4750		10 SEER	Winter	1070 (1370)	0.00	5060
		Spring	3950 (2950)	34.0	10700			Spring	2100 (2250)	0.00	8840
		Summer	8560 (3680)	71.0	14800			Summer	6990 (4010)	0.00	13500
		Fall	2680 (1970)	77.0	7140			Fall	2140 (2590)	0.00	11000
	24	All	4090 (3370)	100	13700		17	All	4020 (4940)	1.00	11400
	IHPAC	Winter	2250 (1190)	46.2	5400		IHPAC	Winter	2150 (6920)	0.00	5820
		Spring	4280 (2490)	96.1	9900			Spring	3960 (2720)	42.3	11400
		Summer	8250 (4020)	119	15600			Summer	7160 (3310)	0.00	12300
		Fall	2560 (1710)	100	7700			Fall	3780 (2290)	19.0	9170
N2	25	All	3120 (2660)	0.00	13100	S2	35	All	2960 (2670)	142	12100
	IHPAC	Winter	2520 (1730)	95.0	7870		IHPAC	Winter	1870 (1100)	142	4690
		Spring	3510 (2970)	6.90	12100			Spring	2480 (1580)	70.4	7600
		Summer	3970 (3860)	0.00	13600			Summer	5230 (3750)	98.3	12600
		Fall	2840 (1750)	95.0	7240			Fall	2900 (2730)	186	13200
	26	All	2350 (2460)	0.00	10200		36	All	2190 (2070)	0.00	8840
	10 SEER	Winter	2040 (1660)	65.0	6560		10 SEER	Winter	1760 (1530)	0.00	4590
		Spring	1950 (2120)	8.30	8900			Spring	2060 (1430)	0.00	5860
		Summer	2920 (3780)	0.00	12700			Summer	3240 (2990)	0.00	8930
		Fall	2740 (2110)	62.9	7990			Fall	1970 (1950)	0.00	9560
	27	All	3070 (2240)	0.00	10400		37	All	2060 (1900)	2.00	8340
	IHPAC	Winter	3110 (1660)	145	7450		IHPAC	Winter	1370 (1000)	6.00	3460
		Spring	2700 (2100)	7.00	9030			Spring	1880 (1350)	12.0	6600
		Summer	3750 (3290)	0.00	11500			Summer	3380 (2600)	5.60	8700
		Fall	2690 (1750)	153	6710			Fall	2000 (2020)	0.00	9560

Table 23. IHPAC operation mode seasonally and annually. The statistics indicate the percentage of time the IHPAC units operated in each of the following modes: supply fan only, fan plus stage one compressor, fan plus stage 2 compressor, or system off. The statistics are provided for 24 hours/7 days per week, and scheduled school hours only.

			All Hours				School Hours			
Location	**Room**	**Season**	**Off**	**Fan**	**Stage 1**	**Stage 2**	**Off**	**Fan**	**Stage 1**	**Stage 2**
N1	20	All Year	68.5%	17.4%	10.7%	3.4%	31.7%	39.4%	21.4%	7.1%
		Winter	42.2%	37.6%	16.6%	3.6%	6.1%	67.9%	18.4%	5.4%
		Spring	76.5%	13.9%	7.8%	1.8%	33.1%	40.7%	23.0%	3.2%
		Summer	69.1%	10.9%	13.0%	7.0%	35.6%	21.3%	26.8%	16.4%
		Fall	81.9%	12.0%	6.0%	0.2%	49.6%	36.2%	13.8%	0.5%
	22	All Year	64.3%	19.8%	11.2%	4.8%	17.1%	46.5%	23.8%	12.2%
		Winter	53.5%	28.6%	13.8%	4.1%	8.9%	62.2%	21.8%	4.8%
		Spring	70.8%	18.2%	8.1%	2.9%	22.4%	51.3%	20.1%	6.3%
		Summer	65.4%	12.1%	13.8%	8.8%	22.6%	21.3%	27.9%	28.1%
		Fall	63.5%	24.7%	9.5%	2.3%	8.6%	62.2%	24.9%	4.3%
	24	All Year	68.0%	0.1%	28.9%	3.1%	19.0%	0.1%	69.7%	10.7%
		Winter	56.4%	0.1%	42.8%	0.7%	4.0%	0.1%	92.7%	1.0%
		Spring	73.2%	0.0%	26.4%	0.3%	16.5%	0.0%	82.3%	1.2%
		Summer	67.2%	0.1%	23.8%	8.9%	32.9%	0.2%	35.4%	31.5%
		Fall	72.7%	0.1%	26.1%	1.1%	16.8%	0.2%	80.3%	2.8%
N2	25	All Year	67.9%	16.3%	8.8%	7.0%	27.9%	44.0%	18.0%	10.1%
		Winter	67.9%	19.2%	8.9%	4.0%	26.6%	58.6%	10.6%	4.2%
		Spring	71.8%	18.2%	6.8%	3.2%	23.0%	48.8%	19.9%	8.3%
		Summer	60.1%	9.8%	12.5%	17.6%	43.7%	12.4%	21.8%	22.1%
		Fall	73.5%	18.5%	6.4%	1.5%	12.9%	63.1%	20.9%	3.1%
	27	All Year	67.4%	15.5%	12.1%	5.0%	27.3%	45.8%	18.5%	8.5%
		Winter	65.2%	18.2%	12.1%	4.4%	26.9%	52.6%	14.6%	5.9%
		Spring	73.7%	18.6%	5.2%	2.5%	23.8%	56.7%	13.8%	5.8%
		Summer	58.5%	6.8%	24.2%	10.5%	37.2%	14.7%	30.0%	18.0%
		Fall	74.5%	19.5%	4.6%	1.3%	17.8%	66.9%	13.6%	1.8%
S1	35	All Year	63.9%	24.9%	7.3%	3.9%	26.1%	47.3%	17.6%	9.0%
		Winter	60.5%	28.3%	8.3%	2.9%	15.0%	68.9%	14.5%	1.6%
		Spring	72.6%	19.3%	5.9%	2.2%	20.8%	57.7%	17.8%	3.8%
		Summer	72.4%	12.5%	9.6%	5.4%	41.1%	21.3%	21.4%	16.3%
		Fall	41.3%	48.5%	5.0%	5.1%	21.7%	51.3%	14.4%	12.7%
	37	All Year	75.7%	15.7%	6.4%	2.2%	40.8%	37.1%	15.0%	7.1%
		Winter	53.0%	37.5%	8.8%	0.7%	31.2%	56.6%	10.2%	2.0%
		Spring	80.2%	14.0%	4.2%	1.6%	33.0%	48.4%	13.7%	4.9%
		Summer	78.4%	8.8%	9.1%	3.7%	47.0%	20.2%	21.2%	11.6%
		Fall	86.7%	7.6%	3.5%	2.3%	52.6%	27.2%	12.0%	8.2%
S2	13	All Year	67.0%	18.4%	7.2%	7.4%	17.2%	39.1%	21.8%	21.5%
		Winter	57.2%	34.5%	6.8%	1.5%	14.3%	67.3%	13.6%	2.4%
		Spring	69.2%	19.6%	7.4%	3.8%	17.1%	46.2%	25.0%	11.7%
		Summer	66.4%	9.9%	7.0%	16.7%	20.1%	15.2%	18.6%	46.1%
		Fall	74.2%	13.3%	7.7%	4.8%	15.5%	38.1%	29.7%	16.7%
	15	All Year	69.7%	16.4%	8.2%	5.7%	19.1%	40.4%	21.2%	18.8%
		Winter	67.1%	24.9%	6.4%	1.7%	18.8%	73.2%	7.4%	0.7%
		Spring	69.0%	18.8%	8.1%	4.1%	14.0%	46.9%	25.3%	12.3%
		Summer	68.3%	10.9%	9.7%	11.1%	25.2%	15.5%	20.5%	38.8%
		Fall	75.2%	12.8%	7.8%	4.2%	17.8%	38.1%	29.2%	15.0%
	17	All Year	59.8%	25.7%	7.6%	6.6%	16.3%	44.8%	17.1%	21.8%
		Winter	64.3%	28.4%	6.1%	1.2%	9.9%	76.5%	11.5%	2.1%
		Spring	69.5%	17.5%	7.9%	5.1%	14.6%	47.4%	22.4%	15.6%
		Summer	58.9%	18.9%	9.4%	12.8%	25.7%	18.7%	12.9%	42.6%
		Fall	41.9%	45.4%	5.9%	5.1%	10.3%	51.1%	20.8%	17.8%

Table 24. 10 SEER operation mode, seasonally and annually. The statistics indicate the percentage of time the IHPAC units operated in each of the following modes: supply fan only, fan plus compressor, or system off. The statistics are provided for 24 hours/7 days per week, and scheduled school hours only.

			All Hours			School Hours		
Location	Room	Season	Off	Fan	Fan + Comp	Off	Fan	Fan + Comp
N1	21	All Year	93.4%	1.9%	4.6%	80.1%	5.7%	13.8%
		Winter	95.8%	0.4%	3.8%	86.8%	1.4%	9.5%
		Spring	93.2%	1.9%	4.9%	82.8%	4.2%	13.1%
		Summer	91.4%	1.7%	6.9%	72.9%	5.1%	22.0%
		Fall	94.3%	3.9%	1.9%	80.1%	13.2%	6.6%
	23	All Year	89.1%	1.5%	9.4%	68.7%	3.8%	27.1%
		Winter	95.7%	1.4%	2.9%	85.1%	4.9%	8.5%
		Spring	89.3%	1.7%	9.0%	71.2%	3.6%	25.3%
		Summer	79.9%	1.4%	18.6%	44.8%	3.7%	51.5%
		Fall	92.6%	1.4%	6.0%	77.4%	2.8%	19.8%
N2	26	All Year	92.5%	0.5%	7.0%	82.6%	0.9%	16.1%
		Winter	97.6%	0.3%	2.0%	88.8%	1.5%	8.2%
		Spring	96.1%	0.5%	3.4%	87.7%	0.6%	11.7%
		Summer	82.5%	0.5%	17.0%	71.7%	0.8%	27.5%
		Fall	94.2%	0.8%	5.0%	82.2%	0.8%	16.9%
S1	36	All Year	87.1%	9.6%	3.3%	46.0%	40.2%	13.4%
		Winter	88.2%	10.7%	1.1%	45.8%	47.7%	4.9%
		Spring	84.4%	12.4%	3.2%	35.9%	51.4%	12.7%
		Summer	87.6%	6.6%	5.8%	50.9%	26.2%	22.9%
		Fall	89.0%	8.1%	2.9%	54.1%	33.9%	12.0%
S2	14	All Year	89.1%	4.6%	6.3%	57.7%	16.8%	24.7%
		Winter	97.2%	2.1%	0.8%	85.7%	8.6%	2.7%
		Spring	88.5%	5.7%	5.7%	57.1%	20.5%	22.5%
		Summer	80.7%	6.8%	12.5%	28.3%	24.0%	47.7%
		Fall	90.3%	3.4%	6.3%	62.1%	12.1%	25.8%
	16	All Year	87.8%	5.1%	7.1%	54.3%	18.2%	27.5%
		Winter	94.4%	4.1%	1.5%	76.3%	17.9%	5.8%
		Spring	89.9%	5.2%	5.0%	64.7%	17.1%	18.2%
		Summer	80.2%	5.8%	14.0%	26.9%	19.8%	53.4%
		Fall	89.6%	5.0%	5.5%	59.5%	17.8%	22.6%

Table 25. 10 SEER operation mode, seasonally and annually. The statistics indicate the average (± standard deviation) of time the IHPAC units operated in each of the following modes: supply fan only, fan plus compressor, or system off. The statistics are provided for 24 hours/7 days per week, and scheduled school hours only.

		All Hours			School Hours		
Location	**Season**	**Off**	**Fan**	**Fan + Comp**	**Off**	**Fan**	**Fan + Comp**
North	All Year	92%±2%	1%±1%	7%±2%	77%±7%	3%±2%	19%±7%
	Fall	94%±1%	2%±2%	4%±2%	80%±2%	6%±7%	14%±7%
	Spring	93%±3%	1%±1%	6%±3%	81%±8%	3%±2%	17%±7%
	Summer	85%±6%	1%±1%	14%±6%	63%±16%	3%±2%	34%±16%
	Winter	96%±1%	1%±1%	3%±1%	87%±2%	3%±2%	9%±1%
South	All Year	88%±1%	6%±3%	6%±2%	53%±6%	25%±13%	22%±7%
	Fall	90%±1%	6%±2%	5%±2%	59%±4%	21%±11%	20%±7%
	Spring	88%±3%	8%±4%	5%±1%	53%±15%	30%±19%	18%±5%
	Summer	83%±4%	6%±1%	11%±4%	35%±13%	23%±3%	41%±16%
	Winter	93%±5%	6%±5%	1%±0%	69%±21%	25%±20%	4%±2%
All	All Year	90%±3%	4%±3%	6%±2%	65%±15%	14%±15%	20%±7%
	Fall	92%±2%	4%±3%	5%±2%	69%±12%	13%±12%	17%±7%
	Spring	90%±4%	5%±4%	5%±2%	67%±19%	16%±19%	17%±6%
	Summer	84%±5%	4%±3%	12%±5%	49%±20%	13%±11%	38%±15%
	Winter	95%±3%	3%±4%	2%±1%	78%±16%	14%±18%	7%±3%

Table 26. IHPAC operation mode, seasonally and annually. The statistics indicate the average (± standard deviation) percentage of time the IHPAC units operated in each of the following modes: supply fan only, fan plus stage one compressor, fan plus stage 2 compressor, or system off. The statistics are provided for 24 hours/7 days per week, and scheduled school hours only.

		All Hours				School Hours			
Location	**Season**	**Off**	**Fan**	**Stage 1**	**Stage 2**	**Off**	**Fan**	**Stage 1**	**Stage 2**
North	All Year	67%±2%	14%±8%	14%±8%	5%±2%	25%±6%	35%±20%	30%±22%	10%±2%
	Fall	73%±7%	15%±9%	11%±9%	1%±1%	21%±16%	46%±28%	31%±28%	3%±1%
	Spring	73%±2%	14%±8%	11%±9%	2%±1%	24%±6%	40%±23%	32%±28%	5%±3%
	Summer	64%±5%	8%±5%	17%±6%	11%±4%	34%±8%	14%±9%	28%±5%	23%±6%
	Winter	57%±10%	21%±14%	19%±14%	3%±2%	15%±11%	48%±28%	32%±34%	4%±2%
South	All Year	67%±6%	20%±5%	7%±1%	5%±2%	24%±10%	42%±4%	19%±3%	16%±7%
	Fall	64%±21%	26%±20%	6%±2%	4%±1%	24%±17%	41%±10%	21%±8%	14%±4%
	Spring	72%±5%	18%±2%	7%±2%	3%±1%	20%±8%	49%±5%	21%±5%	10%±5%
	Summer	69%±7%	12%±4%	9%±1%	10%±5%	32%±12%	18%±3%	19%±4%	31%±16%
	Winter	60%±6%	31%±5%	7%±1%	2%±1%	18%±8%	69%±8%	11%±3%	2%±1%
All	All Year	67%±4%	17%±7%	11%±7%	5%±2%	24%±8%	38%±14%	24%±16%	13%±6%
	Fall	69%±15%	20%±16%	8%±7%	3%±2%	22%±16%	43%±20%	26%±20%	8%±7%
	Spring	73%±4%	16%±6%	9%±6%	3%±1%	22%±7%	44%±16%	26%±20%	7%±5%
	Summer	66%±6%	10%±5%	13%±6%	10%±5%	33%±9%	16%±6%	24%±6%	27%±12%
	Winter	59%±8%	26%±11%	13%±11%	2%±1%	16%±9%	58%±22%	22%±25%	3%±2%

Table 27. Predicted annual classroom 10 SEER and IHPAC energy consumption for traditional nine-month school schedule in 16 California Climate zones using DOE-2. Both continuous and intermittent 10 SEER fan operation modes are shown.

Climate Zone	System	Fan Mode	Heating (kWh)	Cooling (kWh)	Fan (kWh)	Total (kWh)
1	**10 SEER**	**Continuous**	899	27	1197	2123
2			868	450	1369	2687
3			463	149	1033	1645
4			430	255	1083	1768
5			452	190	1056	1698
6			226	438	1048	1712
7			126	386	973	1484
8			203	466	1079	1749
9			263	499	1097	1859
10			348	618	1255	2220
11			820	616	1514	2950
12			635	472	1343	2451
13			690	683	1487	2861
14			523	913	1573	3009
15			164	1258	1557	2979
16			1727	260	1593	3580
1	**IHPAC**	**Continuous**	453	23	748	1224
2			577	282	859	1718
3			215	101	647	963
4			218	167	678	1063
5			264	126	659	1049
6			108	274	657	1039
7			60	247	608	916
8			97	292	675	1064
9			125	311	688	1124
10			181	382	791	1354
11			495	385	953	1834
12			344	294	844	1481
13			430	427	934	1791
14			339	580	1005	1924
15			81	787	999	1868
16			1127	162	996	2285
1	**10 SEER**	**Intermittent**	855	66	181	1103
2			811	421	331	1562
3			436	169	183	788
4			418	258	229	904
5			492	192	198	882
6			221	400	261	881
7			128	359	230	718
8			217	434	284	935
9			240	468	307	1015
10			391	570	379	1340
11			818	557	413	1788
12			612	423	321	1355
13			659	622	412	1693
14			544	880	585	2009
15			194	1213	678	2084
16			1708	223	327	2258

Table 28. DOE-2 Predicted annual classroom 10 SEER and IHPAC energy consumption for traditional nine-month school schedule in 37 U.S. Cities. Both 10 SEER and IHPAC systems were operated in continuous ventilation mode during classroom occupancy.

	10 SEER (Continuous Fan)				IHPAC			
City	Heating (kWh)	Cooling (kWh)	Fan (kWh)	Total (kWh)	Heating (kWh)	Cooling (kWh)	Fan (kWh)	Total (kWh)
Albuquerque	1259	448	1523	3231	881	279	954	2114
Anchorage	7272	18	1868	9158	6481	11	1163	7655
Atlanta	1025	560	1374	2959	706	343	863	1912
Birmingham	771	624	1362	2757	487	381	854	1722
Boston	2416	231	1572	4219	1788	143	983	2915
Brownsville	136	1264	1272	2673	68	751	799	1617
Charleston	583	773	1280	2637	377	466	805	1649
Chicago	3355	297	1656	5308	2746	181	1035	3962
Dayton	3157	285	1576	5017	2619	174	985	3779
Denver	2541	280	1577	4398	2067	172	987	3226
ElPaso	555	740	1443	2738	351	457	909	1717
ElToro	203	466	1079	1749	97	292	675	1064
FortWorth	633	835	1425	2893	387	507	893	1787
Jacksonville	338	1022	1289	2648	202	610	809	1621
KansasCity	2479	469	1621	4569	1988	286	1014	3288
LakeCharles	471	963	1317	2751	285	579	827	1691
LasVegas	396	916	1529	2840	217	578	974	1768
Miami	28	1467	1266	2761	13	871	795	1678
Minneapolis	5927	236	1751	7914	5373	146	1089	6608
Nashville	1686	619	1510	3816	1320	377	946	2643
NewYork	2030	292	1510	3832	1468	180	945	2592
Oakland	463	149	1033	1645	215	101	647	963
Omaha	3628	380	1648	5656	3179	234	1028	4441
Pasadena	263	499	1097	1859	125	311	688	1124
Philadelphia	2055	372	1564	3991	1481	227	979	2686
Phoenix	248	1189	1605	3042	133	742	1022	1897
Raleigh	1185	516	1382	3082	849	314	868	2031
RedBluff	820	616	1514	2950	495	385	953	1834
Reno	1850	317	1560	3727	1407	197	977	2581
Riverside	348	618	1255	2220	181	382	791	1354
Sacramento	649	454	1341	2443	357	282	841	1481
SaltLakeCity	2036	341	1648	4025	1521	213	1031	2765
SanAntonio	467	974	1397	2839	299	587	877	1763
SanDiego	108	437	1006	1551	51	278	629	958
Seattle	1435	106	1421	2961	843	68	889	1800
Sunnyvale	430	255	1083	1768	218	167	678	1063
Washington	1853	394	1535	3781	881	279	954	2114

Table 29. Regression of Nose and Fuji measurements collected from three one-week periods following Fuji calibrations conducted during spring, summer, and fall field visits . The regression model is Nose(ppm) = Slope * Fuji(ppm) + Intercept. The “Shared” column refers to whether the sampling line for a particular Fuji paired with that room’s Nose was multiplexed with another room or outdoor site. Multiplexed sampling lines switched between up to 3 sites on a six-minute sample cycle – the first three minutes of each locations data were dropped to accommodate instrument stabilization.

Location	Room	Slope	Intercept	R^2	Shared
N1	21	1.16	34	0.944	N
	22	1.05	38	0.970	Y
	23	1.00	58	0.980	Y
	24	1.12	26	0.976	N
N2	25	1.04	73	0.917	Y
	26	1.00	94	0.994	Y
S1	13	0.98	33	0.978	Y
	14	0.96	24	0.992	Y
	15	1.01	48	0.986	N
	16	0.95	74	0.996	N
S2	35	0.85	119	0.996	Y
	36	0.99	72	0.982	Y
	37	1.14	13	0.963	N

Figures

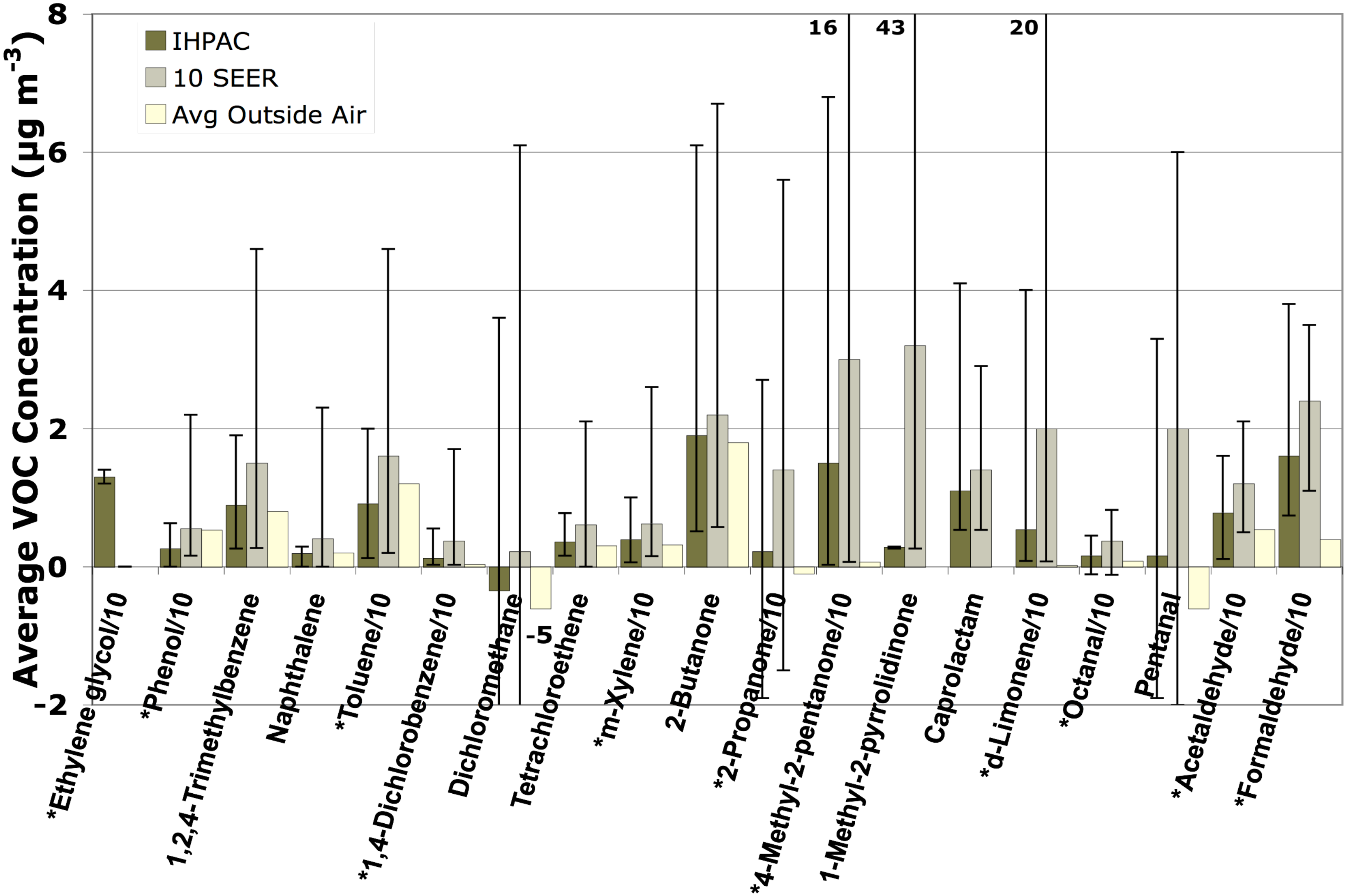


Figure 1. Selected toxic and odorous VOCs measured indoors, averaged across two school districts, four schools and three seasons of data collection. Data for IHPAC and 10 SEER classrooms, and outdoor air are shown. Error bars indicate minimum and maximum VOC concentrations observed during the study. Note that many compound concentrations have been scaled by a factor of 10 to fit on the plot.

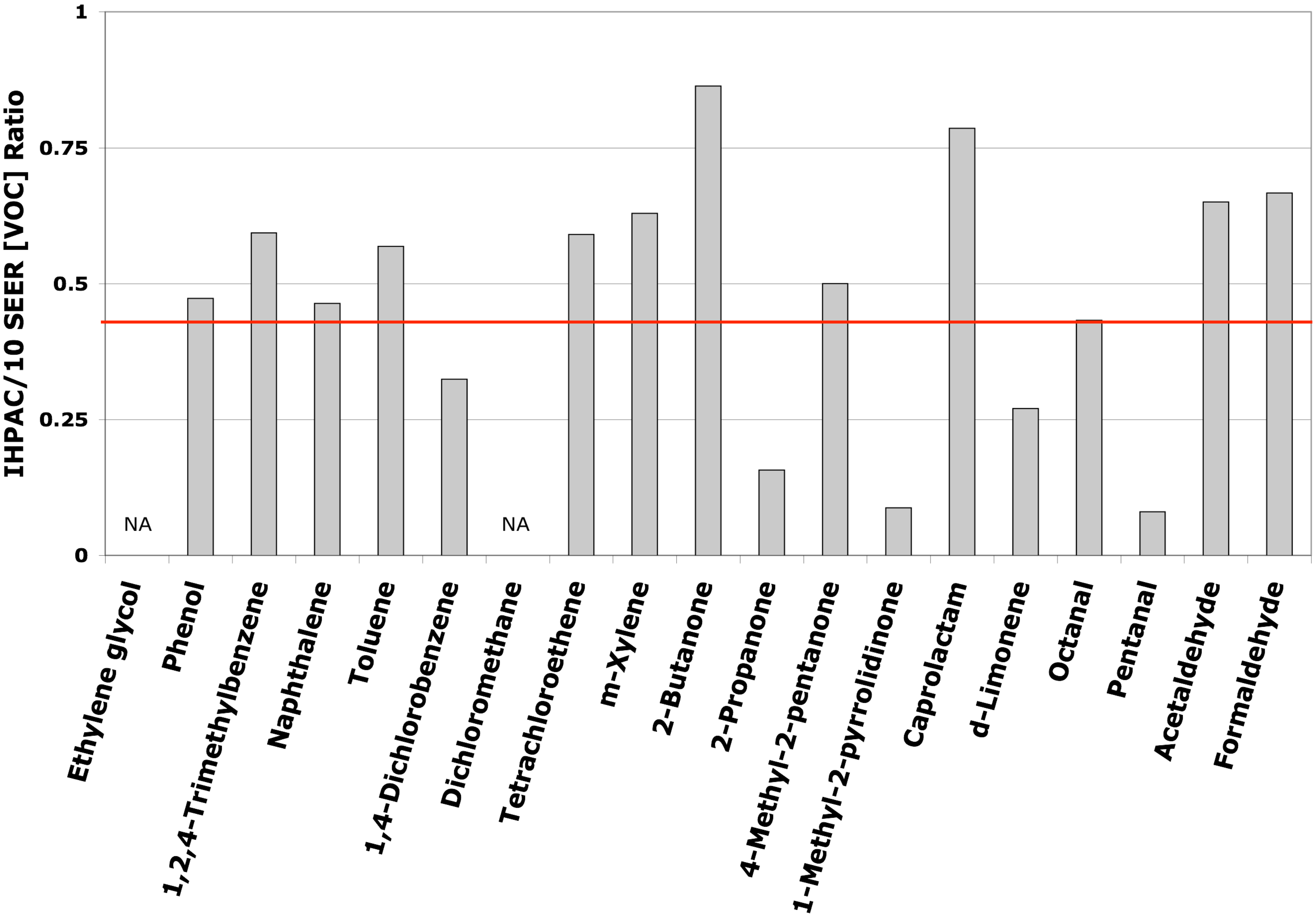


Figure 2. Ratio of Average VOC concentrations measured in IHAPC classrooms to those measured in 10 SEER classrooms. The horizontal line represents the average ratio (0.43) across the 19 compounds.

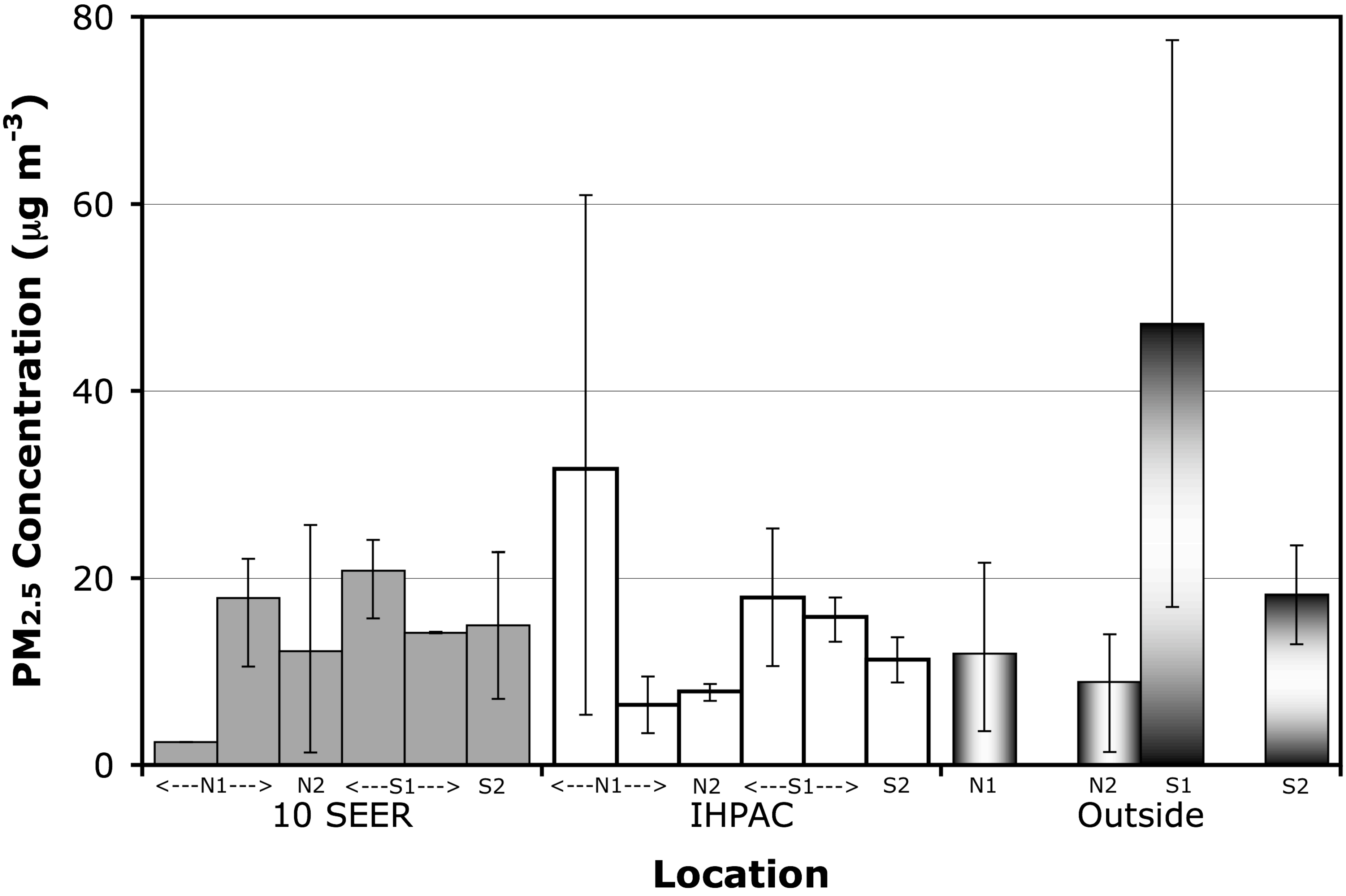


Figure 3. Approximate $PM_{2.5}$ concentrations in the study classrooms and outside averaged across seasonal measurements. Classrooms are arranged by HVAC type. Error bars depict minimum and maximum average concentrations across seasons for each measurement location.

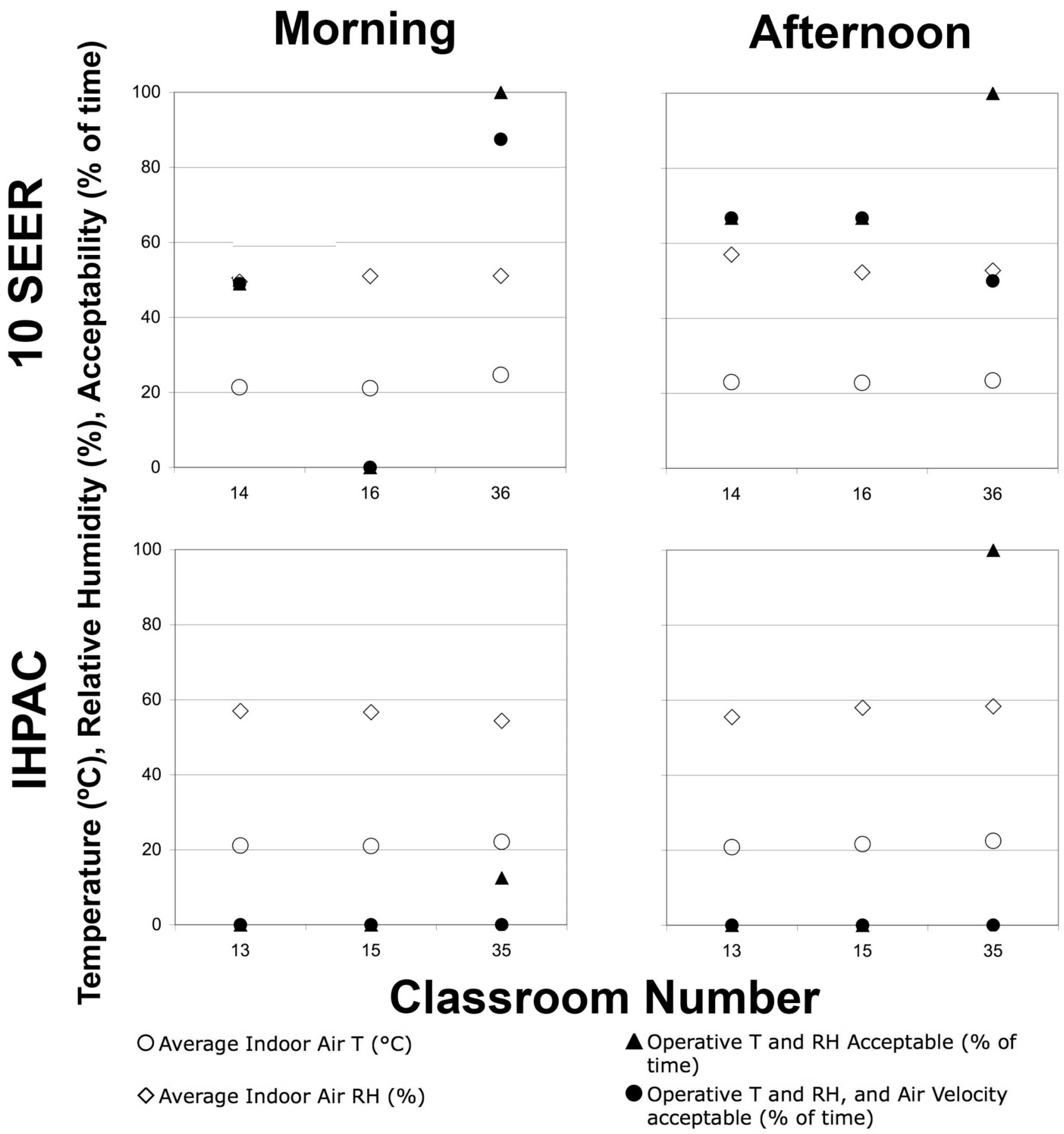


Figure 4. Morning and afternoon thermal comfort (TC) related measurements and ASHRAE Standard 55 calculated acceptable TC levels for study classrooms during the spring of 2005 field measurement visits. Percent time during school day of acceptable TC both with and without air velocity in the ASHRAE 55 calculation are shown

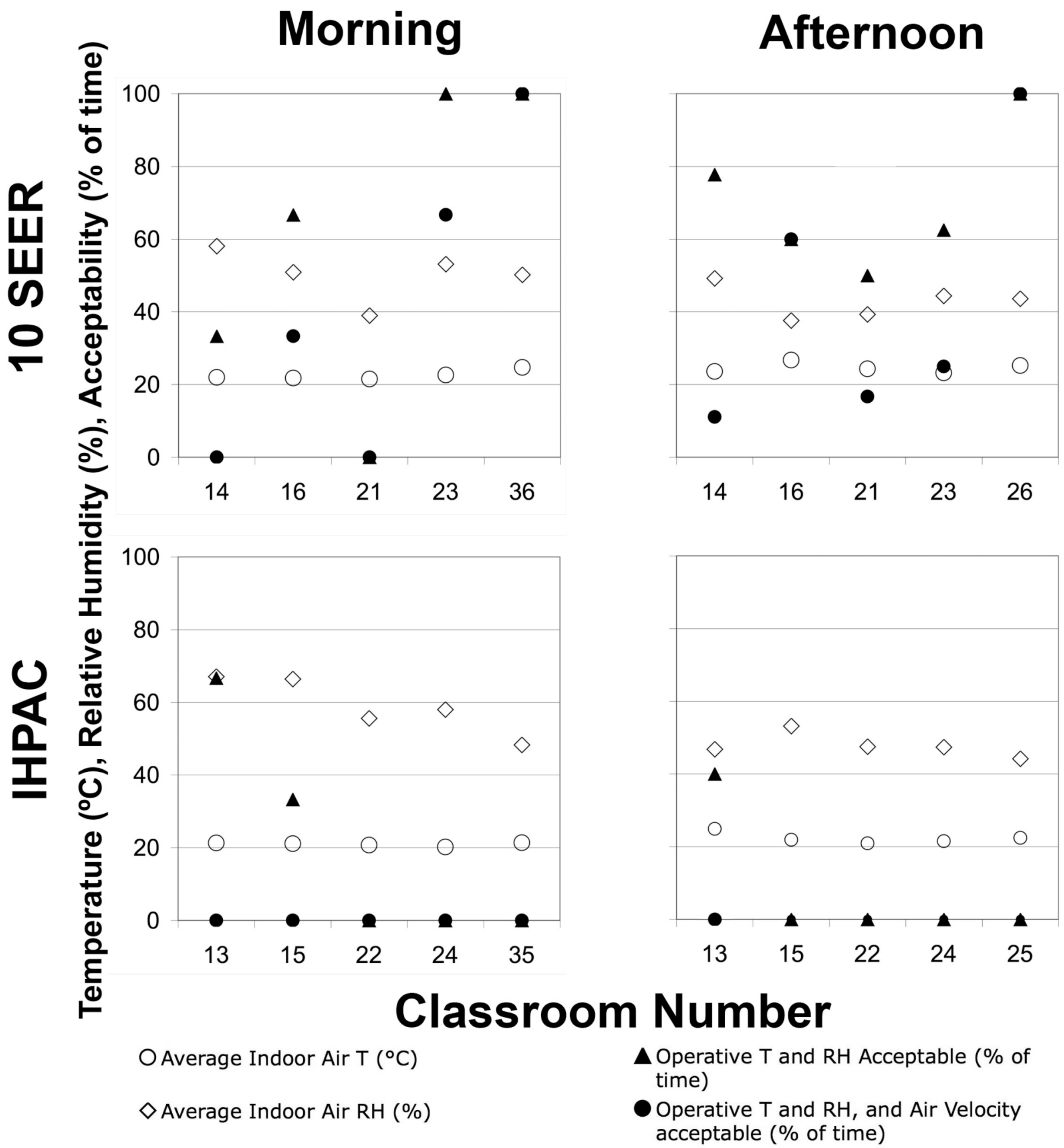


Figure 5. Morning and afternoon thermal comfort (TC) related measurements and ASHRAE Standard 55 calculated acceptable TC levels for study classrooms during the summer of 2005 field measurement visits. Percent time during school day of acceptable TC both with and without air velocity in the ASHRAE 55 calculation are shown

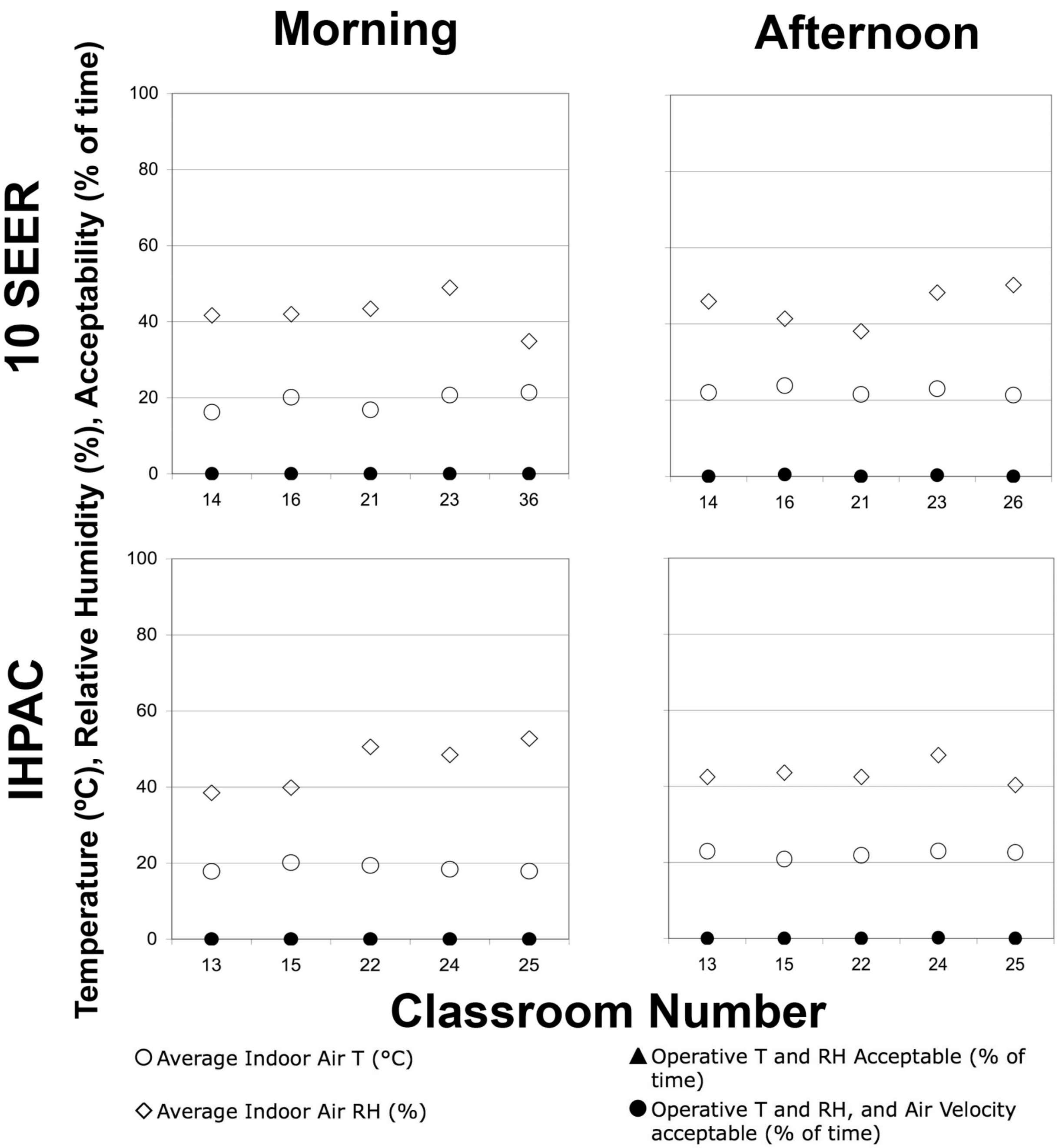


Figure 6. Morning and afternoon thermal comfort (TC) related measurements and ASHRAE Standard 55 calculated acceptable TC levels for study classrooms during the fall of 2005 field measurement visits Percent time during school day of acceptable TC both with and without air velocity in the ASHRAE 55 calculation are shown (no difference in this case).

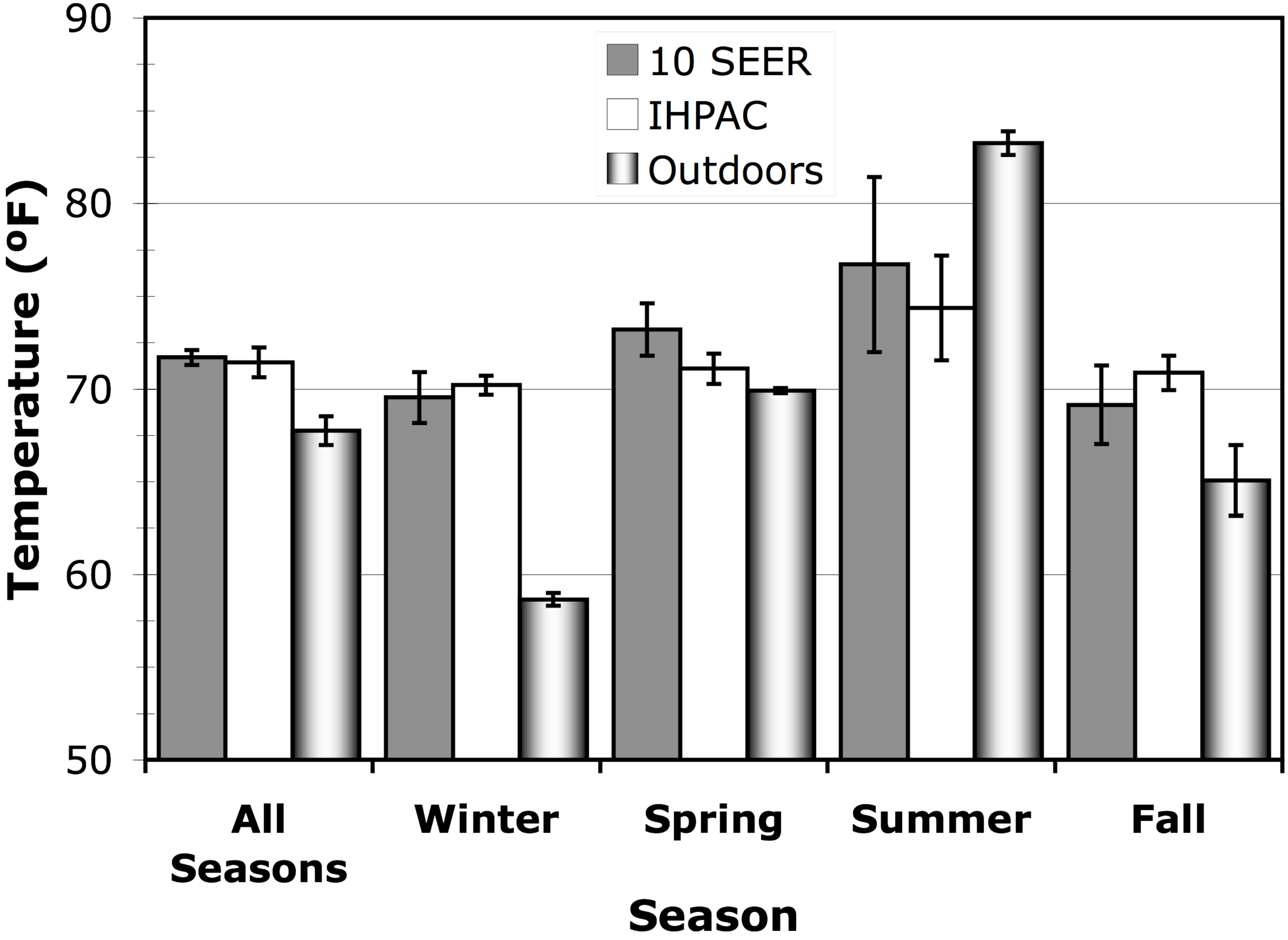


Figure 7. Average seasonal schoolday hour indoor and outdoor temperatures across 10 SEER and IHPAC classrooms in the northern California school district. Error bars indicate ±1 standard deviation.

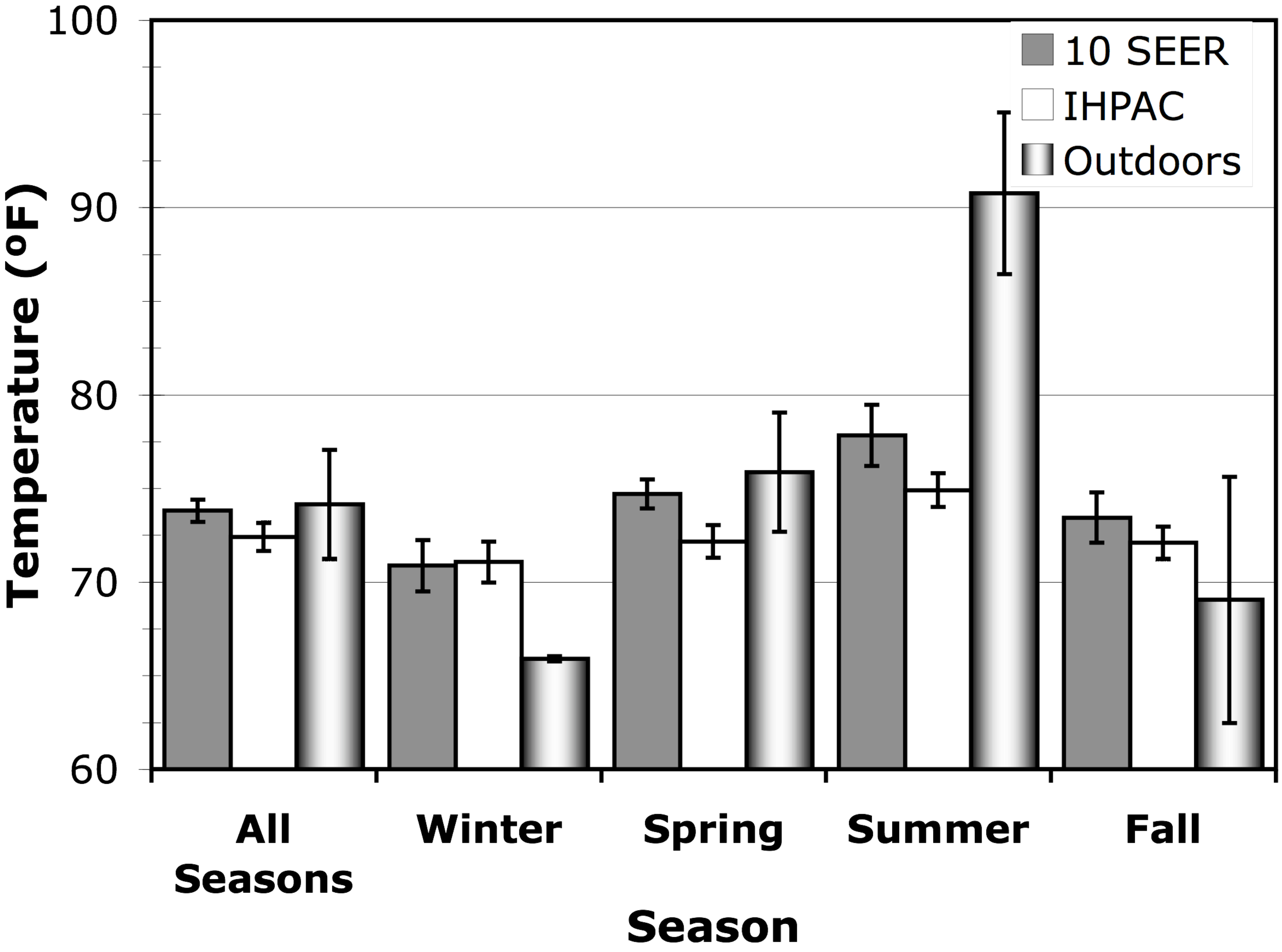


Figure 8. Average seasonal schoolday hour indoor and outdoor temperatures across 10 SEER and IHPAC classrooms in the southern California school district. Error bars indicate ±1 standard deviation.

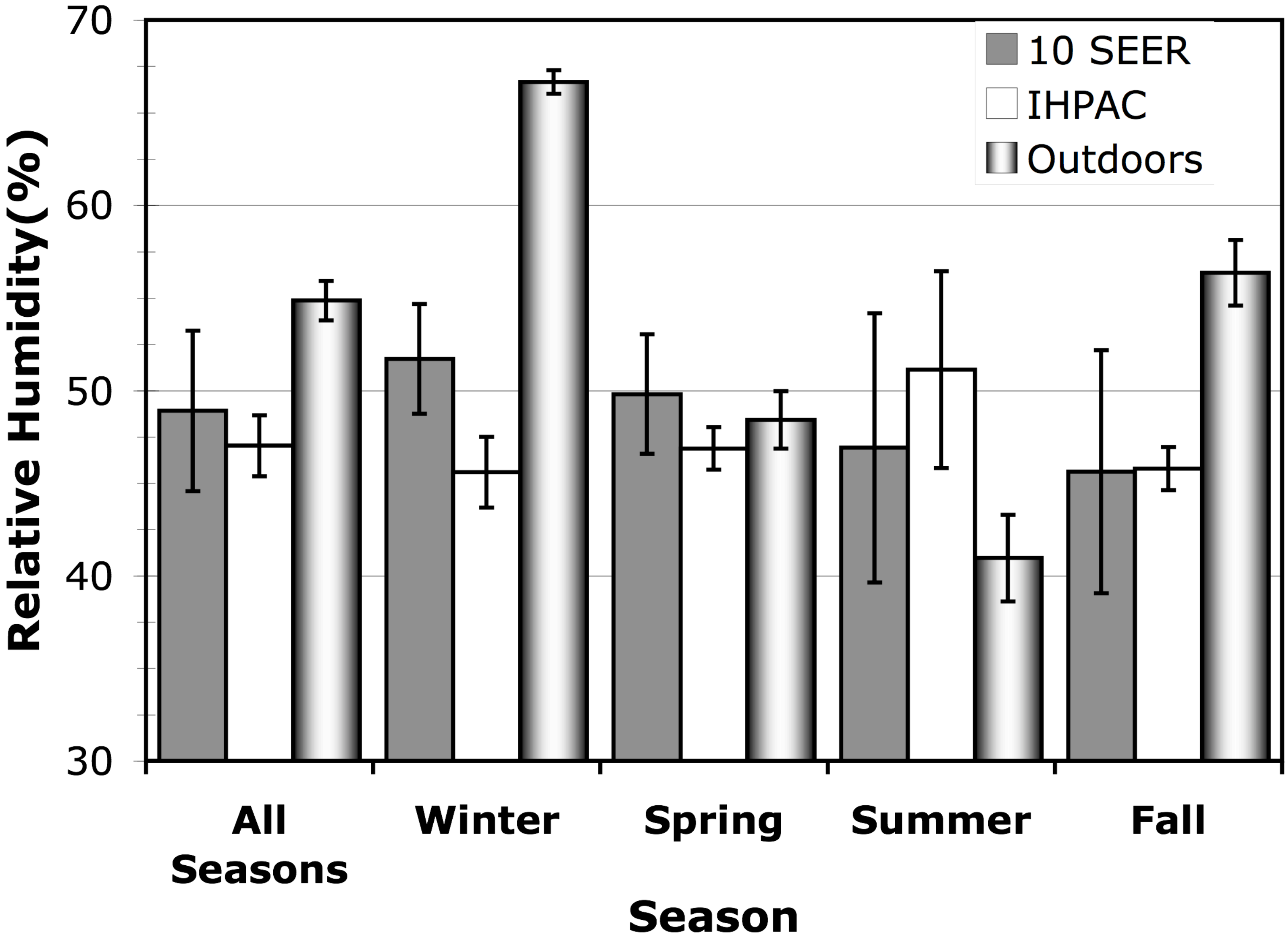


Figure 9. Average seasonal schoolday hour indoor and outdoor relative humidity across 10 SEER and IHPAC classrooms in the northern California school district. Error bars indicate ±1 standard deviation.

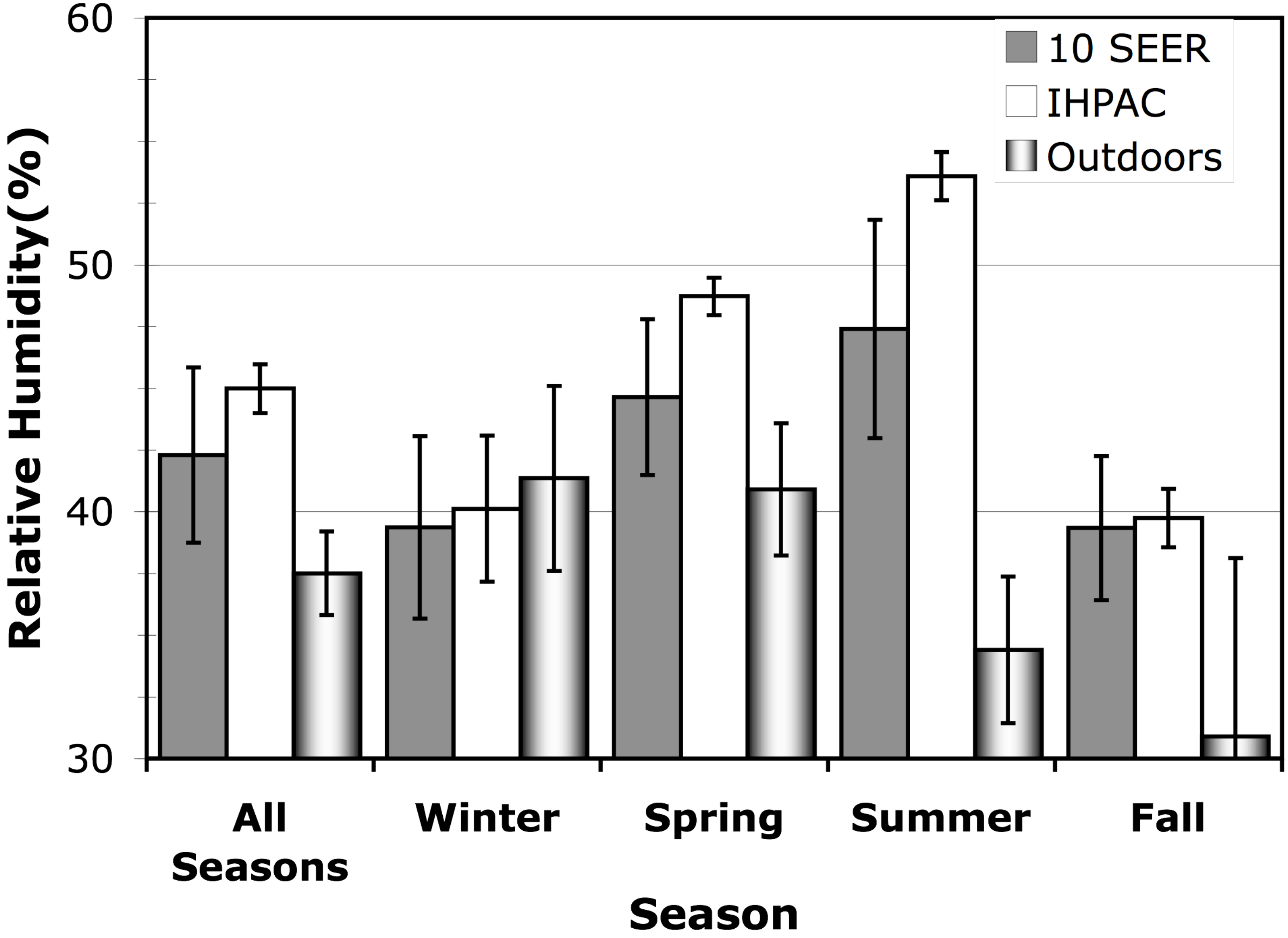
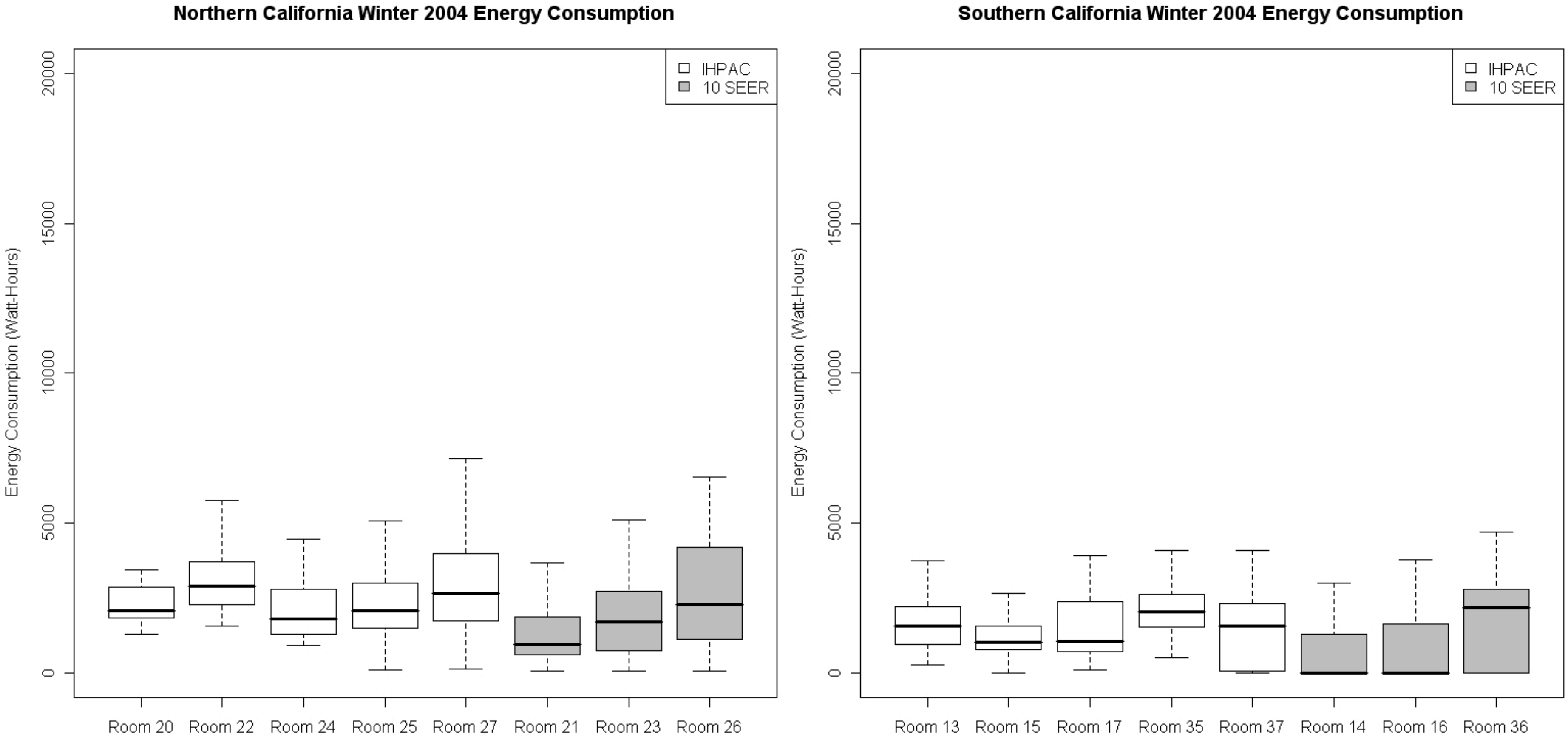


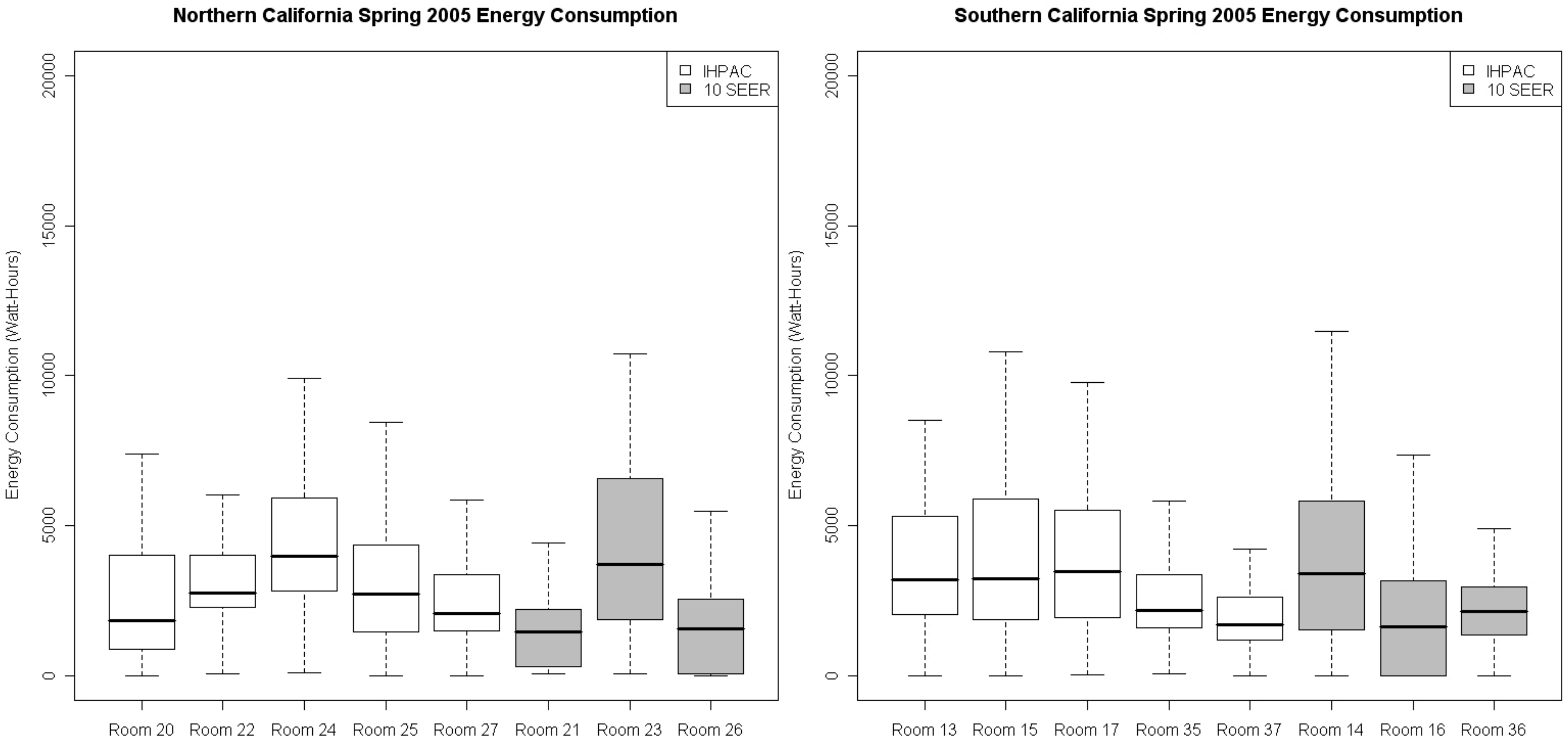
Figure 10. Average seasonal schoolday hour indoor and outdoor relative humidity across 10 SEER and IHPAC classrooms in the southern California school district. Error bars indicate ±1 standard deviation.



Northern California Winter 2004 Energy Consumption

Southern California Winter 2004 Energy Consumption

Figure 11. Box and whisker plots of measured daily energy consumption distributions for Northern and Southern California classroom in the 2004Winter season. The dark center line is the median value and the boxes bound the first and third quartiles. The whiskers mark the minimum and maximum measured values.


Northern California Spring 2005 Energy Consumption

Southern California Spring 2005 Energy Consumption

Figure 12. Box and whisker plots of measured daily energy consumption distributions for Northern and Southern California classroom in Spring 2005. The dark center line is the median value and the boxes bound the first and third quartiles. The whiskers mark the minimum and maximum measured values.

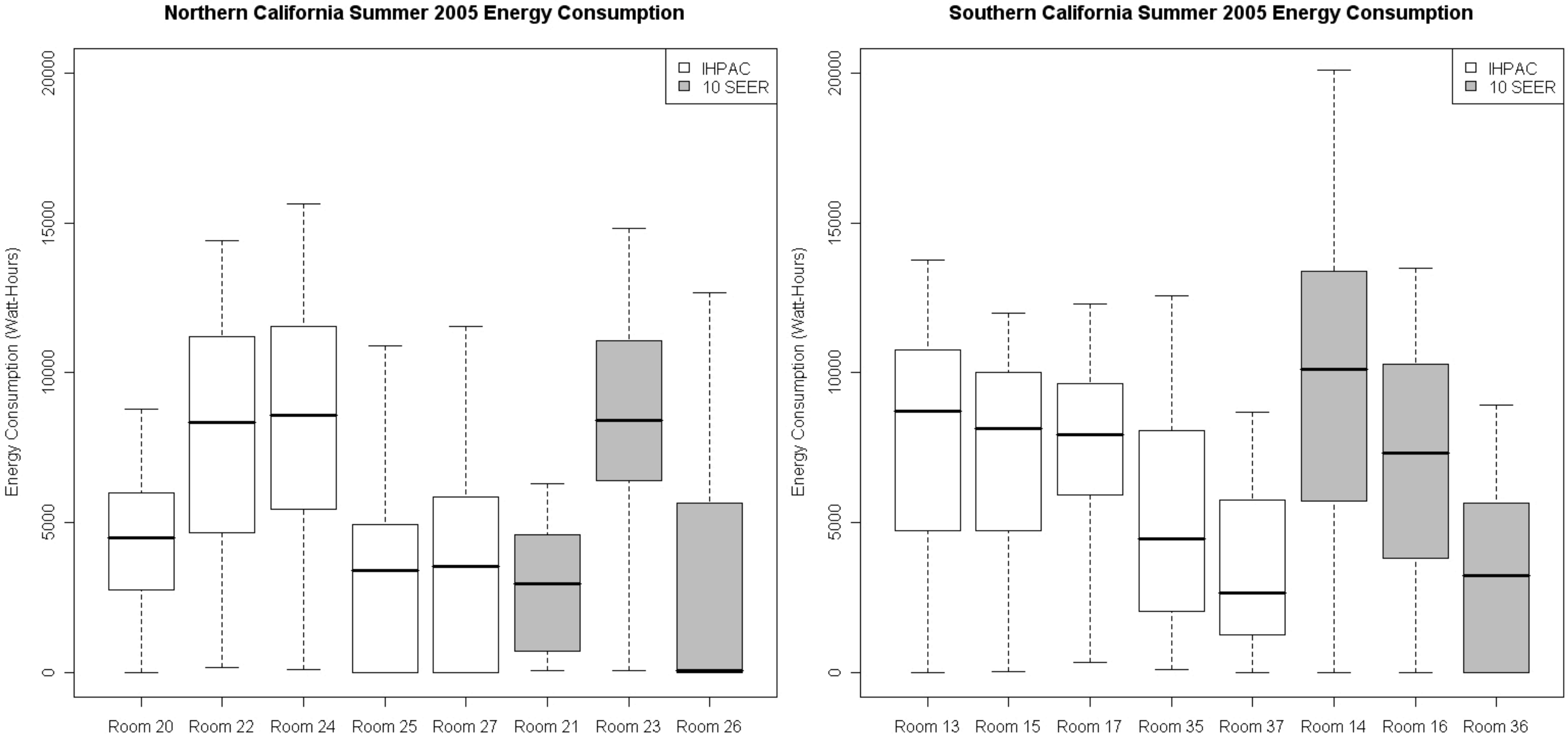


Figure 13. Box and whisker plots of measured daily energy consumption distributions for Northern and Southern California classroom in Summer 2005. The dark center line is the median value and the boxes bound the first and third quartiles. The whiskers mark the minimum and maximum measured values.

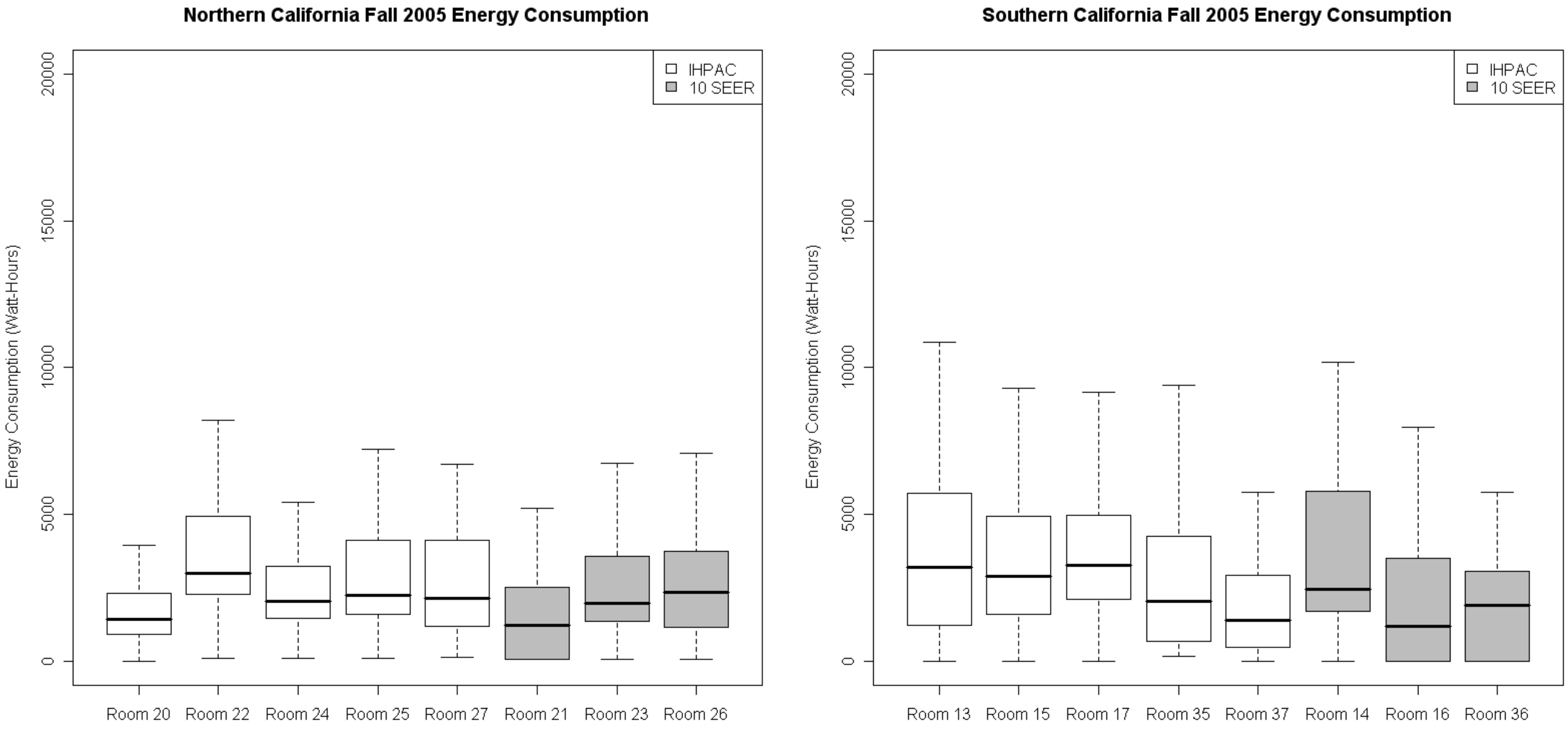
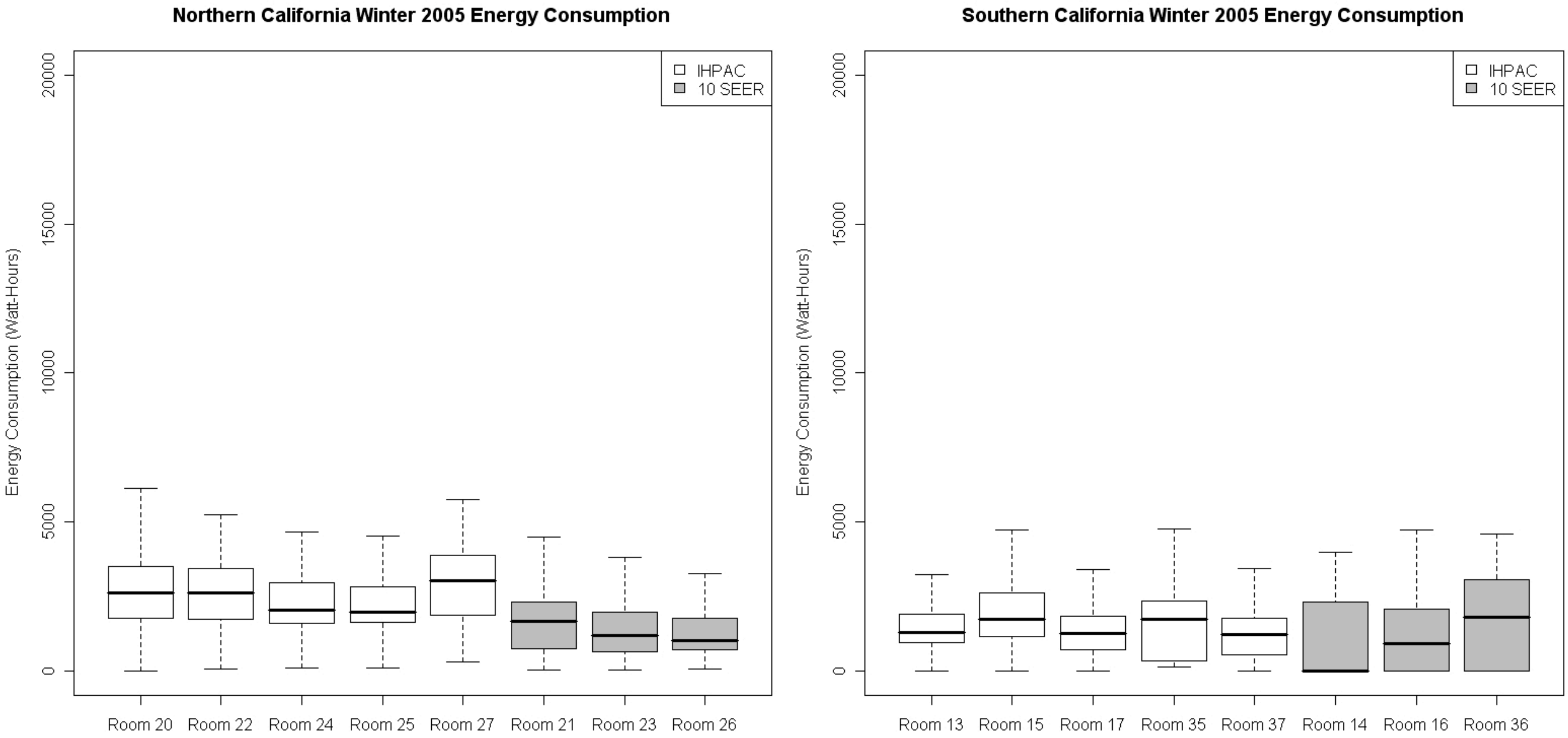


Figure 14. Box and whisker plots of measured daily energy consumption distributions for Northern and Southern California classroom in Fall 2005. The dark center line is the median value and the boxes bound the first and third quartiles. The whiskers mark the minimum and maximum measured values.



Northern California Winter 2005 Energy Consumption

Southern California Winter 2005 Energy Consumption

Figure 15. Box and whisker plots of measured daily energy consumption distributions for Northern and Southern California classroom in Winter 2005. The dark center line is the median value and the boxes bound the first and third quartiles. The whiskers mark the minimum and maximum measured values.

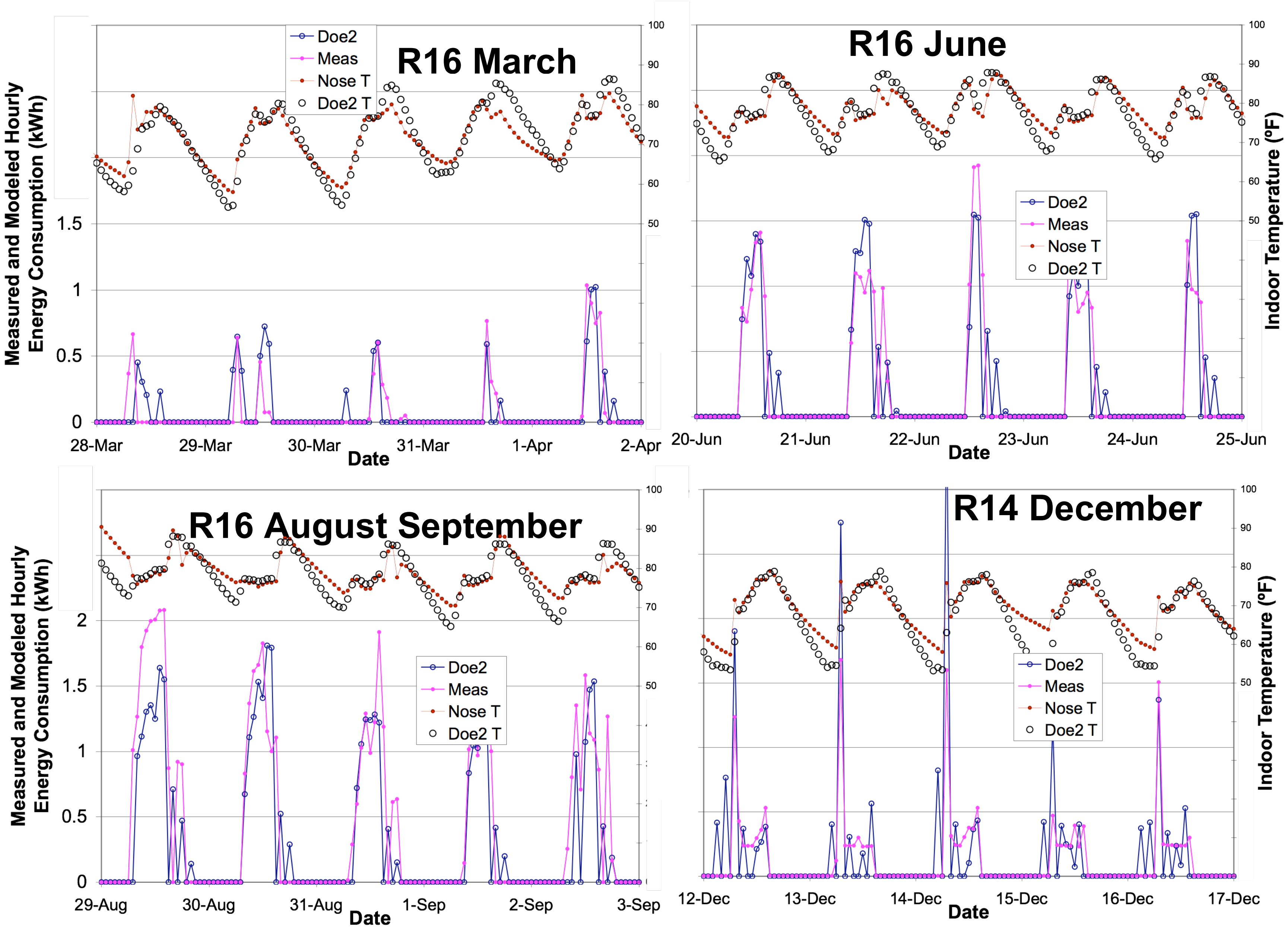


Figure 16. Measured and DOE-2 predictions of hourly energy consumption for the 10 SEER system operating in different northern and southern CA classrooms across four seasons

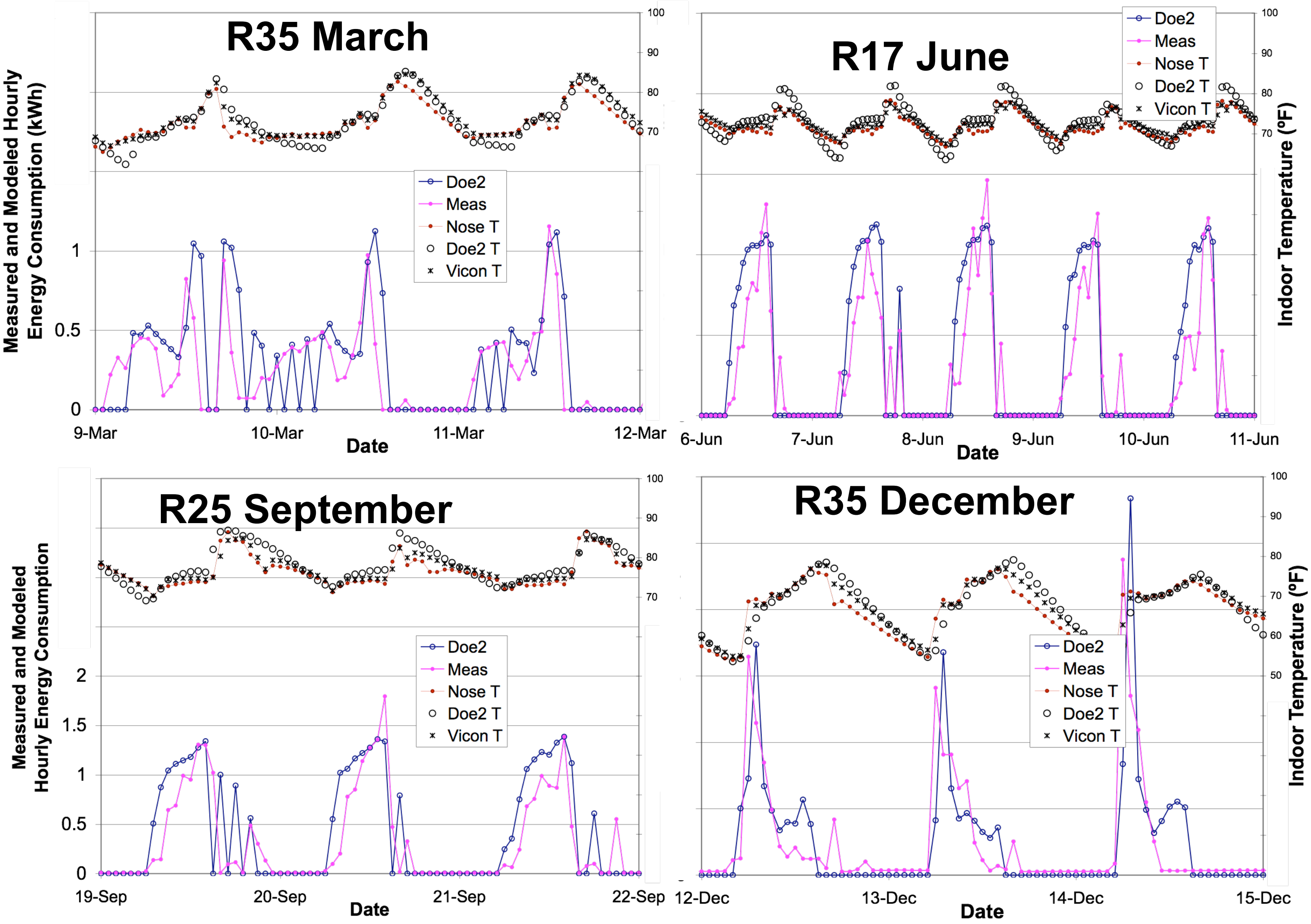


Figure 17. Measured and DOE-2 predictions of hourly energy consumption for the IHPAC system operating in different northern and southern CA classrooms across four seasons.

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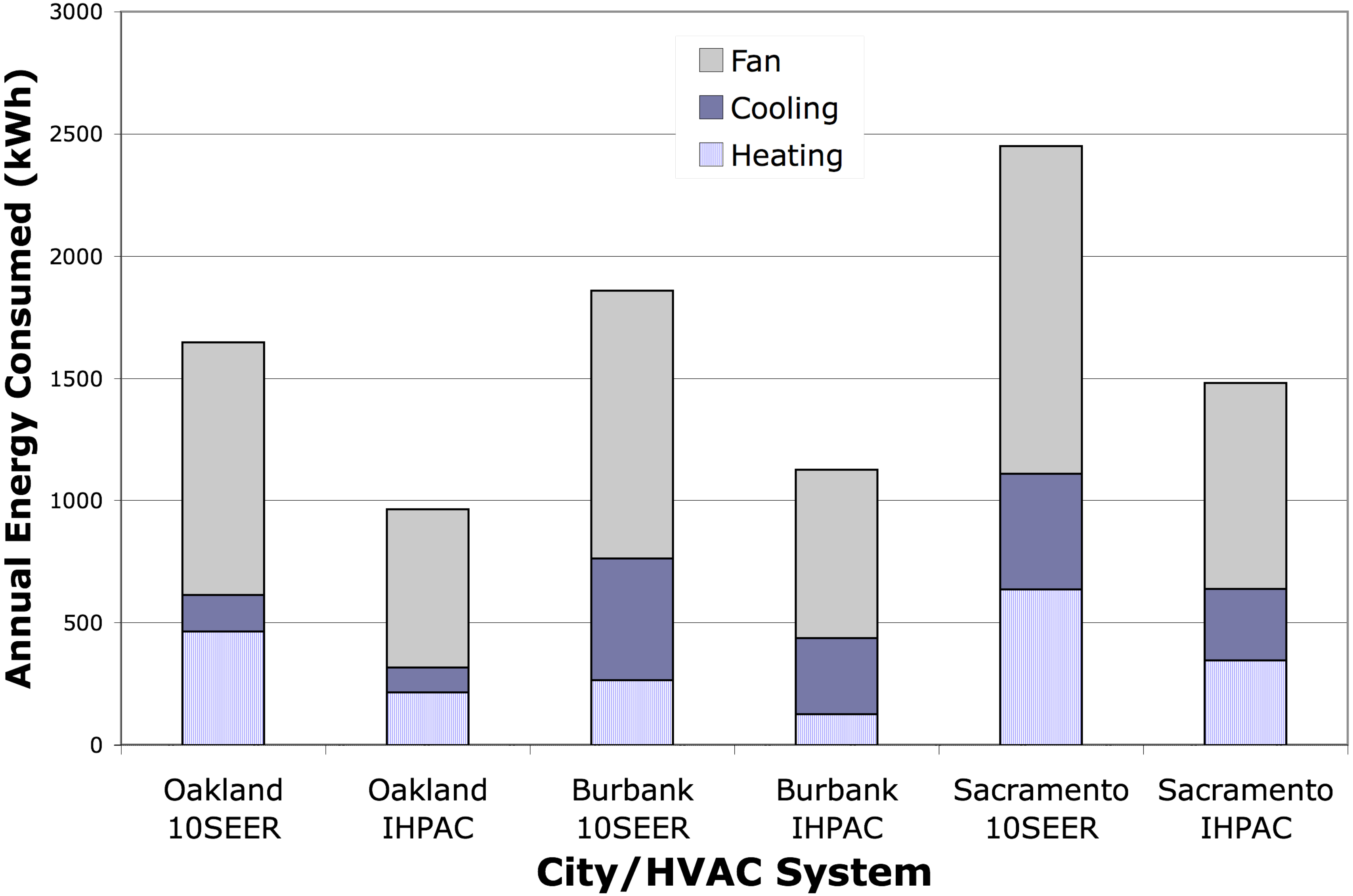

Figure 18 CA Cities. Annual energy consumption for 10 SEER and IHPAC systems in portable classrooms three CA Cities predicted using calibrated DOE-2 models. The energy consumption is broken down by fan, cooling, and heating energy use. Both HVAC systems were modeled using continuous ventilation during occupancy.

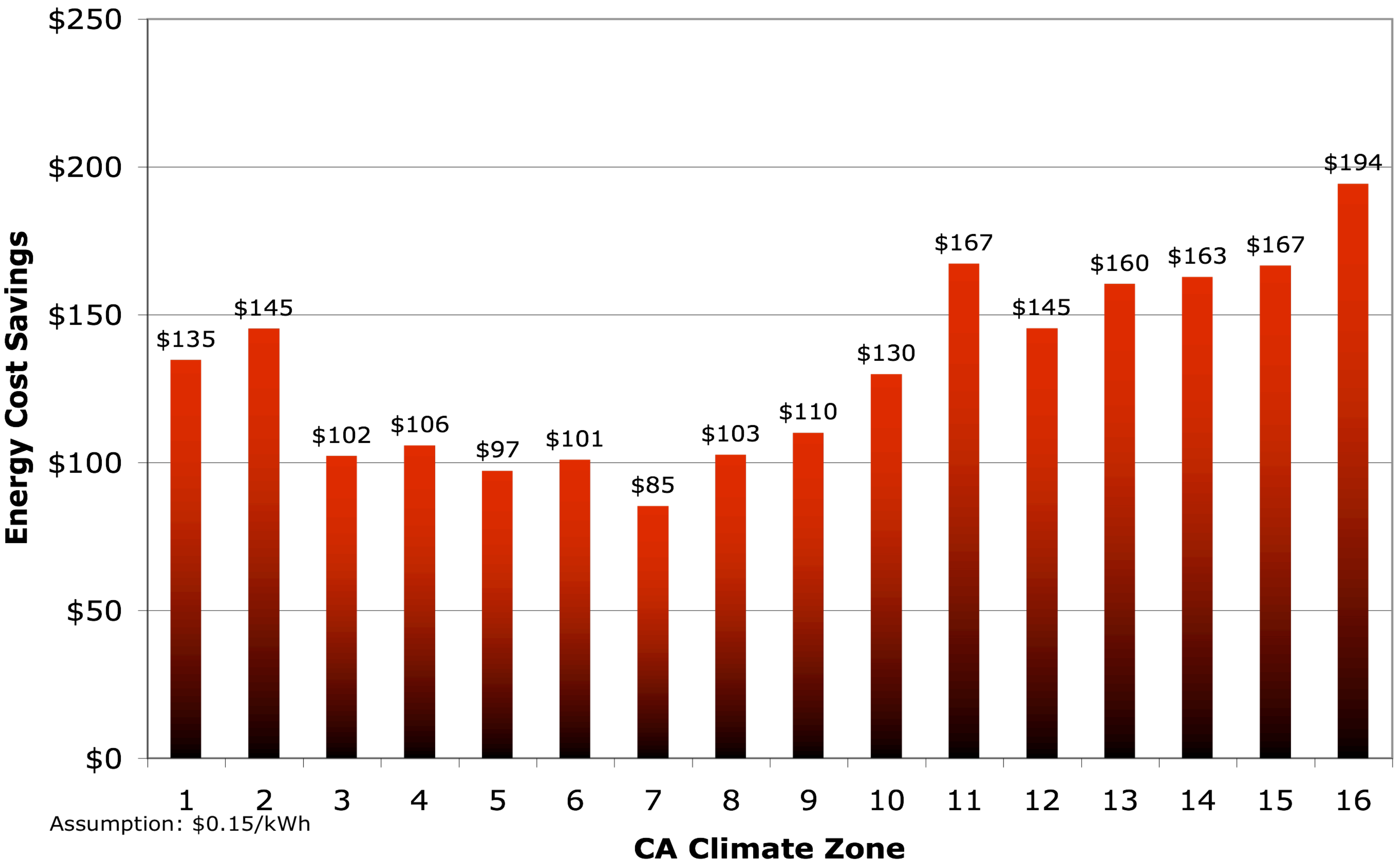

Figure 19. Energy savings in dollars assuming a $0.15 cost per kWh across sixteen California climate zones from operating IHVAC classrooms relative to 10 SEER HVAC systems.

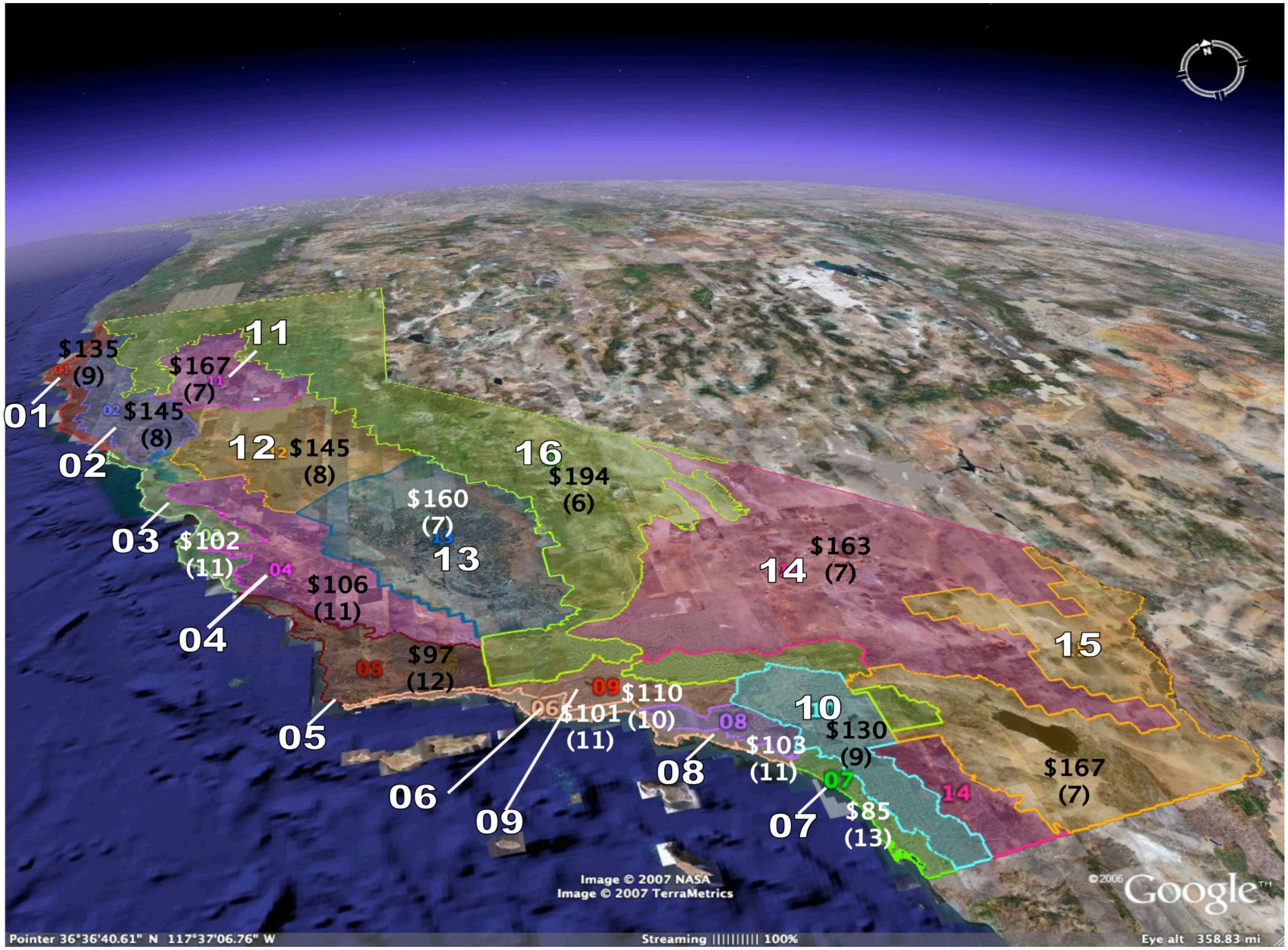

Figure 20. Map of California climate zones with predicted annual energy savings (electricity cost $0.15/kWh) per classroom from using the IHPAC relative to the 10 SEER HVAC system. Climate Zones are highlighted in bold outlined white numerals. Simple payback in years is noted in parentheses based on a net cost premium of $1150 per IHPAC unit. Underlying map from California Energy Commission an Google™.

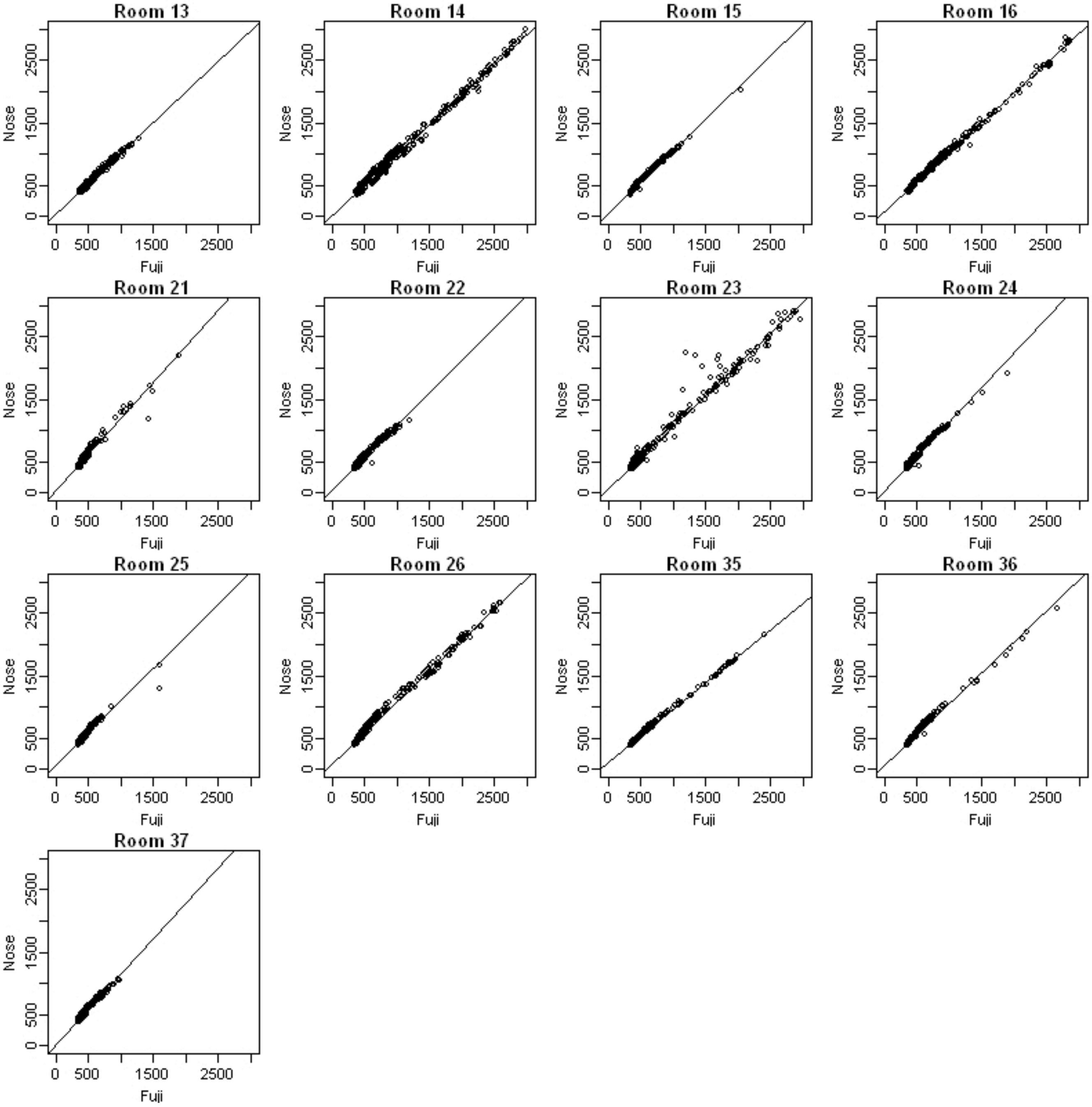

Figure 21. Nose and Fuji CO_2 measurements collected from three one-week periods following Fuji calibrations conducted during spring, summer, and fall field visits. Lines in the plots are least square regression fits. See Table Nose and Fuji for regression statistics..