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THE ASSOCIATION OF HIGHER CARBON DIOXIDE LEVELS AND TEACHERS' PERCEIVED AIR QUALITY AND WELL BEING IN NEW YORK CITY ELEMENTARY SCHOOLS

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THE ASSOCIATION OF HIGHER CARBON DIOXIDE LEVELS AND TEACHERS' PERCEIVED AIR QUALITY AND WELL BEING IN NEW YORK CITY ELEMENTARY SCHOOLS

A DISSERTATION

by

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ABSTRACT

The Association of Higher Carbon Dioxide Levels and Teachers' Perceived Air Quality and Well-being in New York City Elementary Schools

by Leon Levine

Adviser: Professor Frank Mirer

Introduction:

Several recent studies have investigated the direct effects of carbon dioxide (CO_2) at concentrations typically found in office buildings on occupant cognitive functioning. These studies have reported a significant association between (impaired) decision making ability and exposure to increased levels of CO_2 (600 ppm versus 1500 ppm). The findings have serious implications in a classroom setting, since the objective of schools is to provide an optimal environment for learning. If CO_2 levels in schools are elevated, the teachers' health and the students' learning environment will be compromised. Higher CO_2 levels could impact teachers' and students' cognitive functioning and hinder learning. The first aim of the study was to monitor and characterize New York City (NYC) public school teachers' full shift exposure to CO_2; A sub aim was to assess whether school staff can manage air monitoring equipment in classrooms; The second aim was to evaluate the association of school building and classroom factors with higher CO_2 levels; The third aim was to evaluate the association between higher CO_2 levels and perceived air quality and teachers' well being.

Methods:

Schools were selected with the assistance of the teachers union (United Federation of Teachers (UFT)). Air monitoring was conducted in 19 schools throughout NYC and each school was tested during two different times of the year; winter (heating season) and late spring (non-heating season). HOBO MX CO_2 data loggers recorded CO_2 concentrations, temperature, and relative humidity (RH) data inside classrooms continuously for one week. An online questionnaire was developed and deployed via Survey monkey. The questionnaire included 33 questions collecting demographic information, observations of classroom conditions and specific neurophysiological symptom data. A number of metrics of exposure were utilized in the study including a continuous variable representing maximum classroom CO_2 concentration recorded over the monitoring period, and the number of CO_2 measurements exceeding 1000 ppm during the teachers' shift. Survey responses were evaluated through X^2 tests (correlation analysis), Wilcoxon rank test and the relationships between exposures and health symptoms were assessed by logistic regression and multivariable regression analysis.

Results:

Peak CO_2 levels during round 1 and round 2 ranged from 665 ppm to 5000 ppm and 679 ppm to 4085 ppm, respectively. Mean CO_2 levels (7 hours; highest exposure day) during round 1 and round 2, ranged from 471 ppm to 2633 ppm and 462 ppm 2675 ppm, respectively. Approximately 66.3% and 66.2% of teachers reported experiencing fatigue in the winter and late spring seasons, respectively. About 29% and 32.4% of teachers reported the air quality in their classroom as being acceptable most of the time. It was determined that school staff could successfully manage air monitoring equipment in the classrooms (17 of 19 coordinators or 89%

could successfully complete the five tasks). An association was identified between the number of CO_2 measurements exceeding 1000 ppm and teachers' perception of air quality. With more measurements above 1000 ppm, more number of teachers reported the need to open windows. An association of higher CO_2 levels and the reported neurophysiological symptoms was not identified.

Discussion:

The study findings revealed that the majority of the teachers (77.5% and 74.3%) reported experiencing health symptoms while at the school. Peak CO_2 levels and percentage of measurements above 1000 ppm were also greater than reported in some studies. The results of this study underscore the need to reduce CO_2 levels in NYC public school classrooms. A follow up study could evaluate CO_2 levels and classroom academic performance or standardized testing scores. Future studies could assess various interventions within the schools and classrooms to decrease CO_2 levels.

Acknowledgements

I would like to take this opportunity to thank everyone who supported me through the doctoral journey and helped me complete my dissertation. First, I would like to express my sincere gratitude to my committee chairs Dr. Mary Schooling and Dr. Frank Mirer, who provided invaluable insight and guidance. I would like to extend my appreciation to my committee members Dr. Sheng Li for discussing and clarifying statistical approaches, and Dr. Brian Pavilonis for providing his indoor environmental quality expertise and guidance.

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I am grateful to the National Institute of Occupational Safety and Health (NIOSH) Education and Research Center (ERC) and the grant that helped support this study. I would like to thank the United Federation of Teachers for their time and support in helping to implement the study. I would also like to thank NYC Department of Education for approving the study as well as the NYC public school principals, teachers and staff who participated in the study.

I am forever grateful to my close friends and family who have witnessed the different stages of my doctoral journey and were always supportive and understanding. I especially want to thank my wife, Miffy, and my children. I can never thank you enough, and I never lost sight of the fact that you continued to support me in any way you could and were always proud of me. I love you all dearly.

Dedication

This research study is dedicated to all the public school teachers who have a very important and challenging profession but are often overlooked and underappreciated. This study is also in memory of my mother who worked as a music teacher and enjoyed imparting her love of music to her students. I know that she would be very proud of me.

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Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ASHRAE	American Society of Heating, Refrigeration and Air conditioning Engineers
AUC	area under the curve
CFM	Cubic Feet Per Minute
CO_2	Carbon Dioxide
DOE	Department of Education
EPA	U.S. Environmental Protection Agency
GHG	Green House Gas
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IDLH	Immediately Dangerous to Life and Health
IEQ	Indoor Environmental Quality
MERV	Minimum Efficiency Reporting Value
NIOSH	National Institute of Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
ppm	Parts Per Million
RH	Relative Humidity
REL	Recommended Exposure Limit
SBS	sick building syndrome
STEL	Short Term Exposure Limit
TLV	Threshold Limit Value
TWA	Time Weighted Average
VOC	Volatile Organic Compound

Chapter 1. Introduction and Background

1.1 Carbon Dioxide and Health

Carbon dioxide (CO_2) has received a tremendous amount of attention as a green house gas (GHG) and its critical role in climate change.[1] In the field of indoor environmental quality (IEQ), CO_2 levels are used as a proxy in evaluations of ventilation rates and the general air quality inside buildings.[2] Occupants exhale CO_2; high concentrations indicate an insufficient amount of fresh air being introduced into the space. CO_2 concentrations in the built environment typically range from 400-2500 parts per million (ppm).[3] A federal IEQ standard does not currently exist to provide guidance on controlling contaminants at lower levels including CO_2.[4] The United States Occupational Safety and Health Administration (OSHA) has established a permissible exposure limit (PEL) for CO_2 of 5000 ppm.[5] Several recent studies have investigated the direct effects of CO_2 at concentrations typically found in office buildings on occupant cognitive functioning (e.g. information use, crisis response, and strategy).[6,7,8] These studies have reported an association of exposure to increased levels of CO_2 (600 ppm versus 1000 ppm and 1500 ppm) with a reduction in decision making ability. The findings have serious implications in a classroom setting, since the objective of schools is to provide an optimal environment for learning. If CO_2 levels in schools are elevated, the teachers' health and the students' learning environment can be compromised. Higher CO_2 levels could impact teachers' and students' cognitive functioning and hinder learning. Muscatiello et al. found that teachers working in New York State elementary school classrooms with higher CO_2 levels had significantly increased odds (odds ratio (OR)=1.30, 95% confidence interval (CI)=1.02-1.64) of reporting neuro-physiologic symptoms including headache, fatigue and difficulty concentrating.[9]

1.2 The New York City Public School System

1.2.1 School Buildings

The City School District of the City of New York (the New York City public schools) is the largest school system in the United States, with over 1.1 million students and 75,000 teachers. The New York City Department of Education (NYC DOE) manages the city's public school system, covering schools in all five boroughs with an annual budget of nearly 25 billion dollars.[10] The NYC DOE is run by the Panel for Educational Policy and New York City Schools Chancellor. The NYC DOE Division for School Facilities (DSF) is responsible for the maintenance, repair, and operation of all facilities. The maintenance and operation of heating ventilation and air conditioning (HVAC) systems falls under the jurisdiction of DSF, with approximately 1700 employees additionally responsible for cleaning, garbage disposal, plumbing, carpentry, painting, minor repairs, environmental health and safety and other aspects of building maintenance.[11] The School Construction Authority (SCA) is a division of the NYC DOE responsible for managing the construction of new schools, additions and capital improvements to existing schools. Major improvements including the overhaul of a school's entire HVAC system, are most likely managed by the SCA.[12]

As of September 2018, there were 1,840 schools within the DOE, including 227 charter schools. The NYC School system is unique in that it has a wide range in the age of its school buildings. The average age of NYC school buildings is 66 years with some schools constructed in the 1800's and early1900's. At the turn of the century New York City ramped up its school constructions to meet the city's population boom. Charles BJ Snyder, the superintendent of school buildings, also an architect, designed the schools. Snyder used his architectural and engineering prowess to transform the way schools were designed and constructed. Under his direction, over 400 schools were constructed in NYC and many of them are still active schools. Snyder's signature style was the H-plan, a shape that cut through the middle of a block to limit street noise and maximize space while simultaneously creating almost an acre of open play area for children. Many of these buildings are historic incorporating the Romanesque revival, Flemish Renaissance Revival, Collegiate Gothic Revival, Georgian Revival styles with architectural features that included terracota trim, bell towers, and rooftop playgrounds. Snyder utilized steel frame construction, with enormous windows covering a large percentage of the façade, to allow natural light into classrooms. Snyder was also the first architect in the country to fireproof public school buildings, designing a type of interlocking stairs that allowed for a much quicker evacuation during drills and emergencies.[13] Some of these school buildings have been converted to housing, other have been demolished, while many are still being used as schools.

The U.S. Department of Education reported in 2014, that approximately 53% of public schools needed repairs, renovations and modernization to put the school buildings in good overall condition, while about 30% of schools had poor or fair ventilation systems.[14] NYC DOE has also struggled with keeping up with the increasing student population. NYC public schools have been historically overcrowded.[15] Since students and staff are the sources of CO_2, overcrowding along with poor ventilation can result in elevated CO_2 concentrations placing teachers at risk of being exposed to higher levels of CO_2.

1.2.2 Heating Ventilation Air Conditioning (HVAC) Systems

The HVAC system includes all heating, cooling, and ventilating equipment serving a school. A properly designed and functioning HVAC system controls temperature and humidity to provide thermal comfort, distributes adequate amounts of outdoor air to meet the ventilation needs of school occupants, isolates and removes odors and pollutants through pressure control, filtration and exhaust fans.[16] Some school buildings utilize natural ventilation only.[17] Others lack mechanical cooling equipment and many function with little or no humidity control. The American Society of Heating and Refrigeration and Air Conditioning Engineers (ASHRAE) recommends maintaining a steady-state CO_2 concentration in a space, no greater than about 700 ppm above outdoor air levels. This equates to around 1100 ppm indoors.[18] Studies have found that the ventilation rates are below the minimum ASHRAE criterion in many classrooms, resulting in higher CO_2 concentrations.[19,20,21]

NYC Department of Buildings Mechanical Code provides the minimum ventilation requirements for educational buildings including classrooms. Chapter 4, Table 403.3 specifies the minimum people outdoor airflow rate in the breathing zone of 10 CFM/per person, and the area outdoor airflow rate in the breathing zone of 0.12 10 CFM/ft^2. The code states that the ventilation system shall be designed to provide the specified minimum rate of ventilation air continuously when the building is occupied, except as otherwise stated in different parts of the code.[22] For schools utilizing natural ventilation, the NYC Building Code 1203.4 requires that the windows be operable so the occupants can open or close them.[23]

Teachers' exposures to CO_2 are likely to vary immensely depending on several factors. Airflow patterns in buildings result from combined forces of mechanical ventilation systems, human activity, and natural effects. Air-pressure differences created by these forces move airborne pollutants from higher to lower concentrations.[24] The air pollutant concentrations indoors can be influenced by factors other than ventilation air flow rate. Theoretically, steady state concentrations of an airborne pollutant in a well-mixed indoor space can be calculated using equation 1-A:

Equation 1-A $$C_{in}=C_s+ [S/V]/(\lambda_v +\Sigma\lambda_{other})$$

where C_{in} =the indoor concentration, C_s= the concentration in the air entering the space, S/V = the indoor pollutant generation rate per unit air volume, λ_v= the air exchange rate equal to the outside air flow rate divided by the indoor volume, and λ_{other} =the sum of all other indoor pollutant removal rates.[25]

However, actual conditions are more complex than the equation suggests. The equation assumes uniform pollutant mixing in the space. Mixing, however, especially in classrooms where students are often active and the room is filled with various objects, may not occur uniformly, and therefore the concentration of pollutants at the breathing zone may vary depending on the air distribution patterns and the locations of pollutant sources. The generation rate or source strength of the indoor pollutant will likely have temporal variations. This presents a challenge in attempting to accurately characterize teachers' exposure to CO_2 and in effectively mitigating higher CO_2 levels.[26]

In densely occupied spaces such as classrooms, human metabolic production of CO_2 is generally the most significant source. Thus, occupant factors including the number of people, their body sizes, ages, and behaviors will impact CO_2 concentrations. Equations 1-1 and 1-2 can be used to calculate oxygen (O_2) consumption rate VO_2 (L/s) and CO_2 generation rate VCO_2 (L/s), respectively, knowing the physical activity level M (MET) and the surface area of the body or the DuBois surface area, AD (m^2)

Equation 1-1
$$V_{O_2}(A_D M) = \frac{0.00276\, A_D M}{(0.23\, RQ + 0.77)},$$

Equation 1-2
$$V_{CO_2}(V_{O_2}) = RQ \times V_{O_2}.$$

The respiratory quotient (RQ) is the ratio of generated CO_2 and consumed O_2 and its default value is equal to 0.83 for an average adult size (dimensionless). AD is based on body height H (m) and body weight W (kg) as taken from equation 1-3.

Equations 1-3
$$A_D(H, W) = 0.20247 H^{0.725}\, W^{0.425}$$

Table 1-1 shows the metabolic equivalent (MET) levels for typical physical activities. The CO_2 generation rate is expected to increase based on MET level.

Table 1-1. Metabolic equivalent (MET) levels for typical physical activities.

Activity	**Metabolic equivalent (MET)**
Seated, quiet	1.0
Seated, reading	1.0
Writing	1.0
Typing	1.1
Standing, relaxed	1.2
Stead, filing	1.2
Standing, filing	1.4
Walking (0.9 m/s)	2.0
Exercise	3.0-4.0

The number of occupants (S, dimensionless) affects CO_2 generation and ventilation requirements in a linear fashion. The amount of CO_2 generated, G (L/s) and minimum outdoor air ventilation requirement V_b in the breathing zone can be calculated using equations 1-4 and 1-5, respectively:

Equations 1-4

$$G = \sum_{k=0}^{S} G_{i,k} = V_{CO_2} \times S$$

Equations 1-5

$$V_b = R_p \times S + R_a \times A$$

The ventilation requirements are specified by AHSRAE Standard 62.1 and can be used with equation 1-5. Rp is the outdoor rate per person (L/s person), Ra is the outdoor rate per area (L/s m^2), and A is the floor area of the zone (m^2).[27]

In controlling teachers' exposure to higher CO_2 levels, it is important to supply a sufficient amount of outdoor air preferably through mechanical HVAC systems in order properly filter and condition outside air.[25] Operating HVAC systems consumes energy, since the ventilation air is thermally conditioned, i.e., heated, cooled, and dehumidified or humidified. In mechanically ventilated buildings, the operation of ventilation fans also consumes energy. The capacity of HVAC equipment must also be increased as the amount of ventilation air provided increases. Thus, ventilation rates have often been reduced, particularly after the energy crisis in the early 1970s, in order to decrease equipment and utility costs. Buildings, especially in cold climates, have also become more airtight which has reduced ventilation air flow through the building envelope.[28] Building ventilation rates must function to maintain a balance between energy consumption by ventilation and the known benefits of increased ventilation on occupant well being and comfort.[29]

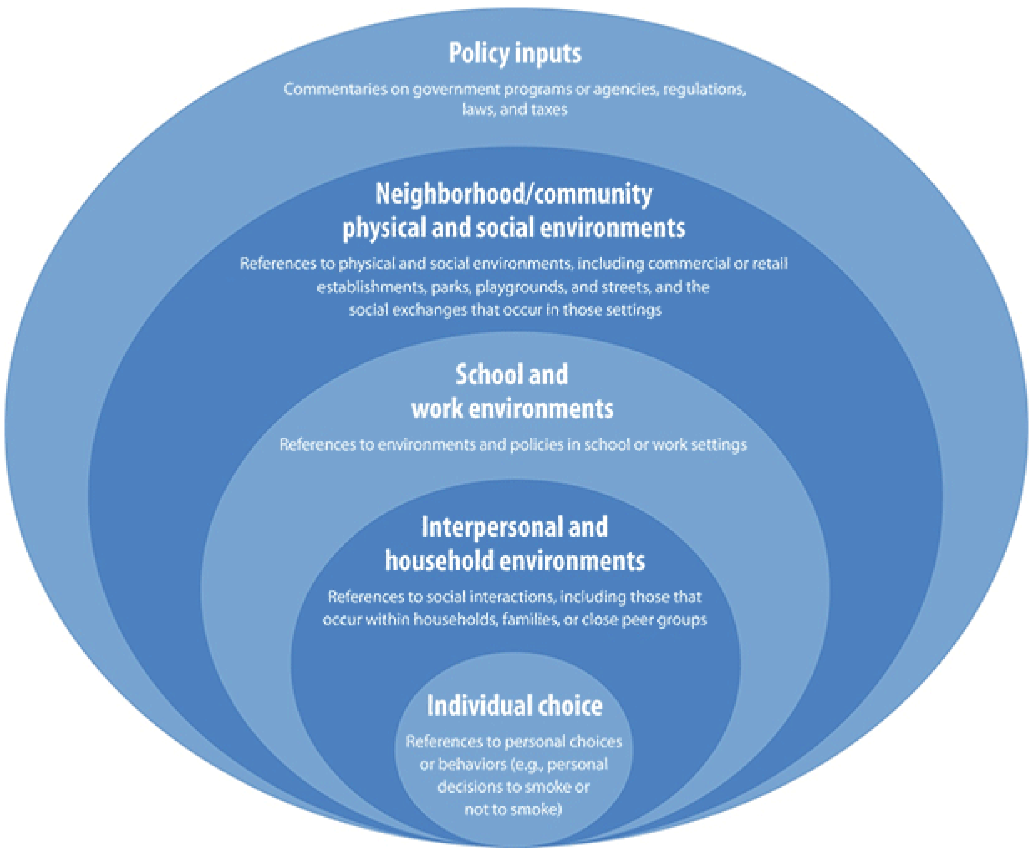
The two most common HVAC designs used in schools are mixed ventilation systems (including unit ventilators) and central air handling systems.[30] The central air handling unit serves multiple rooms whereas the unit ventilator serves a single room. In New York City's older school buildings, the windows were designed to bring outside air into the school building.[31] An exhaust located typically on the opposite side from the windows, when operating properly, creates a negative pressure drawing in air from the outside. This can be considered a mixed ventilation system. One problem with this type of system is that it does not condition the air properly.[17] The air can be heated via steam radiators however air cannot be humidified/dehumidified or cooled.[32] On April 25, 2017 Mayor de Blasio, Chancellor Fariña and the City Council announced funding to provide every classroom in New York City with air conditioning. The City is budgeting $28.75 million over the next five years to buy and install air conditioning units in all classrooms by 2022. Approximately 11,500 classrooms or 26 percent of all classrooms in the NYC school system do not have air conditioning. In the first year of the program, 2,000 classrooms are scheduled to receive air conditioning.[33]

1.3 Conceptual/Theoretical Framework

The proposed research project is based on a number of studies that have evaluated the associations of CO_2 with the health and cognition of office workers. The results of these studies indicated an association of higher CO_2 concentrations with lower cognitive functioning in office workers.[8,6,7,34] The current study will build on these studies to assess the association of CO_2 concentrations with teachers' health and perceived air quality in NYC public elementary schools.

The socio ecological model (see figure 1-1) provides a framework for understanding the interrelations among various personal and environmental factors within the proposed research project. The socio ecological model examines the complex relationships between individual, interpersonal, community, and societal/policy factors. Furthermore, the model also suggests that to reduce exposures and health symptoms, it is necessary to address aspects across multiple levels of the model simultaneously.[35]

Figure 1-1. The socio-ecological model [36]

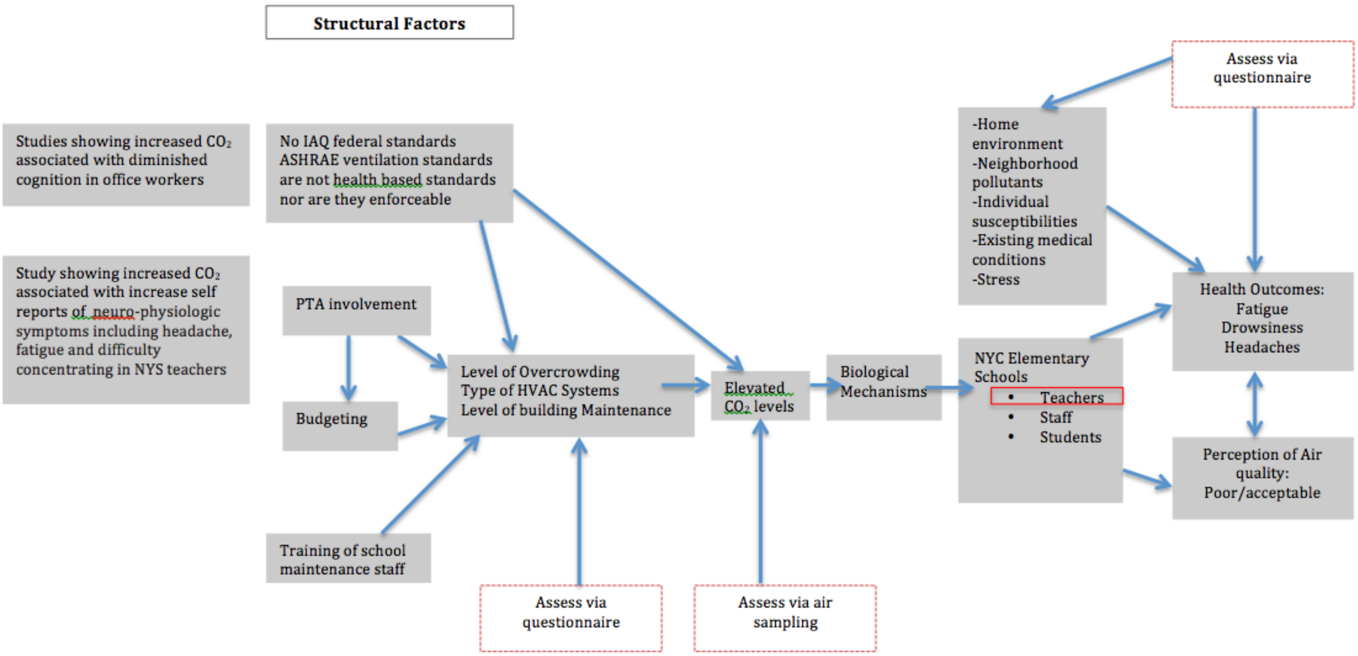


At the individual level (the teachers, in this study), important factors include age, sex, race, level of education, socioeconomic status, underlying medical conditions, smoking, exercise, and stress. The individual is surrounded by the microsystem, which includes the teacher's peers, family, faith based organizations, and the work environment. At the macro level, policy factors can play a role in impacting the public health of teachers including the lack of an OSHA indoor air quality standard[37] and/or exposure limits for CO_2. The absence of enforceable exposure limits of various indoor air pollutants in offices and schools can lead to a lack of air monitoring and exposure assessments being conducted inside schools. Building ventilation codes are checked at the time of construction but may not be enforced once the building is operational.[28] School budgeting is another important macro level or policy level factor. School budgets tend to fluctuate depending on initiatives, policies and priorities.[38] School budget cuts can impact the operation and maintenance of school buildings including HVAC systems, windows and the building envelope.

1.3.1 Conceptual Model

Figure 1-2 shows the conceptual model for evaluating CO_2 levels and the teachers' perception of air quality and wellbeing. Taking a closer look at the conceptual model, on the left hand side, several studies describing the association of higher CO_2 levels and a reduction in cognition in office workers, can have profound implications for school settings for a number of key reasons. First, schools tend to have higher occupancy levels than offices.[39] Second, children are more active and can exhale higher amounts of CO_2 creating the need for more ventilation. Third, schools already face many challenges in providing an optimal environment for learning and having CO_2 levels negatively impacting cognitive skills will compromise the learning environment further. Muscatiello et al. investigated CO_2 levels and teachers' health in New York State schools in 64 classrooms. An association was identified of higher CO_2 levels with neurophysiological symptoms such as headaches and fatigue. Structural factors in the

Figure 1-2. A conceptual model of carbon dioxide concentrations and teachers' perception of air quality and wellbeing



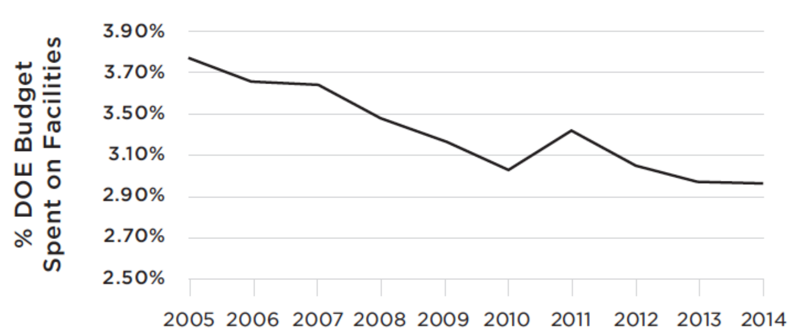
conceptual model including budgeting, PTA involvement, the absence of federal indoor air quality standards, can also have an impact on classroom air quality and CO_2 levels. Some of these factors will be discussed in the following section.

Budgeting

Funds earmarked for schools can fluctuate depending on several factors. NYC public schools have had a history of school budget challenges. In 1993, the Campaign for Fiscal Equity (CFE), consisting of NYC education advocacy groups, parent organizations and community school boards, filed a lawsuit to challenge New York State's school funding system. CFE asserted that the state's school finance system short-changed NYC public schools and deprived students of their constitutional right to the opportunity to a sound basic education. The CFE alleged that students in NYC received about $400 less per student (or 12%) in state education aid than students in the rest of the state, although NYC enrolled approximately 70% of the state's low-income students, over 51% of the state's students with severe disabilities and over 81% of the state's students with English as a second language. It was determined that an additional $5.63 billion in operating aid and $9.2 billion for facilities were needed to meet the standards required by the court. In 2007, under Governor Spitzer, a five year budget phase-in plan was developed to meet the funding goals, however after two years and a new governor, the plan was derailed by spending freezes. The funding gap existed for several more years impacting the proper upkeep and maintenance of public school facilities including HVAC systems that could be affecting ventilation and CO_2 concentrations in schools.[40]

The figure below shows a steady decline in the percent of the DOE budget earmarked for facilities.[41] The significance of this decline in the facilities budgets is the reductions in resources devoted to properly operate and maintain school HVAC systems. Continued lack of maintenance can lead to permanent damage to HVAC systems. The Bill de Blasio administration has focused on increasing school budgets including the allocation to facilities maintenance.[42] Based on the 2018 DOE budget, the percent allocated for facilities has increased to approximately 3.9%.[43]

Figure 1-3. Declining trend in the percentage of DOE budget spent on facilities hitting a historic



low in 2014

The Absence of Federal OSHA IEQ Standards

There currently is no federal OSHA IEQ standard intended to be used in offices and institutions. U.S. OSHA has established airborne limits for specific contaminants but are intended for industrial settings. The absence of an OSHA IEQ standard results in workplaces and communities lacking clear direction on how to approach IEQ issues and/or how to develop and implement proactive IEQ programs. Instead there is an increased reliance on a patchwork of guidelines which can be inconsistent and are not enforceable. Regulatory limits and guidelines for CO_2 will be discussed in more depth in Chapter 2 section 2.

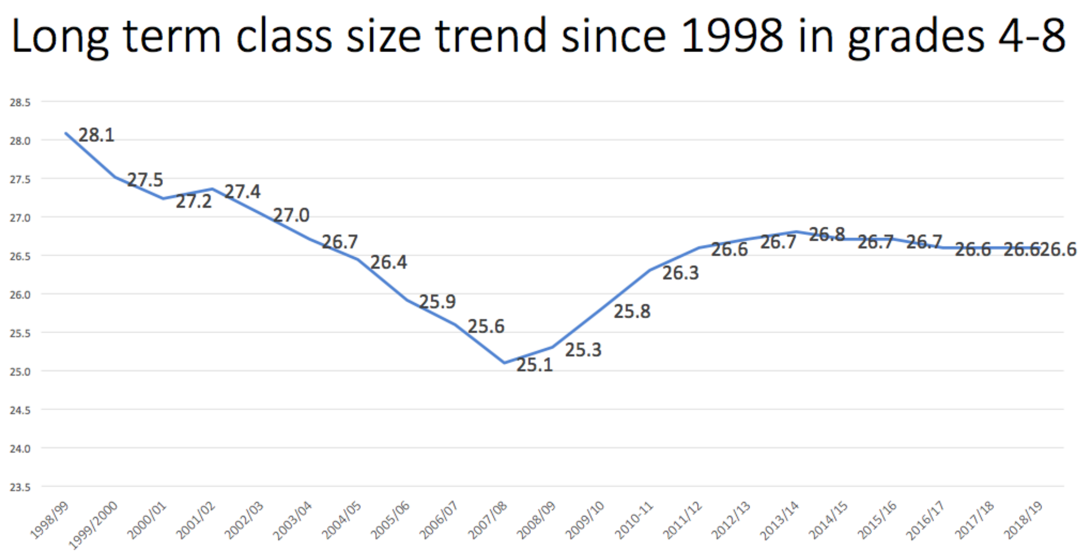
PTA Involved and Socioeconomic Status (SES) of Students

Parent teacher association (PTA) involvement can have an effect on how school facilities are managed. PTAs in some schools can be highly involved in ensuring that the school is properly maintained including proper air quality. The PTA can also provide financial support, through fundraising, when needed and assist with capital improvement projects to supplement the existing budget.[44] The NYC public school system is one of the most diverse public school systems in the US. The student body has been comprised of approximately 40% Hispanic, 30% African-Americans, 15% Asian and 15% White.[10] The demographics reveal that a larger percentage of lower SES students attend schools in the Bronx, whereas larger percentage of more affluent students attend schools in Staten Island.[45] Schools with 90 percent or more Black and Latino student populations are located in areas such as the south Bronx, northern Manhattan, and central/east Brooklyn.[41] School officials and researchers have presumed that school segregation represents segregated housing patterns since most children attend their zoned neighborhood schools. However, a recent analysis of NYC schools found that 124 of the city's 734 neighborhood elementary schools (with a total enrollment of 62,607) are considerably poorer than their school zones. The estimated household income of the zone is at least 20 percent higher than the estimated household income of the children enrolled.[46,41] It is theorized that a high level of PTA involvement and higher SES of students would be associated with increased level of building maintenance and improved functioning of HVAC systems leading to lower CO_2 levels.

Level of Overcrowding

At the macro level policies affecting class sizes can also impact the public health of teachers. Since the main source of CO_2 in classrooms are students, if the class is at or beyond capacity, CO_2 levels may be elevated. The National Center of Education Statistics classifies a school as overcrowded when "the number of students enrolled in the school is larger than the number of students the school was designed to accommodate."[14] The term is based on the physical capacity of a building and whether more students are enrolled than the building can comfortably hold. In school buildings with mechanical ventilation systems, the HVAC systems were designed to deliver a certain volume of air based on an anticipated number of students and if that number has been exceeded, the HVAC system may not be providing the proper volume of fresh air and allowing CO_2 levels to become elevated.[47] The impact of class sizes on CO_2 concentrations in classrooms will be assessed.

Overcrowding in NYC public schools has been an ongoing issue.[48] The Court of Appeals in 2003 agreed that the detrimental effects of overly large classes deprived New York City students of their right to a sound basic education. Despite Mayor Bloomberg's pledge in 2005 to alleviate overcrowding, data shows that 27 more school buildings were at 100 percent utilization or higher in 2012, enrolling 18,867 more total students compared to 2006.[15] The most recent (2018) DOE data indicate that approximately 43% of NYC schools were overcrowded with about 575,000 students (56% of total) enrolled in overcrowded schools. The breakdown between elementary, middle school and high school students was approximately 350,000 (68% of total), 50,000 (33% of total), and 175,000 (49% of total) enrolled in overcrowded schools, respectively. The data show that elementary school classes are the most overcrowded. Why are schools still overcrowded especially if Mayor Bloomberg created 100,000 new seats between 2004 and 2013? A closer look revealed that only 45,000 new NET seats were created after seat loss was taken into account. Approximately 55,000 seats were lost due to lapsed leases, elimination of temporary classrooms (trailers), annexes, and mini-buildings.[49]



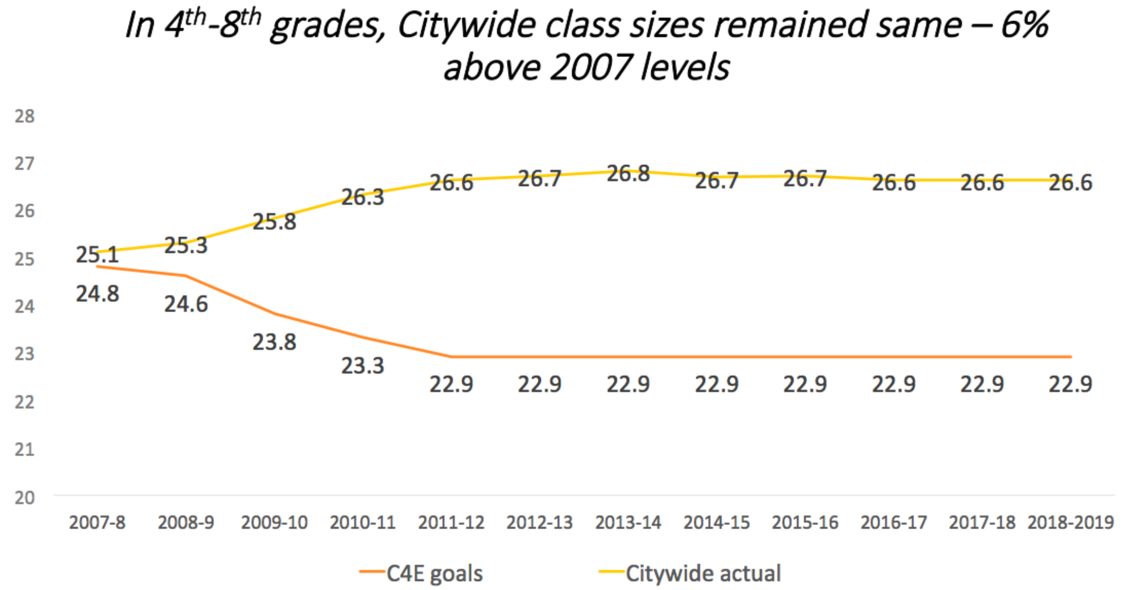


Figure 1-4: NYC Public school class size trends[49]

Level of School Maintenance and Custodial Staff Training

The level of school maintenance has a direct impact on the functioning of school HVAC systems which in turn can affect CO_2 levels in classrooms.[47] The NYC public school system has been plagued by reports of overcrowding, poorly maintained and underfunded schools.[15,48] There has been a steady decline in the percentage of the NYC department of education (DOE) budget allotted for facilities. NYC DOE has spent a smaller percentage on maintenance and operations than six of the seven largest school districts in the U.S.[41] Only two percent of school buildings have been deemed by the Department of Education to be in "good" condition. Hundreds of schools are failing to meet environmental, accessibility, and building code regulations.[14] The City needs to adequately invest in all schools, and particularly those with the most vulnerable student populations. Non functioning or poorly maintained HVAC systems can lead to a build up of CO_2. The level of school maintenance can be assessed through the teacher questionnaire and through reviewing school building facility inspection reports. The NYC DOE DSF conducts facility inspections of school buildings to determine the type of repairs that need to be performed. Copies of these inspection reports are posted on their website. Not all school buildings have inspection reports and some reports are not available.[50]

Type of HVAC System

The association of the type of HVAC system with CO_2 concentrations will be assessed in the study. Approximately 60% of NYC school buildings rely on operable windows for ventilation. These buildings utilize exhaust ventilation typically located in or near a coat closet to exhaust air in the classrooms while creating a pressure differential to allow movement of outside air into the building through any openings in and around windows.[51] In these older buildings, inoperable windows will prevent teachers from opening windows to allow outside air to enter the classroom to dilute the CO_2 concentrations. Many schools have replaced the older leaky windows with more energy efficient windows which result in more tightly sealed classrooms. Also, if the exhaust fans are not functioning, CO_2 concentrations can build up in the classroom. This type of ventilation system has been referred to as a mixed ventilation system. The remainder of NYC school buildings utilize central mechanical ventilation systems. A lack of continuous operations and maintenance of HVAC systems can result in IEQ issues.[52] For example, when HVAC systems are not properly balanced, more air can be supplied to one zone than another, allowing CO_2 concentrations to build up in certain classrooms. For instance, a recent facility inspection report for P.S. 165 included the following quote “There is temperature variation among the classrooms (some hot, some cold)… Very few AC units are operational”.[41]

Teachers' Exposure to CO_2

Carbon dioxide concentrations will be measured continuously for the majority of the week inside several classrooms in each school (teachers' work environment). Higher CO_2 concentrations, through biological mechanisms that are not clear at this point, may affect health outcomes. Kajtar et al. demonstrated increased respiration, mental effort and increased feeling of tiredness in study participants performing mental tasks at 3000 and 4000 ppm of CO_2.[8] Animal studies have shown that CO_2 impairs neurotransmitter functioning via the $GABA_A$ receptor (found in all vertebrates) leading to poor judgment.[53,54] This may also help explain the impacts on cognition observed by researchers.

Information on individual factors will be obtained through the study questionnaire. Health outcomes (headache, fatigue, drowsiness, difficulty concentrating, stress level and other symptoms) and perceptions of air quality will also be solicited through the questionnaire.

In the absence of indoor air quality regulations, the World Health Organization (WHO) recommends utilizing a number of environmental and public health principles to help address environmental risks in the indoor environment.[55] Some of these principles include the precautionary principle and the "right to know" principle. The precautionary principle, in the context of environmental health, states that in the cases where definitive data does not exist proving an environmental hazard causes a specific negative health outcome, its better to err on the side of safety.[56]

The precautionary principle is utilized more often in the European Union, including as a guiding principle in policy making.[57] Even though the precautionary principle became well known in the 1970's as governments and environmental groups began to address many environmental problems, the principle has existed in public health long before then. In 1854, Dr. John Snow used the precautionary principle in addressing the cholera outbreak in central London. Without being certain about the disease mechanism, he recommended removing the handle from the Broad Street water pump where more cases of Cholera had been reported. Some evidence for a correlation between the polluted water and cholera had been published years earlier by Dr, Snow himself, however this evidence was not 'proof beyond reasonable doubt'. The probable costs of inaction would have been far greater than the potential costs of action.[58] Even though the precise mechanism of how CO_2 affects cognitive skills is not clear yet and there have been some studies disputing the connection, showing that the effects are being caused by other contaminants in the air present with CO_2, the precautionary principle instructs us to maintain CO_2 levels as low as possible.

The "right to know" principle in the context of occupational and environmental law, states that the individual has the right to know the chemicals to which they may be exposed in their workplace or community. "Right to Know" laws take two forms: Community Right to Know and Workplace Right to Know. Each grants certain rights to those groups. Many community right to know regulations were enacted after the Bhopal plant disaster in 1984. In the context of this research project, teachers have the right to know the concentrations of CO_2 they are being exposed to, especially because these levels are not routinely measured and there is published research showing that CO_2 can have health effects at much lower levels than originally thought. Monitoring CO_2 levels in classrooms will inform teachers about their exposure levels and determine whether interventions need to be implemented.

1.4 Overview of the Dissertation

1.4.1 Overall Goals

This dissertation aims to examine the association of higher CO_2 levels and teachers' perceived air quality and well-being in NYC elementary schools. Few IEQ studies in schools have focused on teachers' exposure to CO_2.[59] The purpose of the proposed project is to build on the aforementioned studies and to evaluate the direct effects of increased CO_2 levels on teachers' perception of air quality and reported symptoms. The study will collect primary data from representative public schools throughout NYC. Primary data collection will include continuous air monitoring and datalogging for CO_2, temperature and relative humidity in classrooms. The environmental monitoring will characterize CO_2 levels in NYC public school classrooms and teachers' full shift exposures, which has not been previously conducted. Several questions will be explored including: the percentage of teachers that are experiencing symptoms, the ranges of concentrations of CO_2 that the teachers are exposed to, whether teachers can perceive a change in air quality when CO_2 levels increase, whether school staff can assist in evaluating and controlling CO_2 levels, and any associations between CO_2 levels and health symptoms.

1.4.2 Specific Aims

The specific aims are:

Aim 1: To monitor and characterize NYC public school teachers' full shift exposure to CO_2;

Hypothesis 1: Based on published studies of measuring higher CO_2 concentrations in schools, the reports of overcrowding and possible maintenance issues, NYC public school teachers are exposed to CO_2 time weighted average (TWA) levels above 1000 ppm. The criteria of 1000 ppm is being used for a number of reasons. First, 1000 ppm is equivalent to approximately 20 CFM outdoor air per occupant which provides a sufficient amount of air to minimize objectionable odors and maintain IEQ complaints below 20% of the occupants.[60] Second, Satish et al. reported that at 1,000 ppm CO_2 (relative to 600 ppm), moderate and statistically significant decreases occurred in six of nine scales of decision-making performance in the strategic management simulation tests.

H_0: NYC public school teachers are not exposed to CO_2 TWA levels above 1000 ppm.

H_1: NYC public school teachers are exposed to CO_2 TWA levels above 1000 ppm

Sub Aim 1: To assess whether school staff can manage air monitoring devices in order to monitor CO_2 levels in classrooms;

Hypothesis 1a: With appropriate direction and guidance, school staff can independently manage air monitoring equipment and maintain the required documentation. If necessary in the future, school staff can monitor CO_2 levels and take certain actions such as opening windows or communicating with the building custodian to check or ramp up the ventilation system, in the event that CO_2 levels are high.

H_0: NYC public school staff cannot independently manage air monitoring equipment and maintain the required documentation.

H_0: NYC public school staff can independently manage air monitoring equipment and maintain the required documentation.

Aim 2: To analyze the association of school and classroom factors (e.g. type of HVAC system, age of school, level of maintenance, occupancy level of classes, level of parent involvement, square footage of classroom, operable windows) with CO_2 levels and health effects reported by teachers.

Hypothesis 2: A significant association may exist between certain school factors and high carbon dioxide levels and/or health symptoms reported by teachers. For example, a greater number of maintenance issues could be associated with greater CO_2 levels since some of the maintenance problems may deal with the school ventilation or HVAC systems. By knowing certain school building factors we may be able to predict high CO_2 levels in schools without conducting air monitoring. It may be possible to more accurately target schools for an intervention to reduce CO_2 levels based on utilizing predictive modeling.

H_0: Certain school factors are not associated with high carbon dioxide levels and/or self reported health symptoms.

H_0: Certain school factors are associated with high carbon dioxide levels and/or self reported health symptoms.

Aim 3: To evaluate the association between classroom CO_2 levels and the teachers' self reported responses/ or health symptoms including perceived air quality, headache, fatigue, drowsiness and difficulty concentrating.

Hypothesis 3: A significant association may exist between high CO_2 levels and perceived air quality, headache, fatigue, drowsiness and difficulty concentrating experienced by teachers;

> H_0: A significant association does not exist between high CO_2 levels and perceived air quality, headache, fatigue, drowsiness and difficulty concentrating experienced by teachers;
>
> H_1: A significant association does exist between high CO_2 levels and perceived air quality, headache, fatigue, drowsiness and difficulty concentrating experienced by teachers;

The above points lead to a hypothesis that higher concentrations of CO_2 may be associated with an increased number health symptoms and air quality complaints being reported by teachers. Enhanced IEQ in schools could improve health, decrease absenteeism, increase performance and productivity, and reduce operational costs (more effective teaching).[61] This study provides a first step to test this hypothesis, which would need to be validated in an experimental study before policies and interventions to protect teachers, staff and students are implemented.

1.4.3 Organization of the Dissertation

Chapter two is comprised of a thorough, critical, and analytical overview of existing literature and established knowledge pertinent to the aims of the study. The topics reviewed include the physiological effects of CO_2, the effects of CO_2 on cognition, suggestive direct effects of CO_2 in schools and regulatory limits and guidelines for CO_2. Chapter three details the methodology used for participant recruitment, the survey questionnaire, environmental monitoring and statistical approaches used in evaluating the data. Chapter three also discusses ethical considerations, procedures, and IRB approvals. Reliability and validity considerations are also reviewed. Chapter four describes the results obtained from round 1 and round 2, including similarities and differences between the two rounds. The results for each aim are presented. Chapter five summarizes the study, its aims, the hypothesis, and methods. The analytic results, interpretations and the significance of the findings are discussed. Chapter five also describes whether the hypothesis was proven, partially proven, or disproven. The strengths and weaknesses of the study are described. Finally, the public health relevance is discussed, including policy recommendations and practical intervention suggestions.

1.4.4 Significance of the Dissertation

In light of recent studies reporting a link between higher CO_2 levels and reduced cognition, as well as New York State teachers reporting neuro-physiological symptoms in higher CO_2 exposure groups, NYC public school teachers may be at risk. A systematic evaluation of teachers' exposure to airborne CO_2 levels, as well as temperature and relative humidity has not been conducted in NYC public schools, the largest school district in the U.S. The United Federation of Teachers has responded to teachers' complaints of various air quality issues including mold and limited CO_2 measurements have been collected. These investigations provide only a snapshot of the actual conditions. The data collected as part of this dissertation strived to obtain one week of continuous data from each participating teacher's classroom during two points in the school year, representing the heating and non-heating seasons. The results of the study will help characterize the range of teachers' full shift CO_2 exposures. The data will enhance our understanding of time trends by providing details regarding CO_2 peak levels and any fluctuations throughout the school day and week, average levels and the cumulative dose. The results from the heating and non-heating seasons will be compared.

School building and classroom factors that can potentially impact CO_2 levels will also be investigated. The association between higher CO_2 levels and teachers perception of air quality and self reported health symptoms will be assessed. As more studies are published reporting a connection between increased CO_2 levels and cognitive effects, its important to evaluate this relationship in an urban school setting. By systematically characterizing the CO_2 levels we can begin to paint a clearer picture of exposure levels of teachers and students. Increased CO_2 levels can be impacting the cognitive abilities of teachers and limiting the academic performance of students. NYC public schools already face many challenges such as overcrowding, aging school facilities, and limited facility budgets. Increased CO_2 levels may be another factor impacting educational success.

This study is also significant because it was the first study that systematically examined carbon dioxide levels inside classrooms in a large urban public school system. A current trend impacting public health is the shift of populations to urban centers.[62] As the number of students and teachers in urban school systems is expected to increase, its important to understand the levels of CO_2 inside urban schools and classrooms and the possible effect on teachers' health.

A number of public health trends also increase the significance of the current study including the continued rapid population growth and expansion of urban centers and the rise of atmospheric CO_2 levels from burning fossils fuels impacting climate change. First, since populations in city centers are increasing it is anticipated that more teachers will be working in schools in city centers. Results obtained from this study can be generalizable to similar large urban school districts. Second, within the background of increasing ambient CO_2 levels,[63] it may become more difficult to dilute indoor CO_2 levels and any direct effects of CO_2 may be more pronounced. This study may provide data and evidence to place more emphasis on assessing and controlling CO_2 levels. The findings from this study may also lead to swifter actions by the NYC DOE to correct any underlying conditions.

1.5 Data Sources

The target study population was NYC elementary school teachers and since continuous airborne CO_2 levels in NYC classrooms had not been monitored prior to this project, it was necessary to collect primary data. Carbon dioxide, temperature and relative humidity levels inside select classrooms were monitored for approximately one week over the course of the 2017-2018 school year. A questionnaire was developed based the questionnaire used by Muscatiello et al.[9] Permission was given to the research team to adopt the questionnaire. Some minor modifications were made to the questionnaire.

Since research was being conducted on human subjects and some interaction was necessary with the teachers during the study, the required Internal Review Board (IRB) applications were submitted and approvals were received from City University of New York School of Public Health IRB and the NYC DOE IRB. Confidentiality and anonymity were of highest importance.

Questionnaire responses were de-identified and identifying information was maintained in a separate location in secure file cabinet and password protected files. Access to this information was only given to the research team.

Using primary data imparts a number of advantages over secondary data including defining the parameters and designing questions that are better suited to meet the aims of the study. For example, after speaking with Muscatiello regarding his experience with data collection and analysis, it was discussed that information regarding the stress level of teachers would be important. A question to assess the teachers' stress levels was included in the current study. Another advantage of collecting primary data is having more familiarity with data. Since the researcher was involved in collecting the data, he/she will know about any variations in the collection process; for example if the sampling period needed to be abbreviated or shifted to accommodate a teacher's request or a holiday. Some of the disadvantages include the time commitment, the expense of purchasing equipment and logistical challenges in coordinating the data collection.

Chapter 2. Literature Review

In studying the association of higher CO_2 levels and teachers' perception of indoor air quality and well being, it's important to review existing literature regarding the physiological effects of CO_2, studies reporting direct effects of CO_2 on cognition, CO_2 studies in schools as well as the current regulatory levels and guidelines of CO_2.

2.1 Physiological Effects of CO_2

Carbon dioxide plays a key role in human biological activities including the respiration process. The body has a tremendous amount of chemoreceptors that are highly sensitive to CO_2 and are instrumental in controlling homeostasis.[64] At standard temperature and pressure CO_2 is an odorless, colorless, and heavier than air gas, with a faintly pungent odor. In air, CO_2 is very stable and nonflammable, whereas in water, CO_2 is soluble and reacts to form carbonic acid. Dissolved CO_2 and water undergoes hydration according to the following reaction: $CO_2 + H_2O = H_2\ CO_3 = H + HCO_3$. This reaction can impede the acid base balance: *pH = PK plus log* HCO_3/CO_2.[65]

The human body produces CO_2 from cellular respiration. CO_2 diffuses from cells into the surrounding capillaries and is carried by the blood either bound to hemoglobin or dissolved as carbon dioxide, carbonic acid, or bicarbonate ion. A minor amount of CO_2 can be bound to plasma proteins to form carbamino compounds. The partial pressure of CO_2 in pulmonary capillary blood is greater than that in alveolar air. The gas is exchanged freely through the alveolar membrane and is thus released from the lungs by diffusion because of the concentration gradient existing between the blood and the air in the alveoli. CO_2 is one of the main regulators of intracellular pH, due to its ability to freely defuse through lipid cell membranes. Depending on

its concentration, CO_2 can stimulate or cease several cellular processes. The toxicological effects of CO_2 can manifest quickly because of its ability to pass freely through tissue membranes and are detected mainly in the blood pH, lungs, heart and central nervous system.[66]
Chronic CO_2 hypertension exposure results in extra cellular acidity that is stabilized within days. However, intermittent exposure to CO_2 does not permit the compensation mechanisms to be functional. Evidence suggests that, if a higher than normal concentrations of CO_2 is inhaled peripheral and central chemoreceptors are activated, perhaps directly in the Locus coeruleus, thus increasing cell firing and the consequent release of noradrenaline.[67]

In investigating whether IEQ influences allostatic load and its connection to sick building syndrome (SBS), Jung et al. found that higher CO_2 exposures were significantly associated with neuroendocrine effects as indicated by epinephrine and norepinephrine in urine and cortisol.[68] Allostasis is the adaptive process that maintains homeostasis after the body experiences neuroendocrine stress. Mediators such as adrenalin, cortisol and other chemical messengers are produced to promote adaptation in the aftermath of acute stress, but can also lead to allostatic overload, the wear and tear on the body and brain that result from chronic stress.[69] This is also referred to as allostatic load. Jung et al. measured CO_2 levels ranging from 464.0 to 1193.6 ppm. CO_2 levels were also associated with 8-OHdG levels. The oxidized nucleoside 8-OHdG is the most frequently detected DNA lesion resulting from the action of reactive oxygen species and after DNA repair, this molecule is excreted in the urine. Associations have been reported of exposure to indoor pollutants with levels of 8-OHdG.[70]

Usyl et al. investigated the effects of airborne 0.05%, 0.1% and 0.3% CO_2 exposure on early brain development in rats. Levels of insulin-like growth factor-1 (IGF-1) were assessed in the study. IGF-1 is a neuro-protective growth factor involved in brain development. IGF-1 is correlated positively with lower anxiety and improved cognitive functions. Rats exposed to 0.3% or 3000 ppm CO_2 exhibited reduced performance in learning and memory. IGF-1 is produced by many organs, but the liver produces approximately 70% of the total circulating IGF-1. Circulating IGF-1 crosses the brain-blood barrier and regulates hippocampal IGF-1 levels, which affects behavior. Exposure to poor air quality can reduce serum IGF-1 levels.[71]

It's important to review the toxicological effects of CO_2 at various concentrations to understand the possible direct effects at low levels. The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) is based on physiological effects of CO_2 that when inhaled at elevated levels can result in mild narcotic effects, stimulation of the respiratory center and asphyxiation.[72] CO_2 levels of approximately 50,000 ppm cause the brain to lower metabolism and spontaneous neural activity, and induce a reduced arousal state.[73] CO_2 is a powerful cerebral vasodilator. A chronic low concentration of CO_2 induces low to mild effects such as visual impairment, at 1% (or 10,000 ppm) CO_2 and headaches at exposure above 2% (or 20,000 ppm). In general, specific neurobehavioral changes have not been observed with a level at up to 4% for up to two weeks. More recently a decrease in stereoacuity and a decrease in the ability to perceive motion was reported with exposures above 2.5%.[66] Kajtar et al. demonstrated increased respiration, mental effort and increased feeling of tiredness in study participants performing mental tasks at 3000 and 4000 ppm.[8] Animal studies have shown that CO_2 impairs neurotransmitter functioning via the $GABA_A$ receptor (found in all vertebrates) leading to poor judgment.[53,54] This may also help explain the impacts on cognition observed by researchers.

2.2 Carbon Dioxide and Cognition

In recent years several studies have reported an association of higher indoor CO_2 levels with poorer cognitive function. Table 2-1 provides an overview of several studies investigating the carbon dioxide and cognition. Kajtar et al. conducted two studies (2001, 2002) to investigate the direct effects of CO_2 in an office setting. A controlled office environment was established and 10 participants were exposed to the following CO_2 concentrations: 600, 1500, 2500, 3000, 4000, and 5000 ppm, to evaluate cognitive performance and well being. Participants were asked to read a text and search for typographic errors. Their performance was assessed by the number of rows read (quantity aspect), and the percentage of misspelled words found (quality aspect). Prior to and following the work sessions, questionnaires were completed for evaluating subjective comfort and well-being, and physiological tests were conducted and measurements of skin temperature were collected.[8]

The first series of experiments did not identify any significant effects as indicated by the results of the mental exams, however, physiological changes were found. A small but significant increase of the diastolic blood pressure (DBP) was found in subjects during the session with CO_2 at 5000 ppm. The degree of DBP changes within sessions (difference between measurements at the start and end of the same session), sessions with 600 and 5000 ppm CO_2 concentration were significantly different from each other. The researchers theorized that 5000 ppm CO_2 concentration in the air slightly increased the vasoconstriction in subjects. The researchers also concluded that the mental tasks were not sufficiently difficult and increased the level of difficulty for the second series of experiments. The respiratory frequency and the volume of respiration of the majority of subjects were higher in the session with 5000 ppm CO_2 concentration than in the session with 600 ppm. Responses on the questionnaire revealed that subjects performing tasks at

5000 ppm reported feeling more tired. The researchers concluded that more mental effort was required to complete cognitive tasks during conditions with higher airborne concentrations of CO_2.

In the second series of experiments, significant differences were found between the subjects performing tasks at 600 ppm versus 3000 or 4000 ppm. Significantly more mistakes were identified (quality) by subjects in the low exposure versus high exposure scenarios. A difference in the number of rows read at various CO_2 levels was not identified signifying an impact on concentration but not on attention. Physiological test results confirmed increased respiratory volume (via pulmonary function test) and effort exerted by subjects exposed to 4000 ppm versus 600 ppm.[8]

Satish et al. investigated whether higher concentrations of CO_2 within the range typically found in office buildings and without changes in ventilation rate, can impair occupants' decision-making performance. Twenty two study participants were exposed to three different conditions in a controlled environmental chamber resembling an office. Participants were exposed to three different CO_2 concentrations: approximately 600, 1,000, and 2,500 ppm while completing the Strategic Management Simulation (SMS) scenarios. The SMS is a software tool designed to measure the underlying parameters of thinking essential to communication, teamwork, utilization of knowledge, breadth of approach, integration of knowledge with incoming information, use of planning and strategy. Moderate and statistically significant reductions occurred in six of nine scales of decision-making performance in groups exposed to 1000 ppm compared to 600 ppm.[7]

Allen et al. conducted a follow up study to Satish et al. to confirm the effects of CO_2 on higher order cognitive function in 24 office workers. In a double blind study using a similar controlled environmental (office) chamber, three target CO_2 concentrations were tested: 550 ppm, 945 ppm and 1400 ppm. On average, participants' cognitive scores in the SMS software tool were 61% higher on the 945 ppm day and 101% higher on the two 550 ppm days than on the 1400 ppm day ($p<0.0001$).[6] The strengths of the Allen et al. study included the double blind study design. The participants were not aware which condition was being tested since the ventilation air flow was kept constant while the CO_2 levels were being adjusted. It was conducted in a strictly controlled environment, which is often difficult to achieve in a school/classroom where you may have other contaminants or IEQ factors influencing the study outcomes.

Allen at al. (2018) investigated the effect of CO_2 levels on the flight performance of pilots. Thirty active commercial airline pilots used a FAA-approved flight simulator to fly segments at different CO_2 concentrations (700, 1500, 2500 ppm). CO_2 concentrations were controlled with ultra-pure CO_2 while maintaining the same ventilation rates for each segment. The pilots performed a range of predefined maneuvers of varying difficulty without the aid of autopilot, and were assessed by a FAA Designated Pilot Examiner. Compared to segments at a CO_2 concentration of 2500 ppm, the odds of passing a maneuver were 1.52 (95% CI: 1.02–2.25) times higher when pilots were exposed to 1500 ppm and 1.69 (95% CI: 1.11–2.55) times higher when exposed to 700 ppm, controlling for maneuver difficulty, examiner and order of maneuvers. The length of CO_2 exposure was also investigated. The effects of CO_2 on flight performance were only detected after 40 minutes into the flight, becoming more pronounced as the cumulative exposure to CO_2 increased. For five of the seven most difficult maneuvers, there was suggestive (not statistically significant) evidence of poorer passing rates at 1500 ppm versus 700 ppm.[34]

Table 2-1. Overview of studies reporting direct effects of CO_2 on cognition

Investigators	**Year**	CO_2 **Levels**	**Exposure Duration**	**Test Scenario**	**Results**
Kajtar et. al.	2006 2012	6000, 5000, 4000 and 600 ppm	2- 3 hours	Math & reading tests	Participants' well-being and attention significantly diminished. Participants spent more effort and performed worse in proof reading, indicated by decreased mid-frequency components of heart period variance and lower proportion of errors found.
Satish et al.	2012	1000 ppm, 2500 ppm versus 600 ppm	2.5 hours	Strategic Management Simulation (SMS) software tool	Moderate and statistically significant reductions occurred in six of nine scales of decision-making performance in groups exposed to 1000 ppm compared to 600 ppm.
Law et al.[74]	2014	4460 +- 1090 ppm in the International Space Station	7 days	Self reported health effects	Average CO_2 levels need to be maintained below 3300 ppm to reduce reports of headache at or below 1%.
Maddalena et al.[75]	2015	800 ppm and 1600 ppm	4 hours	Computer based cognition exam	Varying the ventilation rate per person or per floor area, did not result in statistically significant effects on perceived air quality or reports of sick building syndrome. Significant and independent negative impact on most decision-making measures were identified.
Vehvilainen et al. [76]	2015	2700 ppm and 700 ppm	4 hours	Office workers	Higher CO_2 concentrations in tissues, changes in heart rate variation and an increase of peripheral blood circulation during exposure to elevated CO_2 concentration.
Allen et al. [6]	2016	550 ppm, 945 ppm and 1400 ppm.	2.5 hours	Strategic Management Simulation (SMS) software tool	Participants' cognitive scores were 61% higher on the 945 ppm day and 101% higher on the two 550 ppm days than on the 1400 ppm day ($p<0.0001$).
Zhang et al.[77]	2016	5000 ppm versus 500 ppm	2.5 hours	Various cognitive exams	No significant changes in perceived air quality, acute health symptoms, cognitive performance and measured physiological responses (except for End-Tidal CO_2).
Zhang et al. [78]	2017	1000 ppm and 3000 ppm versus 500 ppm	2.5 hours	Various cognitive exams	Purely added CO_2 was not associated with changes in perceived air quality, cognitive performance or health symptoms. Adding 3000 ppm of pure CO_2 significantly increased end-tidal CO_2 and heart rate. When bio-effluents were introduced with high CO_2 there was a significant reduction in perceived air quality, elevated arousal/stress and physiological effects, increases in self-reported headache, fatigue, sleepiness, and lower speed of addition, fewer correct links to be made in a Tsai-Partington test.
Allen et al. [34]	2018	700, 1500, 2500 ppm	3 hours	Flight Simulator	Compared to CO_2 concentration of 2500 ppm, the odds of passing a maneuver in the simulator were 1.52 (95% CI: 1.02– 2.25) times higher when pilots were exposed to 1500 ppm and 1.69 (95% CI: 1.11– 2.55) times higher when exposed to 700 ppm.

2.3 Suggestive Evidence of Direct Effects of CO_2 in Schools

Exposure assessment studies conducted at schools have found elevated CO_2 levels; in some instances as high as 4000 ppm and 6000 ppm.[76,79] Studies measuring CO_2 levels and student academic performance have varied in design but have utilized CO_2 as a surrogate for ventilation rates or IEQ to determine the effect of ventilation rates on academic performance. Thus, such studies may only be suggestive of the direct effects of CO_2 concentrations on teacher and student health and cognition.

Twardella et al.[80] assessed the effect of IEQ as indicated by the median CO_2 level in the classroom, on the concentration performance (CP), total characters processed (TN) and total number of errors (TE) of 417 nine and ten year old students. Two test conditions were assessed, poor (median CO_2= 2115 ppm) and improved IAQ (median CO_2=1045 ppm) were established by mechanical ventilation on two days in one week each in every classroom. Results showed that TE was increased significantly by 1.65 (95% confidence interval 0.42–2.87) in poor compared to improved air quality. Sidorin et al. [81] tested the ability of seventh grade students to solve five letter anagram word puzzles requiring mental concentration under low and elevated CO_2 concentration conditions (below 1000 ppm and above 2000 ppm, respectively). Two exams were administered each under low and elevated CO_2 conditions. For exam 1, ten students were tested in each group while 19 and 25 students were tested in exam 2 in the low and elevated CO_2 groups, respectively. Students were matched in two different groups by academic level. Students in the elevated CO_2 group had almost twice as many errors than the low exposure group. Wargocki and Wyon adjusted ventilation rates in classroom settings to investigate the effects on student performance on several tests (subtraction, multiplication, number comparison, logical thinking, acoustic proofreading, reading and comprehension). An improvement in school performance was found by increasing classroom ventilation from about 3.0 to 8.5 L/s (6.4 to 18 CFM) per person as evidenced by the increased speed at which the tests were completed without increased errors.[52] As mentioned earlier, these studies utilized CO_2 as an indicator of air quality and rate of ventilation thus it is only suggestive of the direct effects of CO_2 on cognition and student academic performance since other contaminants can be present when the ventilation rates are low and the classroom is not being exhausted sufficiently.

Haverinen-Shaughnessy et al. examined the association of classroom ventilation rates (as determined by CO_2 concentrations) and academic achievement (using standardized tests as a metric of performance) of 5th graders. A linear association was identified of classroom ventilation rates with students academic achievement within the range of 0.9–7.1 l/s per person. For every unit (1 l/s per person) increase in the ventilation rate within that range, the proportion of students passing standardized test (i.e., scoring satisfactory or above) increased by 2.9% (95% CI: 0.9–4.8%) for math and 2.7% (95% CI: 0.5–4.9%) for reading. The researchers pooled schools from two districts to increase the total number of schools (100) and improve the power of the study. Continuous CO_2 monitoring results from at least one full day from a classroom from each school were correlated with the classroom results from math and reading standardized exams.[79] Since CO_2 concentrations depend on many factors (activity of students, number of students, HVAC system, heating or cooling season, operable windows, etc.) and are highly variable and the one day of monitoring may not be representative of the true CO_2 levels throughout the school year.

Gaihre et al. showed that time weighted average (TWA) CO_2 concentrations were inversely associated with school attendance but not with academic attainments. An increase of 100 ppm

CO_2 was associated with a reduced annual attendance of 0.2% (0.04, 0.4).[82] Elevated classroom CO_2 concentration can have an educational cost to children due to school absences and an economic cost to parents due to missing days at work.[38] Other factors that may affect student performance include socioeconomic status (SES), ethnicity, temperature and humidity, other air contaminants (e.g. mold, VOCs), lighting, noise, classroom size, and teacher effectiveness.[19]

Riham Jaber et al. found that reducing classrooms' temperature from 25°C to 23°C, and also increasing temperature from 20°C to 23°C whilst decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm significantly improved the performance of adult female students on a memory task. Decreasing the temperature from 25°C and 23°C to 20°C whilst decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm significantly improved their performance in an attention task. Cold, hot and warm sensations can negatively affect mental performance for memory and attention tasks while mild cooling sensation can improve mental alertness.[83]

2.4 Current Exposure Limits and Guidelines for CO_2

The Occupational Safety and Health Administration (OSHA) established a permissible exposure limit (PEL) (8 hour time weighted average) for CO_2 of 5000 ppm in 1971.[84] The PEL originated from an American Conference of Governmental Hygienists (ACGIH) threshold limit value (TLV) in turn derived from older studies of healthy younger males and may not be applicable to the populations in offices or schools. ACGIH states that the TLV of 5000 ppm "provides a good margin of safety from asphyxiation and from undue metabolic stress, provided normal amounts of oxygen are present in the inhaled air." The TLV Short Term Exposure Limit STEL is based on the short-term, high CO_2 exposure studies that produced increased pulmonary ventilation rates.

NYC building codes have adopted the ASHRAE 62.1 standard, which recommends maintaining a steady state CO_2 concentration within a space no greater than 700 ppm above outdoor air levels.[85] Since about 1916 (Mechanical Engineer's Handbook by McGraw-Hill) and found in the New York City Building Code of 1929, CO_2 of 800 to 1,000 ppm and 1,000 ppm respectively were recommended. The 1,000 ppm guideline value for CO_2 used in ASHRAE 62.1 1989 standard was based on an assumed ventilation air (outdoor air) rate of 15 CFM/person and an outdoor baseline CO_2 concentration of 300 ppm. (ASHRAE 62.1 1999 standard set a differential CO_2 level of 700 ppm along with minimum ventilation rates for given spaces rather than an absolute value like 1,000 ppm. This change to the standard occurred because background CO_2 levels are closer to 400 ppm than 300 ppm resulting in an indoor level of 1,100 ppm CO_2 using the same 15 CFM/person as was used in the 1989 standard. Thus the current standard would have a baseline above 1,000 ppm CO_2. These CO_2 guidelines were established to ensure that human emitted bioeffluents (i.e., odors) that can compromise occupant comfort inside conditioned spaces are controlled. Thus CO_2 is being used as a surrogate for levels of other bioeffluents that cause odors expected to be viewed as unacceptable by occupants, not because CO_2 is a direct health hazard.

The current ASHRAE Standard "Ventilation for Acceptable Indoor Air Quality" (ANSI/ ASHRAE 62-2016) does not reference the term "1,000 ppm CO_2." The value of 1,000 is a guideline value only and not considered a regulated standard. Interpretation documents support the notion of 1,000 ppm as a guideline level to be used as a proxy for odor causing compounds from human activity that may be objectionable by occupants. The European Committee for

Standardization (CEN)/Technical Committee (TC) has developed an international standard for IEQ, CR 1752-Ventilation for Buildings: Design Criteria for the Indoor Environment.

The standard describes three categories of attainment based on the estimated percentage of occupants that will express dissatisfaction with the air quality. These thresholds of 15%, 20%, and 30% dissatisfied are associated with a ventilation rate ranging from 0.47 – 1.18 CFM/ft^2 for classrooms and 0.14 – 0.33 CFM/ft^2 for open office spaces. The three thresholds in CR 1752 are associated, respectively, with CO_2 levels of 460 parts per million (ppm), 660 ppm, and 1190 ppm **above** outdoors CO_2 levels.[86]

For classrooms with students ages 5 to 8 and ages 9 and up, ASHRAE 62.1-2016 recommends a per person default value of combined outdoor air of 15 CFM per person and 13 CFM per person, respectively.[18] This ventilation requirement is greater than the current NYC mechanical code requirement of 10 CFM.

Table 2-2 provides an overview of current regulatory levels, recommended criteria for CO_2 and associated health effects.

Table 2-2. Carbon dioxide limits/criteria and associated health effects

CO_2 Level (ppm)	Type of Limit or Criteria	Basis /Health Effects
70,000 – 100,000	-	Loss of consciousness and death
40,000	NIOSH IDLH	Intoxication, unconsciousness
30,000	OSHA Short Term Exposure Limit	Narcotic effects
20,000	-	Headaches reported
10,000	-	Visual impairment reported
5,000	OSHA PEL (8 hour TWA) NIOSH REL ACGIH TLV MAK (German) (8 hour TWA)	Mild narcotic effects, stimulation of the respiratory center and asphyxiation
3,500	Health Canada (Recommended residential chronic exposure limit)	Undesirable changes in the acid-base balance and subsequent deleterious effects such as release of calcium from bones[87]
3,000 – 4,000	-	Increased respiration, mental effort and increased feeling of tiredness reported
1,000	ASHRAE	Objectionable bio-effluent/odor

Chapter 3. Methodology

This section presents information on the teacher population that participated in the study, the questionnaire administered to the teachers, the air monitoring methods, as well the statistical methodology of the data. There were two rounds of data collection conducted, round 1 and round 2, corresponding to the heating and non-heating seasons, respectively. The first round was conducted from December 2017 to March 2018. The second round was conducted from April 2018 to June 2018. Some additional monitoring was conducted in September 2018. Equivalent approaches were used for both rounds including the same study population, an identical questionnaire and consistent air monitoring procedures.

3.1 The study population

NYC public school teachers were recruited with the assistance of the United Federation of Teachers (UFT), the teachers' union representing NYC public school teachers. Several meetings were held with the UFT to discuss the study design and the logistics. The UFT emailed an explanatory summary of the study to their list of school contacts and school sustainability coordinators. Many schools have a sustainability coordinator, who is typically designated by the principal. The sustainability coordinator is responsible for developing and implementing a site-specific sustainability plan including energy conservation, recycling and waste reduction programs. Approximately 30 schools responded (out of about 100 schools) and 20 schools were deemed eligible. Eligible schools needed to: (1) be established inside the school building for several years, (2) include grades three through five, (3) obtain written permission from the principal, and (4) have at least five teachers agreeing to participate. One school did not receive final approval from their principal and was excluded from the list, resulting in 19 schools.

Elementary schools were preferred for the study rather than middle or high schools because elementary school teachers tend to stay with their students for the majority of the day. Grades three to five were preferred because those grades usually complete standardized testing which could be evaluated as part of a future study. Previous research studies have examined associations of indoor air quality with standardized test scores.[61] For schools to participate in the study the principals had to submit written consent via the school coordinator and select five or six teachers to have their classrooms monitored for CO_2, temperature and relative humidity (RH).

3.2 Environmental Monitoring

Onset HOBO MX1102 CO_2 data loggers were used to record CO_2, temperature, and RH data throughout the study (the technical specifications are included in Appendix F). The MX1102 utilizes non-dispersive infrared (NDIR) self-calibrating CO_2 sensor technology and integrated temperature and RH sensors. The data loggers can be programmed to record data at a specific logging interval. Throughout the study the data loggers were set to collect measurements every two minutes. Previous studies have used a five minute logging interval. Collecting more data points (2 minutes compared with 5 minutes) provides a more accurate picture or more resolution of CO_2 concentrations. The HOBOmobile® app and HOBOware software were utilized to configure the data loggers and download the data.

The environmental testing schedule was established and confirmed with each school coordinator. Each school had a coordinator that assisted in the study and an explanation of the study including specific instructions were provided to the coordinator. Five or six dataloggers were utilized per school (one per classroom) and typically two schools were monitored each week. The environmental technician delivered the data loggers to the school on Friday (usually in the early afternoon), prior to the start of upcoming school week. The environmental technician manually calibrated the data loggers, outdoors, following the manufacturer's user manual. The data loggers were activated immediately prior to being dropped off at the school and the display screen on each data logger was turned off. The coordinator was given the precalibrated/activated data loggers and a binder containing instructions, a school data sheet form and a classroom activity log. The data loggers were placed on the teacher's desk and not moved. The data loggers remained in the classroom for approximately one week and were retrieved by the technician at the end of the week. While in the classroom, the display screen on the data logger was turned off to ensure that the teachers would not be able to view the measurements. Knowing the measurements could have influenced the teachers' responses on the questionnaire. The teachers completed the daily activity log (printed sheet) each day of the monitoring. The teachers recorded the times the classroom was occupied by students and whether the windows were opened during the day. A reminder email was sent to the teacher to complete the questionnaire. The environmental technician picked up dataloggers and binder the following Friday morning. Since Fridays were typically used as the drop off and pick up day, data from Friday in most cases were not evaluated. Immediately after dataloggers and binder were picked up, the data were downloaded and uploaded to Dropbox and the school data forms were scanned and also saved on Dropbox.

3.3 Questionnaire

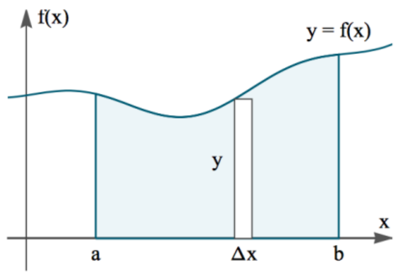
An online questionnaire was developed and deployed via surveymonkey.com. The questionnaire (see Appendix 6.3) had 33 questions collecting demographic information and health symptom information. A link to the online questionnaire was emailed to the teacher. The teachers were asked to complete the questionnaire while in the classroom during the week of the air monitoring. The recall period was the last few days within the context of the current school year. The first two questions asked about the school and classroom number. The next three questions asked demographic information. Question 10 asked about health symptoms experienced during the workday or during the last few workdays including: headache, fatigue, drowsiness, and difficulty concentrating. Question 13 asked about noticing odors from various sources such as mold, diesel fumes, pesticides, arts/ crafts supplies, white board markers, air fresheners, perfumes, paint, construction or renovation, cleaning chemicals. Information about these sources could provide an indication on other potential exposures that could affect the health of teachers. Question 14 asked teachers whether they have observed the following environmental conditions to which they could also be exposed and potentially experience health symptoms: visible mold, moisture problems, dust, construction, dust reservoirs, roaches/rodents, secondhand smoke, noise or other conditions. Question 15 asked if classroom windows were operable and if the teacher opens the windows. If the windows are broken and non-operable this could lead to an increase in CO_2 levels and would also be a violation of building code. Teachers were also asked if their desk was located near the window to determine proximity to fresh air which would help reduce exposure to higher CO_2 levels. Teachers were asked if they are able to control air conditioning and or heating in their classroom to determine how much control they had over classroom environmental conditions. Teachers were asked to describe the air quality in their classrooms. Question 27 asks the teacher to rate their current stress level on a scale from one (minimal stress) to seven (high stress). Question 28 asked if there was an air quality problem if it would occur more frequently during specific seasons. If there was an air quality issue it would help to pinpoint the specific season or time of the school year when it was occurring. Question 30 asked about current medications that the teacher is taking. This information could potentially indicate any side effects from medications. Question 31 asked about the number of hours of sleep. Sleep deprivation could result in fatigue, drowsiness and lethargy. Question 32 and 33 asked about exposure to cigarette smoke. Exposure to cigarette smoke first hand or secondhand could affect the health of the individual.

3.4 Statistical Analysis

For Aim 1, descriptive statistics were compiled to evaluate NYC public school teachers' full shift exposure to CO_2. Only measurements during the school day were used, while measurements collected during the evening and overnight were excluded. The teachers' daily activity logs, which were part of the documentation included in the binder, indicated the start and end of the school day. Metrics of daily CO_2 exposure included mean, max, minimum, median. The day of the week with the highest full shift CO_2 exposure was identified for each teacher by reviewing and comparing data from each day. This was considered the "worst case scenario". In the field of industrial hygiene, the worst case scenario is commonly used to compare with established exposure limits and/or guidelines.[88] Other metrics of daily CO_2 exposure included the number of measurements exceeding 1000 ppm (during the worst case scenario day). Graphs of the entire monitoring week and each day were created using the HOBO software as well as Microsoft Excel and SPSS, and analyzed. The analysis focused on identifying the day of the week having the highest peak levels and the day with the highest time weighted average exposure (TWA). The day and time of the peak CO_2 level were determined. The area under the CO_2 curve, which can also be thought of as the cumulative dose was calculated (during the worst case scenario day) for each teacher. Equations 3-1 and 3-2 were used to calculate the area under the curve.

Equation 3-1

$$\text{Area} = \int_a^b f(x)\,dx$$



Equation 3-2

$$\text{AUC} = \Sigma\ ((y1+y2)/2*\Delta x)$$

Table 3.2. The environmental parameters used during the study and the rationale for their use

Environmental parameter	Rationale
Peak CO_2	The maximum CO_2 level during the week was identified to determine the highest CO_2 level the teacher was exposed to and to evaluate if this level approached any regulatory limits or guidelines.
Time and day of Peak CO_2	The time and day of the maximum CO_2 level during the week was identified to evaluate any possible trends in peaks. For example, if the peak CO_2 levels were being consistently observed during the same day and time this information could result in more accurate control measures. Additional fresh air could be introduced into the classroom(s) around those specific time frames preemptively to reduce peak levels.
Number of CO_2 measurements > 1000 ppm	The number of CO_2 measurements exceeding 1000 ppm on the day with the highest exposure. The rationale for using the criteria of 1000 ppm is two fold: First,1000 ppm has been equivalent to approximately 20 CFM outdoor air per occupant which provides a sufficient amount of air to minimize objectionable odors and maintain IEQ complaints below 20% of the occupants.[60] Second, Satish et al. reported that at 1,000 ppm CO_2 (relative to 600 ppm), moderate and statistically significant decreases occurred in six of nine scales of decision-making performance.[7] Others have used the 1000 ppm criteria as well.[19,25,39,89,90,91]
Mean, median and minimum CO_2	The mean, median and minimum CO_2 were determined for each monitoring day to evaluate central tendencies and the range of exposures. The mean was compared to the 1000 ppm criteria as well as to the OSHA PEL of 5000 ppm.

Weekly CO_2 Average	The average of all full shift daily exposures was determined. This was used as a weekly exposure metric and compared to each daily TWA.
Area under the curve (AUC)	The AUC was determined for the day with the highest daily exposure and considered as the cumulative dose. Teachers' cumulative doses were compared.
Mean, maximum, minimum temperature Mean, maximum, minimum relative humidity	Mean, maximum, minimum temperature and relative humidity were determined for the day with the highest daily exposure. These metrics were evaluated to determine whether they exceeded the recommended criteria and as possible confounders.

The area under the curve can be calculated by adding the areas of all the small rectangular sections under the curve. The y's are the CO_2 levels and Δx for the equation is 2 (minutes).

For Sub Aim 1, to evaluate whether school staff can independently manage air quality monitoring, each school coordinator was assessed using five criteria shown in table 3-3, during the first round of monitoring (heating season).

Table 3-3. Criteria used for evaluating school coordinators

	Criteria	Relevance
1	Communicating and coordinating with the environmental technician	If school staff will need to manage air monitoring equipment in the future, they will need to communicate and coordinate with the environmental team.
2	Understanding the testing procedure	Being able to understand the overall environmental testing process and ensuring procedures are followed will ensure more accurate results.
3	Ensuring the school data form is complete and the teachers are completing the daily logs	Data forms and daily logs provide critical information regarding the location of the dataloggers, classroom occupancy and activities. The more complete and accurate the record keeping is, the more successful the environmental monitoring will be.
4	Checking periodically (at least twice during the week) on the dataloggers and ensuring the dataloggers are not moved	It's important that the dataloggers are not moved or tampered with. Checking in with teachers and on the dataloggers helps to ensure this.
5	Collecting the dataloggers and data binder from each teacher	Being able to collect the equipment and the data binders promptly and efficiently without losing any records or equipment is critical to the success of the project

The following rating system was used to assess each school coordinator in the criteria described above. Each coordinator received a score which was converted to a percentage; with the maximum score set at 100%. A successful score was $\geq$ 75%. The number of successful scores was evaluated and the average of all scores was also evaluated.

Table 3-4. Rating system utilized for the evaluation criteria

Rating	Definition
1	Not able to complete the required tasks even with assistance from the environmental technician
2	Able to complete the required tasks with substantial assistance from the environmental technician
3	Able to complete the required tasks with some assistance from the environmental technician
4	Able to complete the required tasks independently with some minor deficiencies
5	Able to complete the required tasks independently with no deficiencies

Assistance from the environmental technician was defined as assisting in completing the school data form, assisting in placing the dataloggers in classrooms, verifying the daily logs have been completed. Substantial assistance was defined as the environmental technician completing more than 50% of the tasks on behalf of the school coordinator. Some assistance was defined as the environmental technician completing less than 50% of the tasks on behalf of the school coordinator. The following hypothesis was established:

H_0 - School staff are not able to independently manage air quality monitoring equipment.

H_1 - School staff can independently manage air quality monitoring equipment.

The Wilcoxon signed-rank test was used to compare results of round 1 with round 2. The Wilcoxon signed-rank test does not assume normality in the data and is typically used to compare two sets of data that originate from the same participants.

To analyze the association of school factors (e.g. type of HVAC system, age of school, level of maintenance, occupancy level of classes, level of PTA support/socioeconomic status, window issues) with CO_2 levels and health effects reported by teachers, first a correlational analysis was conducted using the Spearman chi-square (X^2) test. Table 3-5 provides a description of building and classroom factors used in the analysis.

Table 3-5. Description of building and classroom factors used in the analysis.

Building/classroom factor	Source	Comments
Window issues	Questionnaire	Window issues were coded as 1 if teachers reported the windows in their classroom being broken or not able to be open. No window issues were coded as 0.
Poverty/Socioeconomic Status	Census tract economic data (median household income 2018)	The median household income data were obtained for the census tract where the school is located. It was presumed that a majority of students were living near the school.
Mechanical Ventilation	Multiple sources	The type of mechanical ventilation was determined through the following: 1) Observing the HVAC systems at the school during the environmental monitoring; 2) through discussions with school custodial staff; 3) The school building assessment survey/inspection reports were also reviewed for information on HVAC system.
Building Year	NYC DOE Data[50]	The year of construction was obtained from NYC DOE sources.
Classroom area (square footage)	NYC DOE Data[92]	Data on classroom square footage was obtained from NYC open data
Maintenance issues	Questionnaire	Maintenance issues were coded as 1 if teachers reported observing moisture, mold, roaches or vermin in their classroom. No maintenance issues were coded as 0.
Class size (number of students)	Questionnaire	Teachers reported the number of students in their class.

To evaluate the association of CO_2 levels with perceived air quality, headache, fatigue, drowsiness, and difficulty concentrating by teachers (Aim 3) Spearman chi-square (X^2) tests, logistic regression and multiple regression analysis were conducted.

When the data have a hierarchical structure (schools, classrooms, teachers, observations) a multilevel approach is preferable to conventional single-level statistical methods. Multilevel regression analysis was used to address dependent observations. Teachers within the same school may have more similar health outcomes than teachers from different schools because they may be exposed to similar conditions.

Health responses (outcome variable) were reported as binary variables and thus logistic regression was necessary. Predictor variables were CO_2 levels as well as temperature and RH (all continuous variables). SPSS version 25 (IBM Corp.) was utilized to analyze the data.

Chapter 4. Results & Interpretation

4.1 Teacher Questionnaire Results

4.1.1 Round 1

During the first round of the study, 103 classrooms (from 19 schools) were assessed. Most classrooms had one teacher. A few classrooms had two teachers. Multiple teachers assigned to one classroom were noted on the school data form. The response rate for the questionnaire was approximately 90%. Fourteen classrooms were not included in the analysis due to missing corresponding questionnaires or datalogger failure, resulting in 89 teachers being included (86%). Table 4-1 shows the proportion of teachers reporting work-related symptoms by demographic characteristic. Almost 90% of teachers in the study were women, with 68.5% of teachers age 30-49. The majority of the teachers (61.8%) were white, while the second highest reported ethnicity/race was Hispanic (21.3%). About 50.6% of teachers had been teaching at their current school for more than ten years. Only one teacher reported being a smoker and three percent indicated a smoker in their household. Approximately 77% (women and men) reported experiencing at least one of the following symptoms during the workday: headache, fatigue, drowsiness and difficulty concentrating. Of the four symptoms, fatigue was reported the most for women and men teachers, 65% and 77.8%, respectively, followed by headache, drowsiness and difficulty concentrating. Approximately one third and one half of the teachers reported a high and medium stress level, respectively. Difficulty concentrating was associated with less hours of sleep per night ($p=0.046$).

Table 4-1. Round 1 self-reported symptoms among teachers (n=89) in classrooms with CO_2 monitoring, by demographic characteristic, for each symptom group.

		Total		Any Symptom		Headache		Fatigue		Drowsiness		Difficulty concentrating		Stress Level					
														Low		Moderate		High	
		n=89		n=69, 77.5%		n=46, 51.7%		n=59, 66.3%		n=35, 39.3%		n=28, 31.5%		n=16, 18%		n=43, 48.3%		n=30, 33.7%	
Gender	Female	80	89.9%	62	77.5%	42	52.5%	52	65.0%	33	41.3%	26	32.5%	13	16.3%	40	50.0%	27	33.8%
	Male	9	10.1%	7	77.8%	4	44.4%	7	77.8%	2	22.2%	2	22.2%	3	33.3%	3	33.3%	3	33.3%
Age	21-29	9	10.1%	7	77.8%	5	55.6%	5	55.6%	4	44.4%	3	33.3%	2	22.2%	5	55.6%	2	22.2%
	30-39	35	39.3%	27	77.1%	17	48.6%	24	68.6%	16	45.7%	11	31.4%	3	8.6%	16	45.7%	16	45.7%
	40-49	26	29.2%	23	88.5%	13	50.0%	20	76.9%	10	38.5%	11	42.3%	7	26.9%	14	53.8%	5	19.2%
	50-59	14	15.7%	8	57.1%	7	50.0%	7	50.0%	2	14.3%	2	14.3%	3	21.4%	6	42.9%	5	35.7%
	60 or older	5	5.6%	4	80.0%	4	80.0%	3	60.0%	3	60.0%	1	20.0%	1	20.0%	2	40.0%	2	40.0%
Race/ethnicity	White	55	61.8%	43	78.2%	28	50.9%	37	67.3%	22	40.0%	17	30.9%	9	16.4%	25	45.5%	21	38.2%
	Hispanic	19	21.3%	14	73.7%	11	57.9%	11	57.9%	4	21.1%	5	26.3%	5	26.3%	10	52.6%	4	21.1%
	Asian	6	6.7%	4	66.7%	3	50.0%	4	66.7%	4	66.7%	2	33.3%	0	0.0%	4	66.7%	2	33.3%
	African-American	3	3.4%	2	66.7%	2	66.7%	2	66.7%	1	33.3%	1	33.3%	1	33.3%	1	33.3%	1	33.3%
	Mixed	1	1.1%	1	100.0%	0	0.0%	1	100.0%	0	0.0%	0	0.0%	0	0.0%	1	100.0%	0	0.0%
	Other	1	1.1%	1	100.0%	1	100.0%	1	100.0%	1	100.0%	1	100.0%	0	0.0%	0	0.0%	1	100.0%
	Not specified	5	5.6%	4	80.0%	1	20.0%	3	60.0%	3	60.0%	2	40.0%	1	20.0%	2	40.0%	1	20.0%
Years worked at the school	>10	45	50.6%	33	73.3%	24	53.3%	28	62.2%	17	37.8%	15	33.3%	7	15.6%	23	51.1%	15	33.3%
	<10	43	48.3%	36	83.7%	22	51.2%	31	72.1%	18	41.9%	13	30.2%	8	18.6%	20	46.5%	15	34.9%
Hours of sleep per night	About 5-6 hours	46	51.7%	37	80.4%	23	50.0%	32	69.6%	17	37.0%	**19***	**41.3%**	7	15.2%	19	41.3%	20	43.5%
	About 7-8 hours	42	47.2%	32	76.2%	23	54.8%	27	64.3%	18	42.9%	9	21.4%	9	21.4%	23	54.8%	10	23.8%
Currently smoke cigarettes?	Yes	1	1.1%	1	100.0%	0	0.0%	1	100.0%	0	0.0%	1	100.0%	0	0.0%	1	100.0%	0	0.0%
	No	85	95.5%	66	77.6%	44	51.8%	56	65.9%	33	38.8%	26	30.6%	16	18.8%	41	48.2%	28	32.9%
Smoker in household	Yes	3	3.4%	2	66.7%	1	33.3%	2	66.7%	0	0.0%	1	33.3%	0	0.0%	1	33.3%	2	66.7%
	No	85	95.5%	66	77.6%	44	51.8%	56	65.9%	35	41.2%	26	30.6%	16	18.8%	42	49.4%	27	31.8%
	Not sure	1	1.1%	1	100.0%	1	100.0%	1	100.0%	0	0.0%	1	100.0%	0	0.0%	0	0.0%	1	100.0%

* The Chi-square statistic is significant at the .05 level (0.046)

4.1.2 Round 2

During the second round of the study, 107 classrooms were assessed (from 19 schools) and the questionnaire response rate was approximately 87%. Two schools did not complete the school data sheet and could not be included in the second round of the study. Several other classrooms were excluded from the analysis due to missing corresponding questionnaires or datalogger failure, resulting in 71 teachers being included (68%).

Table 4-2 shows the proportion of teachers reporting work-related symptoms by demographic characteristic. About 87% of teachers in the second round were women, with 69.2% of teachers age 30-49. About 74% reported experiencing work related symptoms: either headaches, fatigue, drowsiness or difficulty concentrating. Approximately 74% (women and men) reported experiencing at least one of the following symptoms during the workday: headache, fatigue, drowsiness and difficulty concentrating. Of the four symptoms, fatigue was reported the most for teachers, 66.2%, respectively, followed by headache, drowsiness and difficulty concentrating. In the second round, more teachers reported experiencing medium stress levels and less reported high stress levels.

Table 4-2. Round 2 self-reported symptoms among teachers (n=71) in classrooms with CO_2 monitoring, by demographic characteristic, for each symptom group.

		Total		Any Symptom		Headache		Fatigue		Drowsiness		Difficulty concentrating		Stress Level					
														Low		Medium		High	
		n=71		n=52, 74.3%		n=42, 59.2%		n=47, 66.2%		n=31, 43.7%		n=24, 33.8%		n=10, 14.1%		n=43, 60.6%		n=16, 22.5%	
Gender	Female	62	87.3%	48	77.4%	**40***	**64.5%**	44	71.0%	28	45.2%	22	35.5%	8	12.9%	40	64.5%	13	21.0%
	Male	8	11.3%	4	50.0%	2	25.0%	3	37.5%	3	37.5%	2	25.0%	2	25.0%	3	37.5%	3	37.5%
Age	18-20	1	1.4%	1	100.0%	1	100.0%	1	100.0%	0	0.0%	0	0.0%	0	0.0%	1	100.0%	0	0.0%
	21-29	10	14.1%	9	90.0%	6	60.0%	9	90.0%	7	70.0%	4	40.0%	1	10.0%	7	70.0%	2	20.0%
	30-39	22	31.0%	16	72.7%	15	68.2%	16	72.7%	10	45.5%	10	45.5%	3	13.6%	14	63.6%	5	22.7%
	40-49	20	28.2%	13	65.0%	10	50.0%	12	60.0%	9	45.0%	5	25.0%	2	10.0%	13	65.0%	5	25.0%
	50-59	15	21.1%	11	73.3%	9	60.0%	8	53.3%	5	33.3%	4	26.7%	2	13.3%	8	53.3%	4	26.7%
	60 or older	3	4.2%	3	100.0%	2	66.7%	2	66.7%	0	0.0%	1	33.3%	2	66.7%	1	33.3%	0	0.0%
	White	48	67.6%	36	75.0%	28	58.3%	32	66.7%	23	47.9%	15	31.3%	7	14.6%	29	60.4%	11	22.9%
Race/ethnicity	Hispanic	10	14.1%	8	80.0%	7	70.0%	8	80.0%	5	50.0%	5	50.0%	0	0.0%	7	70.0%	3	30.0%
	Asian	2	2.8%	1	50.0%	1	50.0%	1	50.0%	1	50.0%	1	50.0%	0	0.0%	1	50.0%	1	50.0%
	African-American	1	1.4%	1	100.0%	1	100.0%	1	100.0%	1	100.0%	0	0.0%	0	0.0%	1	100.0%	0	0.0%
	Mixed	5	7.0%	5	100.0%	5	100.0%	4	80.0%	1	20.0%	2	40.0%	1	20.0%	3	60.0%	1	20.0%
	Not Specified	5	7.0%	2	40.0%	1	20.0%	2	40.0%	0	0.0%	1	20.0%	2	40.0%	3	60.0%	0	0.0%
Years worked at school	>10	36	50.7%	27	75.0%	23	63.9%	24	66.7%	15	41.7%	12	33.3%	5	13.9%	20	55.6%	10	27.8%
	<10	35	49.3%	26	74.3%	20	57.1%	24	68.6%	16	45.7%	12	34.3%	5	14.3%	24	68.6%	6	17.1%
Hours of sleep per night	4 or fewer hours	1	1.4%	1	100.0%	1	100.0%	1	100.0%	1	100.0%	0	0.0%	0	0.0%	0	0.0%	1	100.0%
	About 5-6 hours	41	57.7%	27	65.9%	22	53.7%	25	61.0%	16	39.0%	13	31.7%	7	17.1%	22	53.7%	11	26.8%
	About 7-8 hours	28	39.4%	24	85.7%	19	67.9%	21	75.0%	13	46.4%	10	35.7%	3	10.7%	22	78.6%	3	10.7%
	9 or more hours	1	1.4%	1	100.0%	1	100.0%	1	100.0%	1	100.0%	1	100.0%	0	0.0%	0	0.0%	1	100.0%
Currently smoke cigarettes	Yes	3	4.2%	3	100.0%	2	66.7%	3	100.0%	1	33.3%	2	66.7%	0	0.0%	2	66.7%	1	33.3%
	No	68	95.8%	50	73.5%	41	60.3%	45	66.2%	30	44.1%	22	32.4%	10	14.7%	42	61.8%	15	22.1%
Smoker in household	Yes	1	1.4%	1	100.0%	0	0.0%	1	100.0%	0	0.0%	0	0.0%	0	0.0%	1	100.0%	0	0.0%
	No	70	98.6%	52	74.3%	43	61.4%	47	67.1%	31	44.3%	24	34.3%	10	14.3%	43	61.4%	16	22.9%

4.1.3 Round 1 versus Round 2

Table 4-3 compares the prevalence of health symptoms between round 1 and round 2. The prevalence of health symptoms are similar in the two rounds and the Wilcoxon rank test did not indicate that they were significantly different. The profile of stress levels reported by teachers was slightly different but that could be related to some schools being excluded form round 2. Table 4-4 shows a comparison of teachers' perceptions of classroom air quality, between round 1 and round 2. The results indicate that overall, the teachers' responses regarding their perception of air quality were similar in both rounds. Some differences were observed between round 1 and round 2 with respect to perceptions of thermal conditions (temperature and RH). Approximately 30% of teachers in both rounds reported the air quality as being acceptable most of the time (28.9% versus 32.4%). Approximately 11% and 15.5% of teachers in round 1 versus round 2, respectively, reported that the air quality was rarely or never acceptable. Approximately 35.6% and 39.4% of teachers in round 1 versus round 2, respectively, reported feeling the air becoming more stuffy in the afternoon. About 32.2% and 29.6% of teachers in round 1 versus round 2, respectively, responded that the air was stuffy all the time. Approximately 18.9% and 16.9% of teachers in round 1 versus round 2, respectively, reported that they have complained about their classroom air quality. More teachers in both rounds perceived their classroom air quality to be better in the morning rather the afternoon (approximately three times and nine times more in round 1 and round 2, respectively). Round 2 or the non-heating season, probably due to the warmer temperatures magnified the difference between the air quality in the morning compared to the afternoon, underscoring the influence of temperature and RH on the perception of air quality. Significant differences were reported between round 1 and round 2 with respect to perceptions of thermal conditions (temperature and RH). This difference corresponds to the varying thermal conditions measured in round 1versus round 2. More teachers in round 1 (heating season) reported the air in their classrooms being too hot and too dry as compared to round 2 (41.6% versus 31.0%; 23.6% versus 9.9%, respectively). More teachers in round 2 reported the air in their classrooms being too humid as compared to round 1 (25.4% versus 7.9%).

Table 4-3. Prevalence of health symptoms, round 1 versus round 2

	Round 1 (%)	Round 2 (%)
Any Symptom	77.5	74.3
Headache	51.7	59.2
Fatigue	66.3	66.2
Drowsiness	39.3	43.7
Difficulty Concentrating	31.5	33.8
Low Stress Level	18	14.1
Medium Stress Level	48.3	60.6
High Stress Level	33.7	22.5

Table 4-4. Teachers' perceptions of classroom air quality, round 1 versus round 2

		Round 1 (%)	Round 2 (%)
Questions regarding perceptions of general air quality and any daily trends inside the classroom	Do you feel the air quality in your classroom is acceptable:		
	- Most of the time	28.9	32.4
	- Some of the time	44.4	43.7
	- Rarely or never	11.1	15.5
	Which best describes the air quality in you classroom?		
	- In the afternoon, I can feel the air becoming more stuffy	35.6	39.4
	- The air is stuffy all the time	32.2	29.6
	- I have previously complained about the air quality	18.9	16.9
	- The air quality is better in the morning than the afternoon	15.6	18.3
	-The air quality is better in the afternoon than the morning	5.6	2.8
	Do you feel like there is enough fresh air in your classroom?		
	- Most of the time	20.0	26.8
	- Some of the time	43.3	36.6
	- Rarely or never	23.3	22.5
Questions regarding perceptions of classroom thermal conditions	Do you feel like the temperature in your classroom is too hot?		
	- Most of the time	41.6	31.0
	- Some of the time	53.9	63.4
	- Rarely or never	3.4	5.6
	Do you feel like the temperature in your classroom is too cold?		
	- Most of the time	3.4	1.4
	- Some of the time	34.8	31.0
	- Rarely or never	60.7	64.8
	Do you feel like the air in your classroom is too dry?		
	- Most of the time	23.6	9.9
	- Some of the time	64.0	59.2
	- Rarely or never	11.2	29.6
	Do you feel like the air in your classroom is too humid?		
	- Most of the time	7.9	25.4
	- Some of the time	47.2	49.3
	- Rarely or never	39.3	23.0

4.2 Monitoring Results

4.2.1 Round 1

Table 4-5 presents the descriptive statistics for the results of the environmental monitoring conducted during round 1. The mean CO_2 (worst case scenario) ranged from 471 ppm to 2633 ppm. The average of all mean CO_2 was 1169.15 ppm, which is higher than the guidelines of 1000 ppm. Many of the peak CO_2 levels were unusually high, with two measurements reaching 5000 ppm, the instrument maximum and also the PEL established by OSHA. The number of measurements within a classroom exceeding 1000 ppm ranged from 0 to 238 (or almost all the measurements). The weekly average CO_2 levels ranged from 510 ppm to 1944 ppm. The mean, maximum and minimum temperature (°F) levels measured in classrooms ranged from 67.19 to 85.09, 69.39 to 92.53, and 61.55 to 88.35 (°F), respectively. The mean, maximum and minimum relative humidity (% RH) levels measured in classrooms ranged from 8.7 to 55.48, 15 to 83.56, and 5.59 to 48.92 (% RH), respectively. A number of the temperature and relative humidity measurements were outside the established guidelines

Table 4-5. Descriptive statistics of environmental monitoring results during round 1

Exposure Parameter	*N*	*Min.*	*Max.*	*Range*	*Mean*		*Std. Deviation*	*Variance*
						SE		
Mean CO_2 [1] (ppm)	89	471	2633	2162	1169.15	43.18	407.38	165960.06
Median CO_2 (ppm)	89	453.5	2607	2153.5	1094.74	45.62	430.34	185189.50
Weekly Average CO_2 (ppm)	89	511	1944	1432.9	988.85	32.89	310.29	96281.66
Peak CO_2 (ppm) [2]	89	665	5000	4335	1902.38	86.90	819.80	672072.42
Number of CO_2 Measurements >1000 (ppm)	89	0	238	238	113.08	7.87	74.20	5505.46
AUC	89	191846	1210954	1019108	525998.83	20842.37	196626.56	38662004280.41
Mean Temp. (°F)	89	67.18	85.09	17.91	74.24	0.36	3.44	11.83
Max Temp. (°F)	89	69.39	92.53	23.14	77.08	0.42	3.93	15.41
Min Temp. (°F)	89	61.55	88.35	26.8	70.29	0.45	4.23	17.92
Mean RH (%)	89	8.7	55.48	46.78	31.12	0.94	8.84	78.07
Max RH (%)	89	15	83.56	68.56	36.57	1.10	10.42	108.60
Min RH (%)	89	5.59	48.92	43.33	26.04	0.88	8.32	69.23

[1] highest exposure day during the week
[2] Maximum CO_2 *level measured during the week*
AUC= area under the curve

Figure 4-1 shows an example of a weekly graph of measurements to provide an idea of the daily trends. Close to a thousand graphs were generated and evaluated. The datalogger was calibrated and activated on Friday afternoon, when the dataloggers were dropped off and placed into the participating teachers' classrooms. The calibration was performed outdoors near the school away from any combustion sources including vehicles. The outdoor CO_2 levels for all schools ranged from 350 ppm to 500 ppm. The graph shows CO_2 levels decreasing towards the end of Friday and remaining at background levels (around 400 ppm) during the weekend when the classroom was unoccupied. The CO_2 concentrations begin to rise on Monday morning as the students occupy the classroom and declined when the students left the classroom. Two or three peaks were measured during the first full monitoring day (Monday) towards the end of the school day the CO_2 levels return to background levels and similar patterns are observed for the next four days. On Friday, the datalogger was collected in the morning and thus data from that day was not used. Measurements from Monday through Thursday were evaluated approximately from 8am to 3pm (teacher's shift). Most of the daily CO_2 averages during the week for the teacher were similar but on occasion there would be one day that was less similar than the others. Figure 4-2 shows an example of plot for one day of measurements (CO_2=green, temp=black, RH=blue) inside a teacher's classroom. Two peak CO_2 levels are evident, one in the morning and another in the afternoon. The peak in the afternoon reaches a CO_2 level of approximately 2600 ppm. This exposure profile is expected since the CO_2 starts to build up as the students arrive to class and spend more time inside the classroom. The CO_2 levels decline as the students leave the classroom to go lunch or to another activity, and then increase again as the classroom is populated again. In this particular classroom temperature and RH follow the same trend as CO_2, increasing and decreasing in tandem. Correlations between temperature, RH and CO_2 will be discussed in an upcoming section.

An evaluation of any temporal trends or patterns in peak CO_2 concentrations revealed the following results. Figure 4-4 shows that CO_2 peak concentrations occurred during the morning and the afternoon but were more frequent in the afternoon. Figure 4-5 shows that CO_2 peak concentrations occurred more frequently on Tuesday and Thursday.

Figure 4-1. An example of a weekly plot of CO_2, temperature and RH measurements

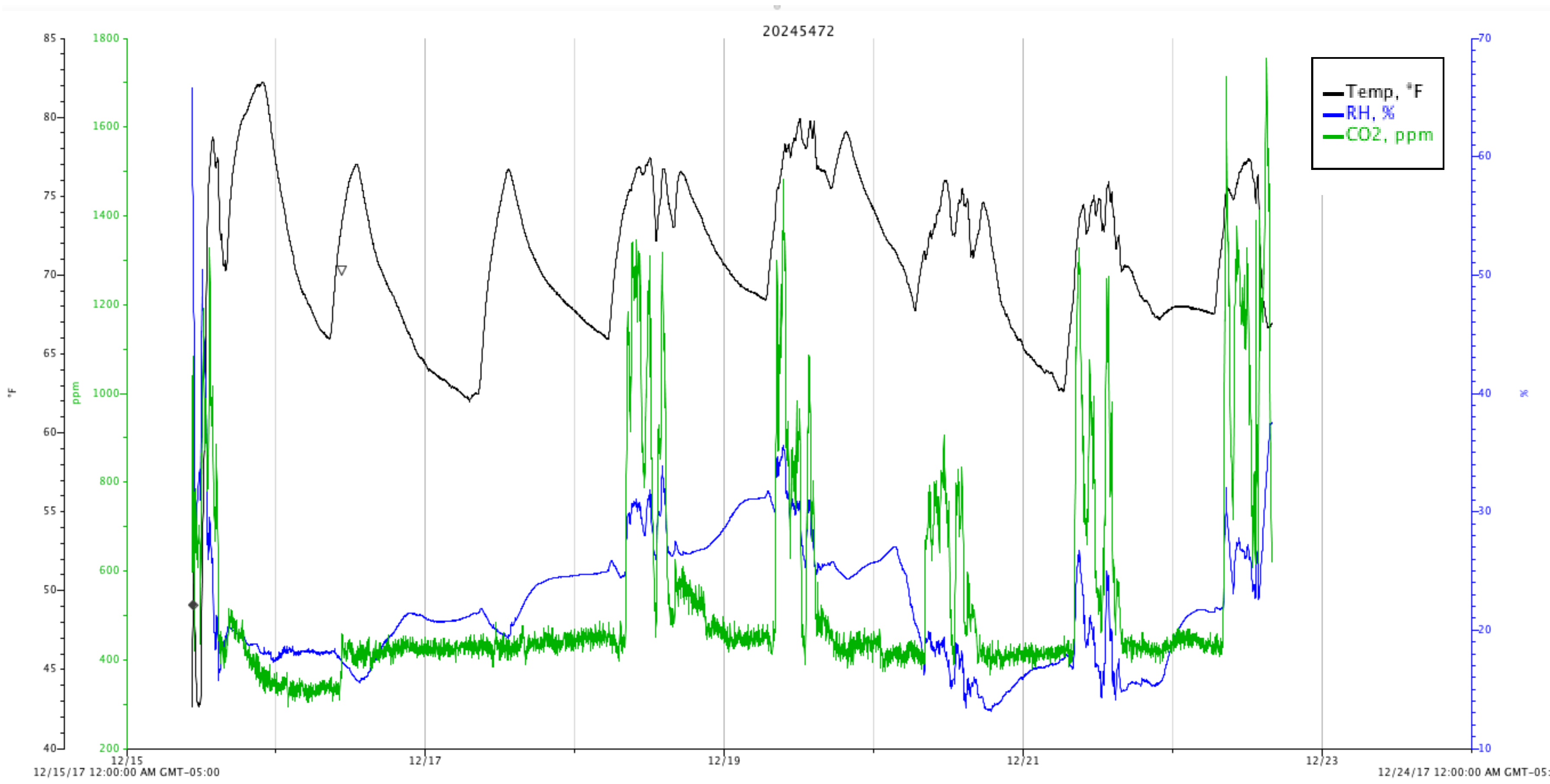
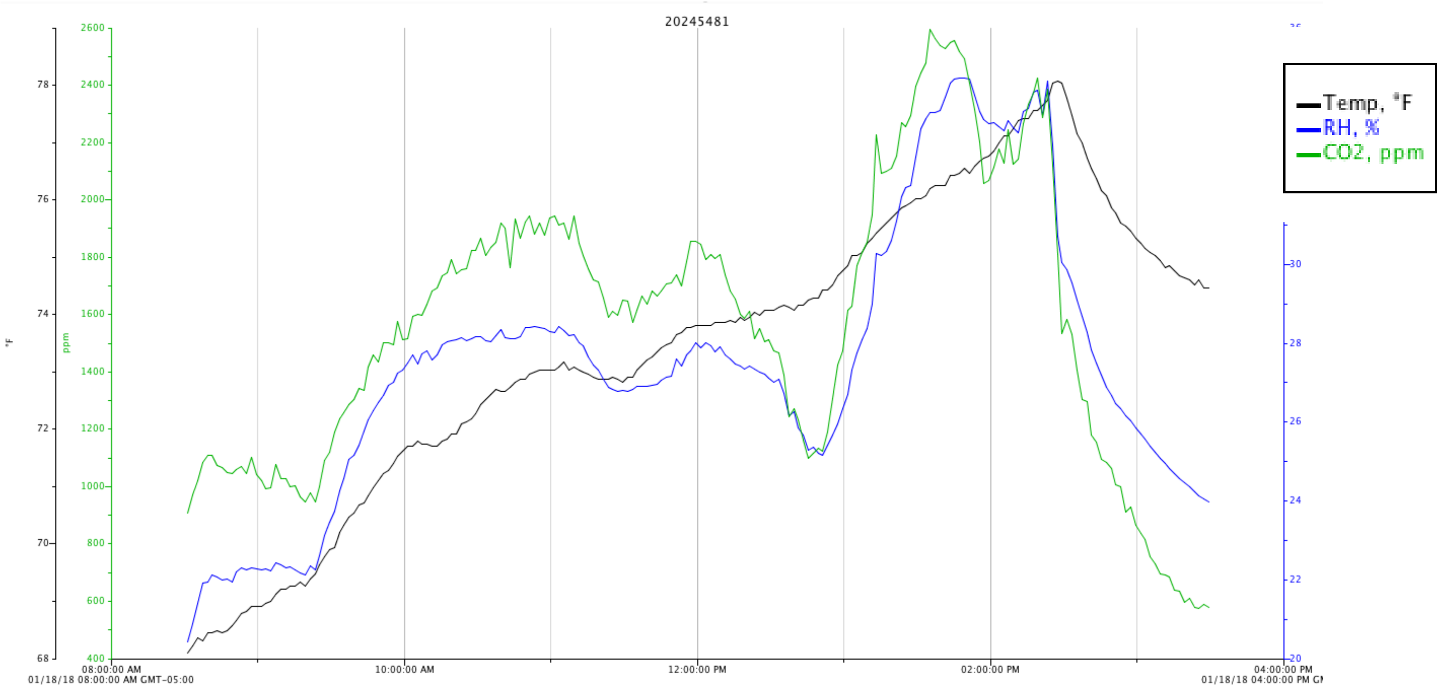


Figure 4-2a & 4-2b. Examples of a daily plot of CO_2, temperature and RH measurements



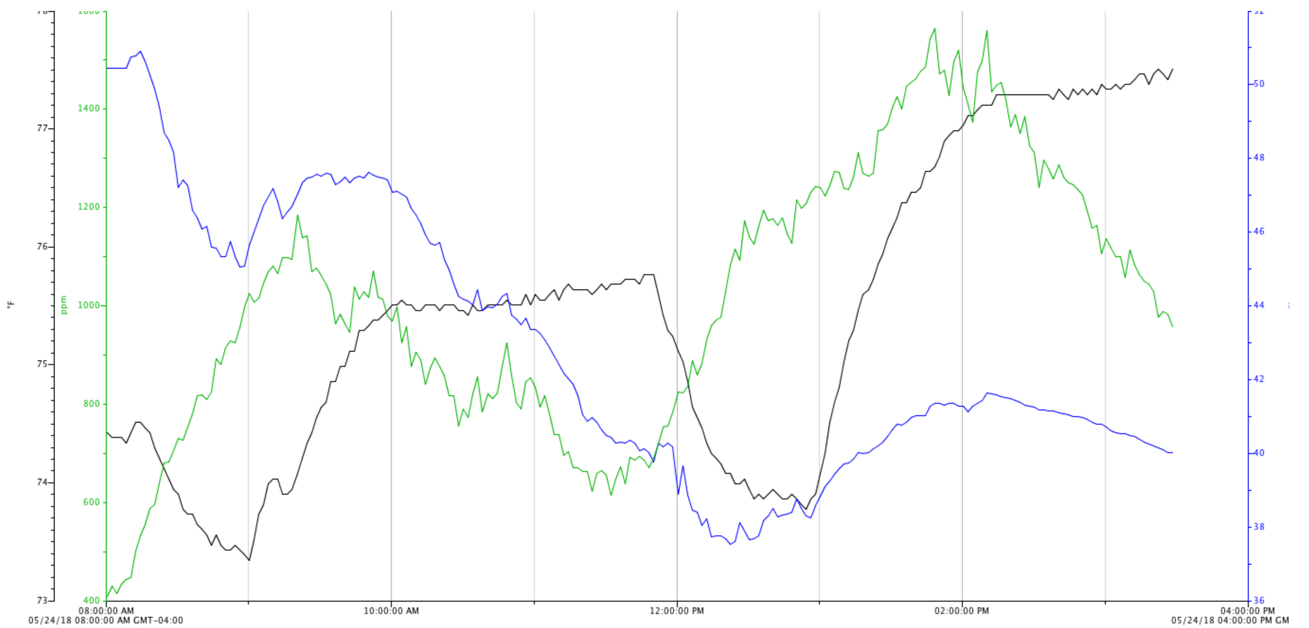


Figure 4-4. Frequency chart of peak CO_2 times (round 1)

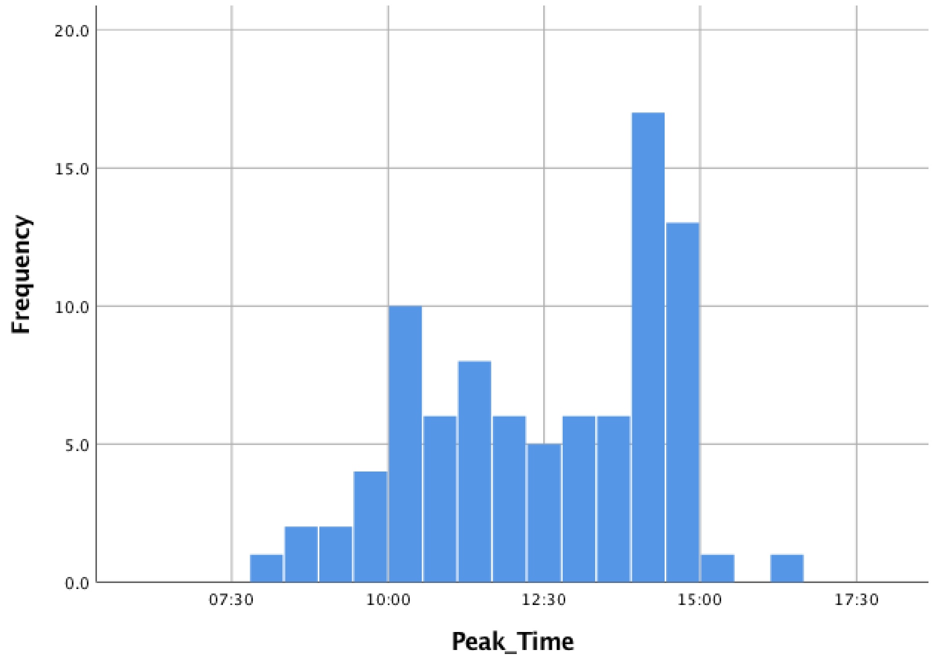
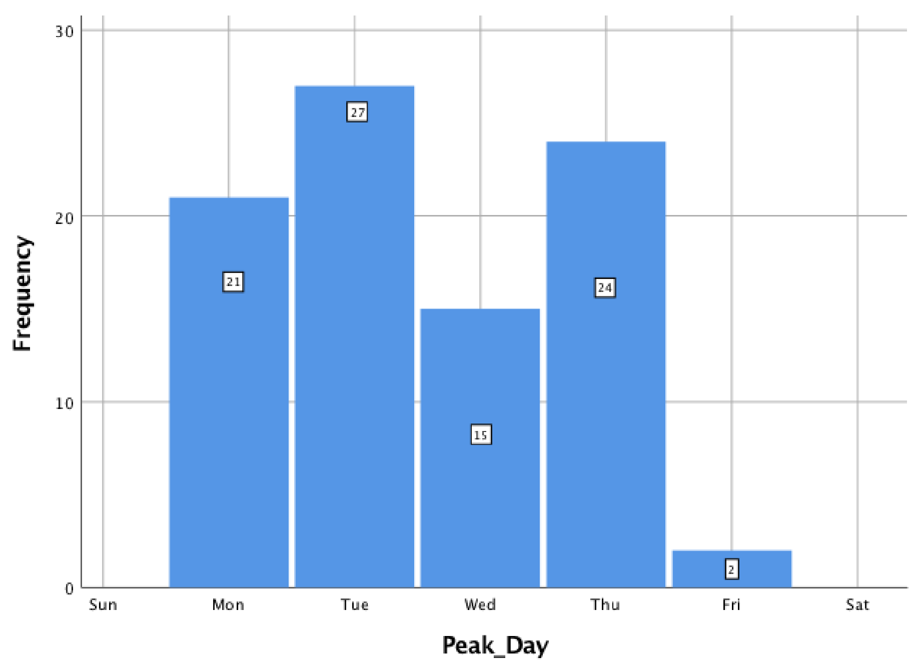


Figure 4-5. Frequency chart of peak CO_2 days (round 1)



4.2.2 Round 2

Table 4-6 shows the descriptive statistics for the results of the environmental monitoring conducted during round 2. The mean CO_2 (worst case scenario) ranged from 462 ppm to 2675 ppm. The average of all mean CO_2 was 1160.65 ppm, which is higher than the guidelines of 1000 ppm. Many of the peak CO_2 levels were unusually high ranging from 679 ppm to 4085 ppm. The number of measurements within a classroom exceeding 1000 ppm ranged from 0 to 226 (or almost all the measurements). The weekly average CO_2 levels ranged from 425 ppm to 2233 ppm. The mean, maximum and minimum temperature (°F) levels measured in classrooms ranged from 71.04 to 81.84 72.31 to 88.17, and 68.44 to 79.39 (°F), respectively. The mean, maximum and minimum relative humidity (% RH) levels measured in classrooms ranged from 25.33 to 81.93, 31.49 to 85.08, and 18.32 to 79.35 (% RH), respectively. A number of the temperature and relative humidity measurements were outside the established guidelines.

Table 4-6. Descriptive statistics of environmental monitoring results during round 2

Exposure Parameter	*N*	*Min.*	*Max.*	*Range*	*Mean*	*SE*	*Std. Deviation*	*Variance*
Mean CO_2 [1] (ppm)	71	462	2675	2213	1160.65	63.54	535.43	286690.09
Median CO_2 (ppm)	71	380	3106	2726	1115.13	67.48	568.59	323297.24
Weekly Average CO_2 (ppm)	71	425	2232.67	1807.67	991.44	53.30	449.16	201740.76
Peak CO_2 (ppm) [2]	71	679	4085	3406	1814.83	105.68	890.49	792979.86
Number of CO_2 Measurements >1000 ppm	71	0	226	226	101.59	9.96	83.95	7046.99
Mean Temp. (°F)	71	71.04	81.84	10.8	75.43	0.27	2.29	5.25
Max Temp. (°F)	71	72.31	88.17	15.86	77.35	0.34	2.88	8.27
Min Temp. (°F)	71	68.44	79.39	10.95	73.19	0.28	2.40	5.75
Mean RH (%)	71	25.53	81.93	56.4	52.91	1.39	11.73	137.67
Max RH (%)	71	31.49	85.08	53.59	58.14	1.37	11.55	133.46
Min RH (%)	71	18.32	79.35	61.03	47.73	1.50	12.66	160.19

[1] Highest exposure day during the week
[2] Maximum CO_2 *level measured during the week*

An evaluation of any temporal trends or patterns of peak CO_2 concentrations was conducted for round 2 data as well. Figure 4-6 shows that CO_2 peak concentrations occurred more frequently in the morning prior to noon and also towards the end of the day (2pm or 3pm). Figure 4-7 shows that CO_2 peak concentrations occurred more frequently on Tuesday than Monday, Wednesday and Thursday (Friday was not evaluated in most cases).

Figure 4-6. Frequency chart of peak CO_2 times (round 2)

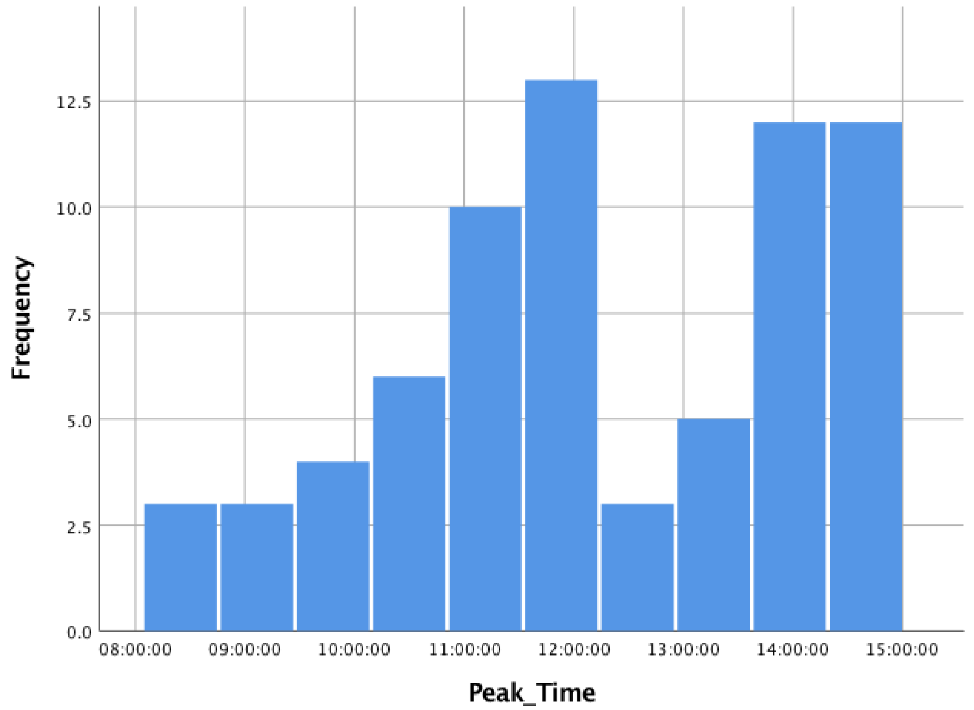
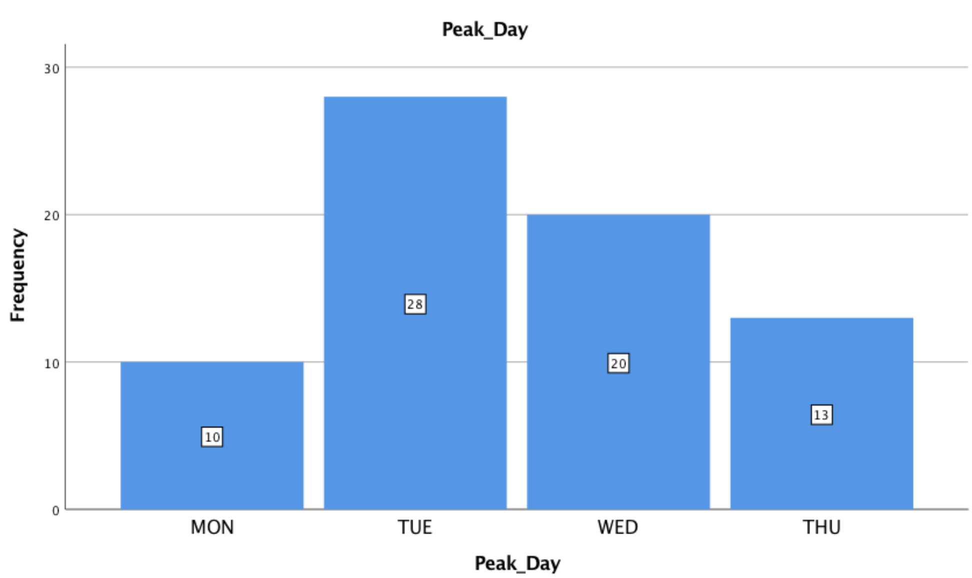


Figure 4-7. Frequency chart of peak CO_2 days (round 2)



The exposure metrics were compared between round 1 and round 2. The Wilcoxon rank test indicated that the measurements between the two rounds were not statistically different with respect to CO_2. Temperature and RH measurements had more variability between round 1 and round 2, as would be expected between the heating and non-heating seasons.

Table 4-7. Comparison of mean of metrics between round 1 and round 2

	Round 1	Round 2
Mean CO_2 [1] (ppm)	1169.15	1160.65
Median CO_2 (ppm)	1094.74	1115.13
Weekly Average CO_2 (ppm)	988.85	991.44
Peak CO_2 (ppm) [2]	1902.38	1814.83
Number of CO_2 Measurements >1000 ppm	113.08	101.59
Mean Temp. (°F)	74.24	75.43
Max Temp. (°F)	77.08	77.35
Min Temp. (°F)	70.29	73.19
Mean RH (%)	31.12	52.91
Max RH (%)	36.57	58.14
Min RH (%)	26.04	47.73

[1] Highest exposure day during the week
[2] Maximum CO_2 *level measured during the week*

4.2.3 Round 1 versus Round 2

Mean CO_2 (worst case scenario)

Each teacher's exposures were compared between the two rounds. Fifty-four teachers were matched with a round 1 and round 2 mean CO_2 exposure. The results are provided in figure 4-11a and 4-11b. The results of the Wilcoxon Signed Rank Test (see figure 4-8) indicated that the round 1 and round 2 were not significantly different ($p=0.384$). Figure 4-12 shows a comparison of round 1 and round 2 mean CO_2 exposures by school (15 schools).

Figure 4-8. Significance testing between round 1 and round 2 (worst case exposure day)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Round_1 and Round_2 equals 0.	Related-Samples Wilcoxon Signed Rank Test	.384	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Approximately 80% of mean CO_2 levels by school were equal to or greater in round 1 versus round 2. Four schools had significantly lower (p=0.021) mean CO_2 levels (round 1 versus round 2) and two schools had significantly higher mean CO_2 levels (round 1 versus round 2). Figures 4-13a and 4-13b show peak CO_2 levels in round 1 versus round 2. Approximately 63% of peak levels were higher in round 1 versus round 2.

Figure 4-9. Significance testing between a subset of classrooms from schools 7, 8, 11 and 15 round 1 and round 2 (worst case exposure day)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Round_1_Subset and Round_2_Subset equals 0.	Related-Samples Wilcoxon Signed Rank Test	.021	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Classrooms from the four schools that showed a decrease were evaluated using the Wilcoxon rank test. The results are provided in figure 4-9.

Peak CO_2

Round 1 and round 2 peak CO_2 levels were compared and overall were not significantly different. The results of the comparison testing are provided in figure 4-10.

Figure 4-10. Significance testing between round 1 and round 2 (Peak CO_2)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Round_1_Peak and Round_2_Peak equals 0.	Related-Samples Wilcoxon Signed Rank Test	.297	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Figure 4-11a. Round 1 versus round 2 – mean CO_2 (worst case scenario)- teachers #1-29

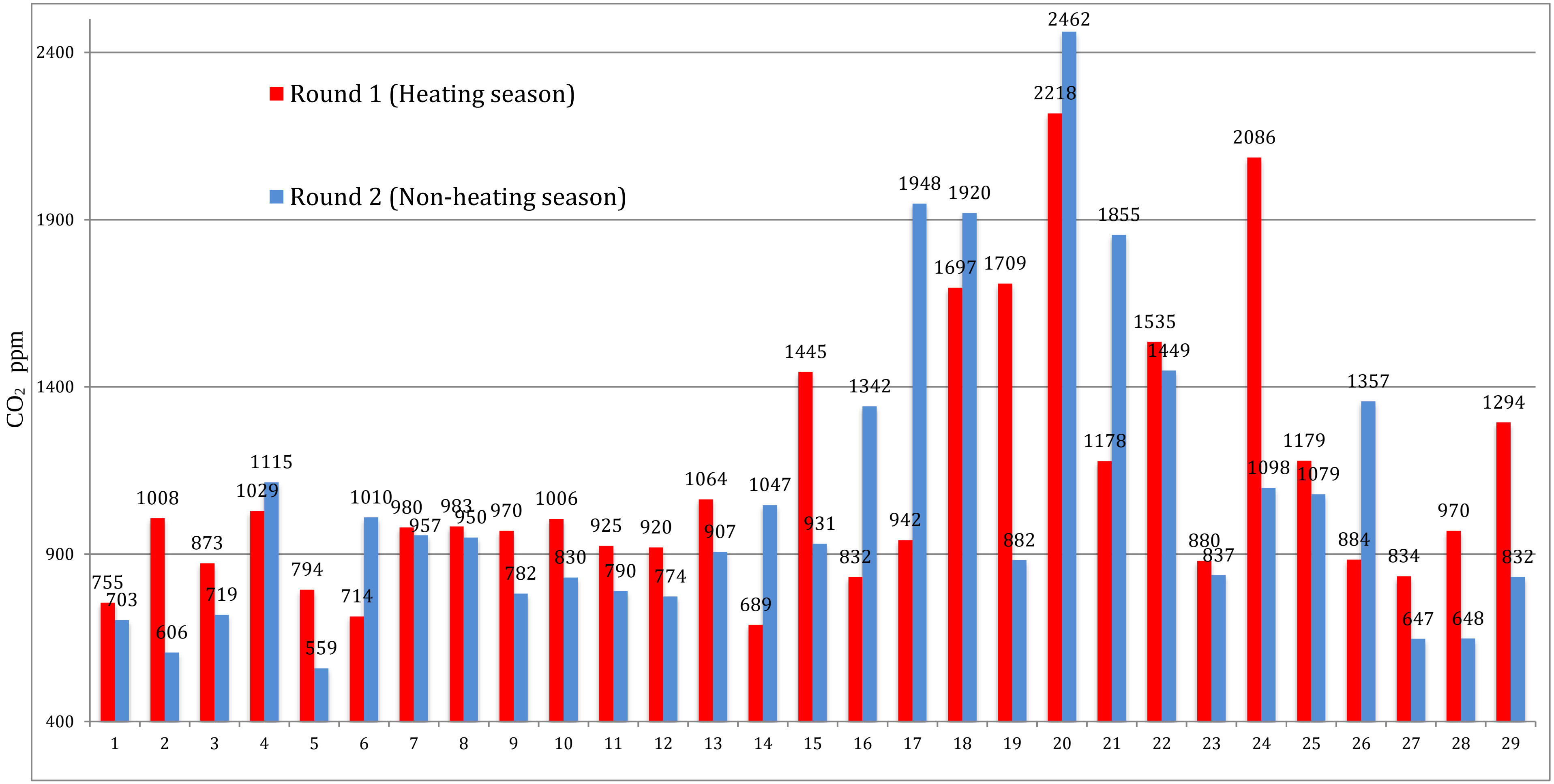
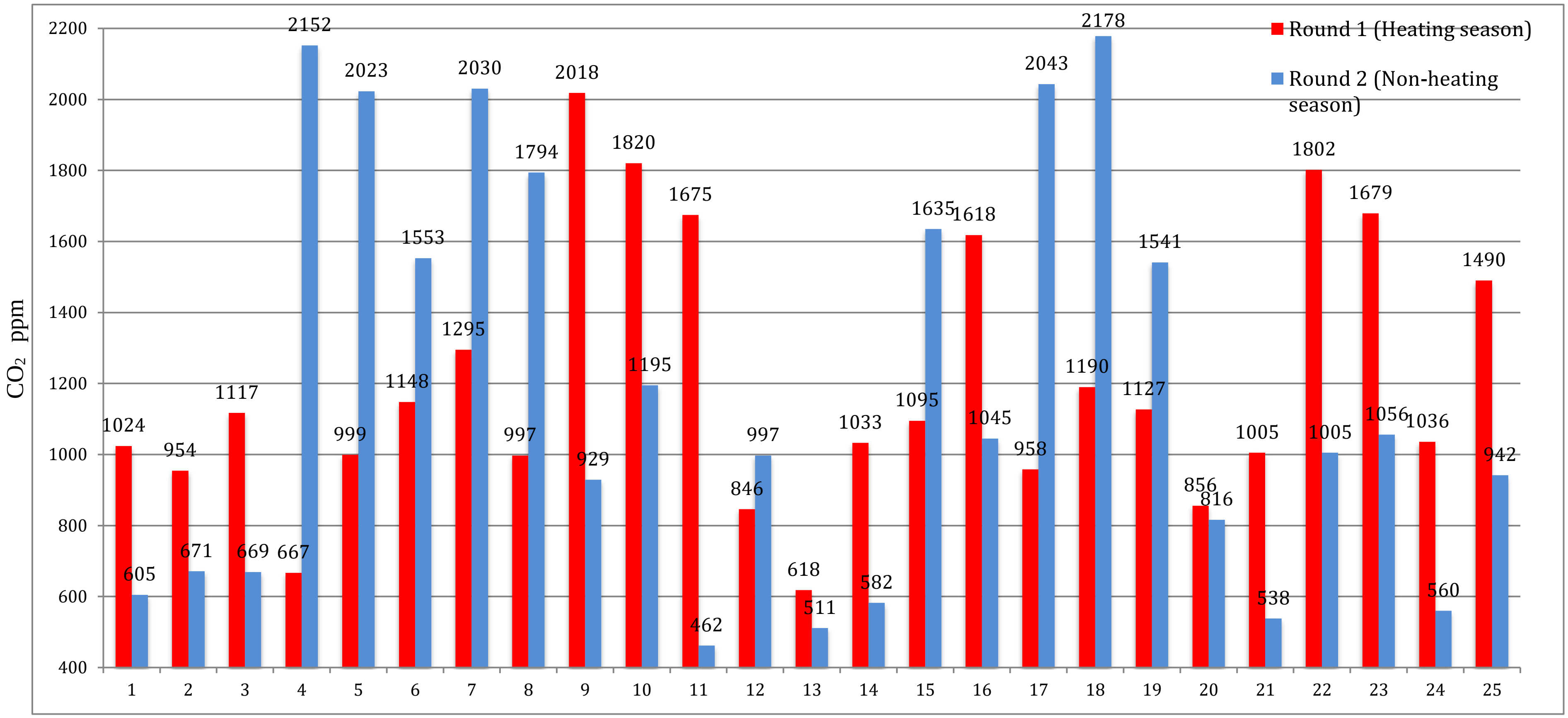


Figure 4-11b. Round 1 versus round 2 – mean CO_2 (worst case scenario)- teachers #30-54



Round 1 versus Round 2 - Mean CO_2 by School

Figure 4-12. Round 1 versus round 2 - mean CO_2 by school

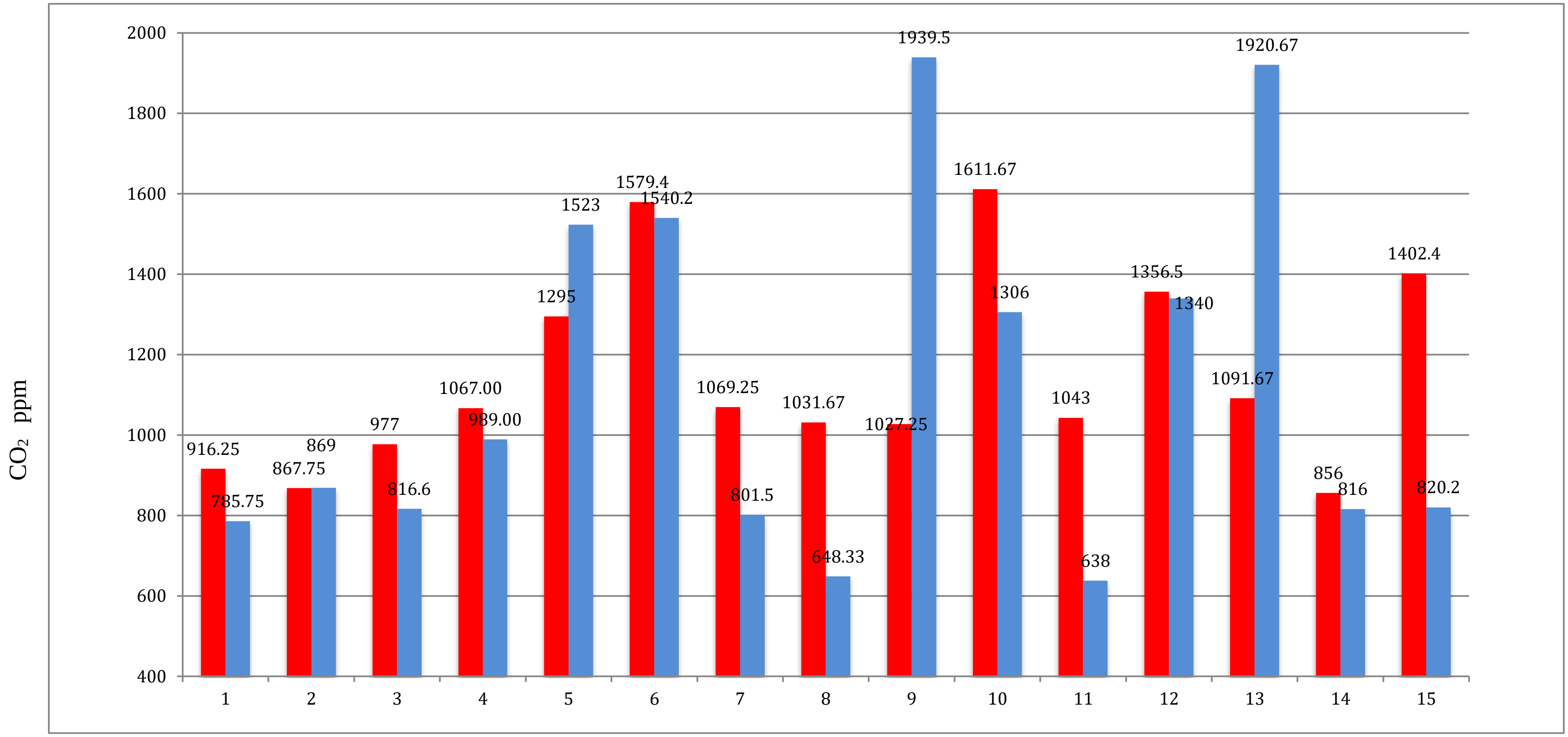


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Figure 4-13a. Round 1 versus round 2 - peak CO_2 teachers #1-29

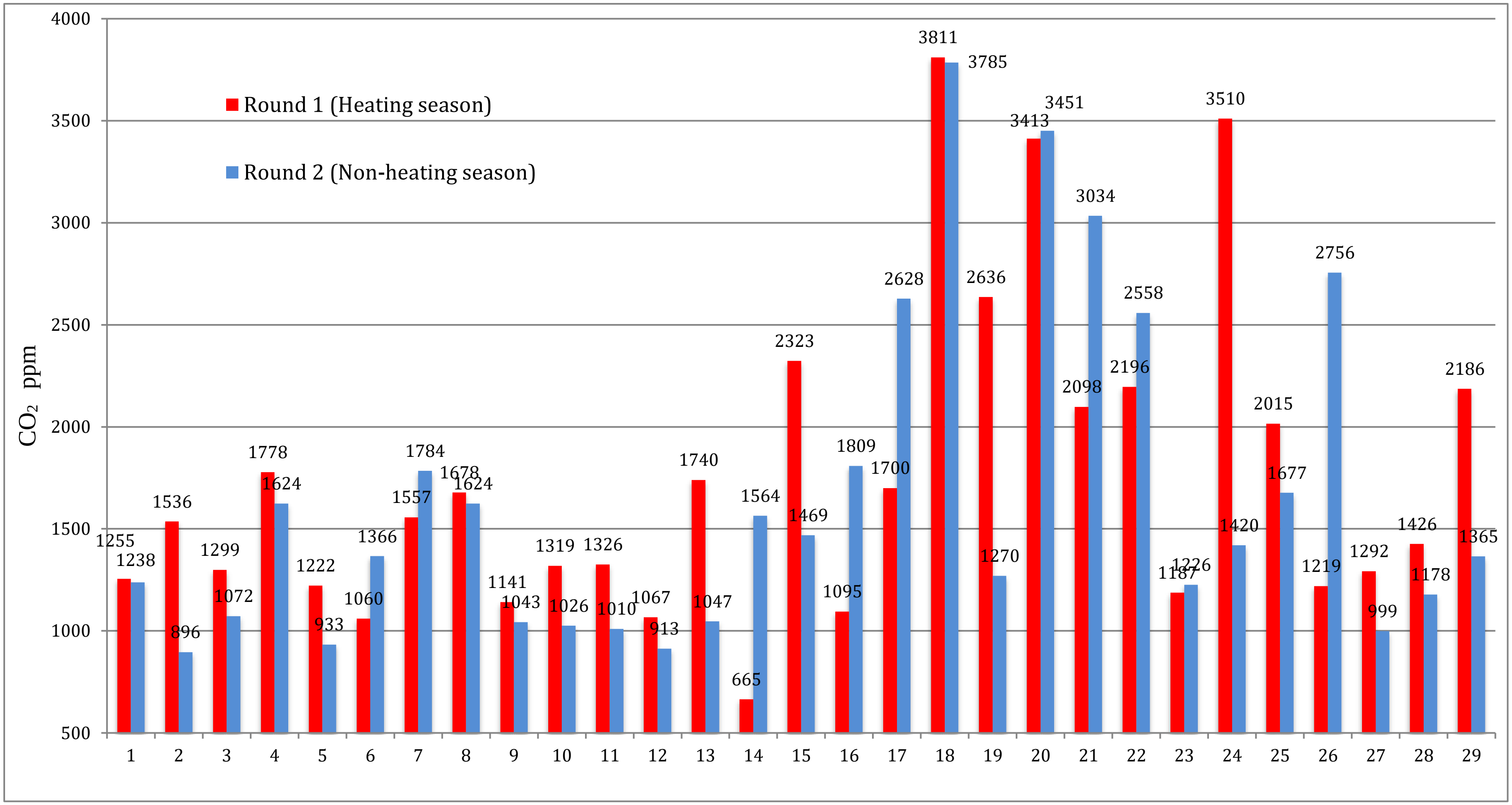
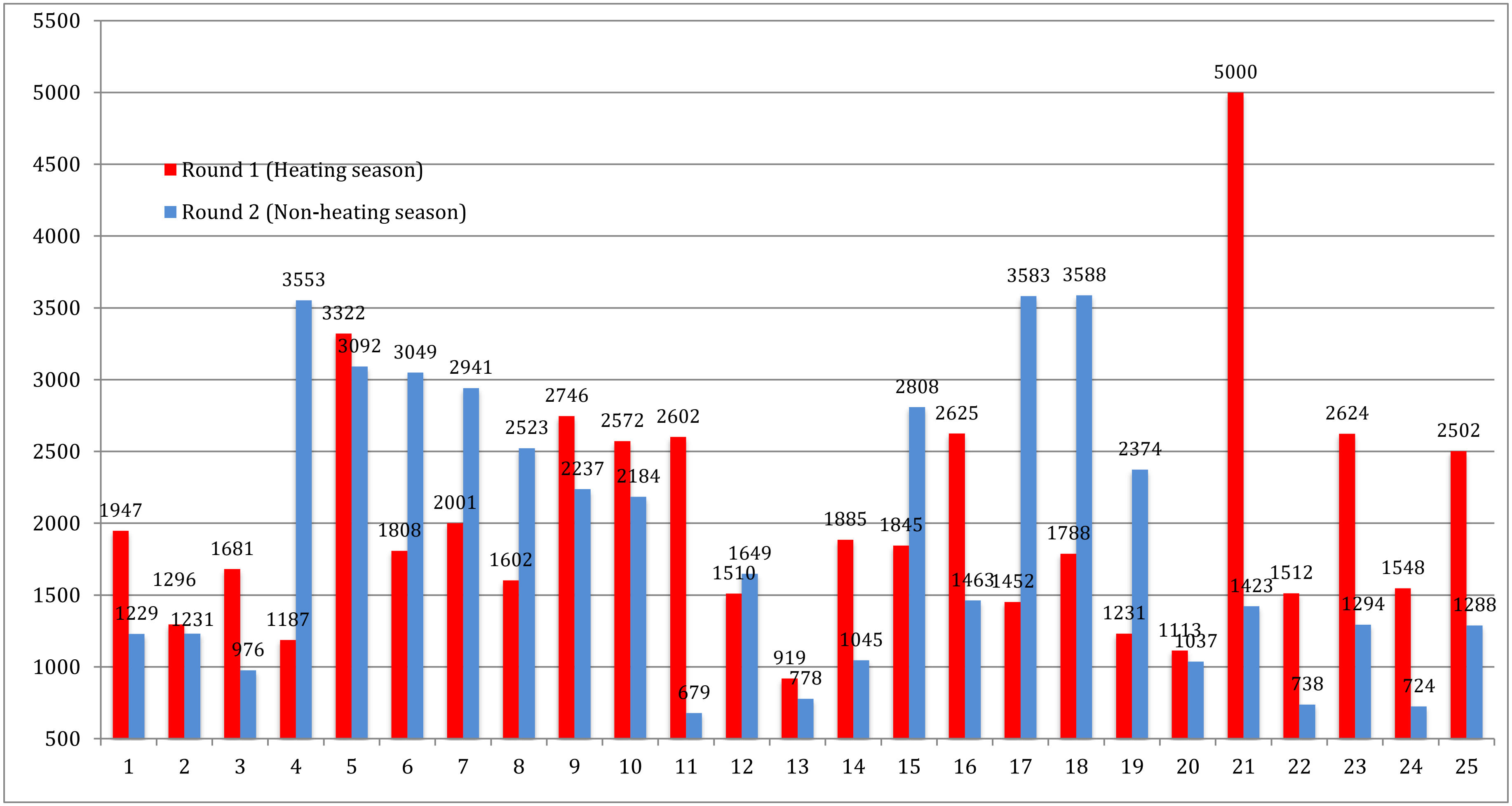


Figure 4-13b. Round 1 versus round 2 - peak CO_2 teachers #30-54



4.3 Evaluation of Coordinators

Table 4-8 provides the results from the evaluation of coordinators (during round 1). All but one of the school coordinators received scores greater than the established passing score. Fifteen of nineteen school coordinators received a perfect score, indicating that they could successfully manage all the given tasks without assistance from the researchers. One coordinator had trouble with all of the five tasks. While another coordinator had trouble completing two of the five tasks. The task that seemed to be challenging for some school coordinators was collecting the dataloggers and data binder from each teacher. This may have been impacted by the teachers' schedules and available time to complete the task prior to the environmental technician arriving at the school to pick up the equipment.

Table 4-8. The evaluation of school coordinators

School	Communicating and coordinating with the environmental technician	Understand ing the testing procedure	Ensuring the school data form is complete and the teachers are completing the daily logs	Checking periodically on the dataloggers and ensuring the dataloggers are not moved	Collecting the dataloggers and data binder from each teacher	Coordinator Score
1	3	3	3	3	3	60%
2	5	5	5	5	5	100%
3	5	5	5	5	5	100%
4	5	5	5	5	5	100%
5	5	5	5	5	5	100%
6	5	5	5	5	5	100%
7	3	5	5	5	5	92%
8	5	5	3	5	3	84%
9	5	5	5	5	5	100%
10	5	5	5	5	5	100%
11	5	5	5	5	5	100%
12	5	5	5	5	5	100%
13	5	5	5	5	5	100%
14	5	5	5	5	5	100%
15	5	5	5	5	5	100%
16	5	5	5	5	5	100%
17	5	5	5	5	3	92%
18	5	5	5	5	5	100%
19	5	5	5	5	5	100%

4.4 School Building and Classroom Factors

4.4.1 Schools Selected

The schools and teachers were selected based on who volunteered to participate in the study. The teachers' schools were located throughout the five boroughs (see figure 4-14) with 52% of schools being located in Brooklyn and Queens. Figure 4-15 shows that 63% of the schools in the study were constructed prior to 1940 and did not have central mechanical HVAC systems. These schools relied on exhaust ventilation with fresh air being supplied via windows. The oldest school building in the study was constructed in 1865 while the most recently constructed school was from 1996.

Figure 4-14. Location of school buildings

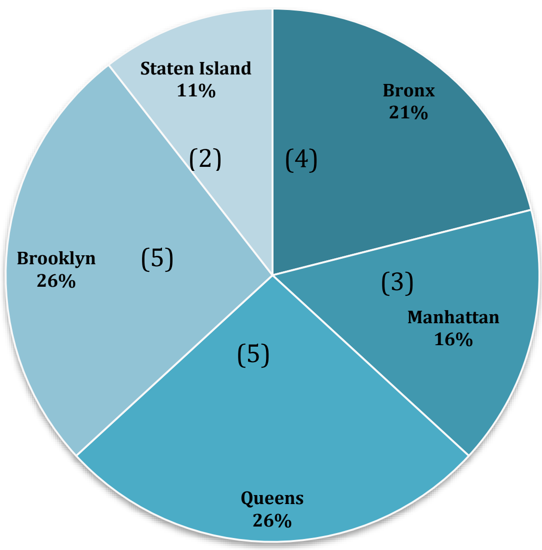
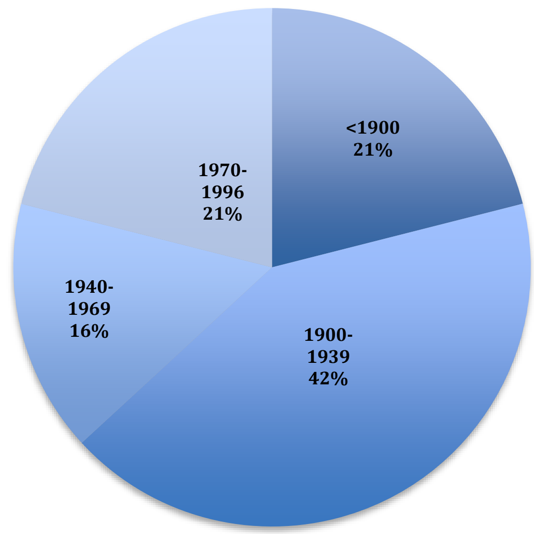


Figure 4-15. Age of school buildings



4.4.2 Median Household Income/Socioeconomic Status

An analysis of the median household income levels at each school location indicated that there was a wide disparity in median household income levels between the schools in the study. Table 4-9 shows the results of the economic analysis. Median household income levels ranged from $20,413 (which is at or below the Federal poverty line) to $122,537. The schools were categorized into three groups based on median household income. Table 4-10 defines the income groups. Nine of the nineteen schools were in the lowest income group including all the schools from the Bronx. Regression analysis did not identify an association of median household income with increased CO_2 levels.

Table 4-9. Median household income

School	Borough	Median Household Income
1	Queens	$59,417
2	Bronx	$23,860
3	Bronx	$26,438
4	Bronx	$33,020
5	Brooklyn	$82,448
6	Staten Island	$107,589
7	Bronx	$20,413
8	Staten Island	$28,793
9	Brooklyn	$36,615
10	Queens	$52,243
11	Brooklyn	$92,768
12	Queens	$64,189
13	Manhattan	$23,875
14	Queens	$20,920
15	Queens	$76,786
16	Manhattan	$122,537
17	Manhattan	$82,176
18	Brooklyn	$48,052
19	Brooklyn	$34,850

Table 4-10. Median household income groups

Group	Median household income Range	Number of Schools
red or 3	20K-40K	9
yellow or 2	40K-80K	5
green or 1	80K>	5

4.4.3 Building and Classroom Factors

Descriptive statistics for building/classroom factors are presented in table 4-11a & 4-11b. Window issues were reported with a similar frequency in round 1 and round 2, 13.2% and 14.1%, respectively. The frequencies of maintenance issues were also comparable in round 1 and round 2, 71.4% and 69.0%, respectively. The percentage of classrooms with mechanical ventilation in round 1 and round 2, was 36.3% and 40.8%, respectively.

The median classroom square footage was equivalent in round 1 and round 2, 616.0 ft^2. The minimum and maximum square footage (from either season) was 110 ft^2 and 1120 ft^2, respectively.

Table 4-11a & 4-11b. Descriptive statistics for building/classroom factors

	Round 1 N=89	Round 2 N=71
Window issues	12 (13.2 %)	10 (14.1%)
Maintenance issues	65 (71.4%)	49 (69%)
Mechanical Ventilation	33 (36.3%)	29 (40.8%)

	Round 1 N=89				Round 2 N=71			
	Mean	Median	Max	Min	Mean	Median	Max	Min
Classroom area (square footage)	608.2	616.0	1120	110	616.8	616.0	1020.0	110
Class size (number of students)	22.3	25	32	6	23.6	25	50	4
Building/classroom Year	1935.9	1930	1996	1867	1942	1930	1996	1895

Utilizing the combined round 1 and round 2 data to examine the relationship between building/classroom and environmental parameters, revealed the following results. Table 4-12 describes the building/classroom factors and the environmental parameters used in the analysis. The results of the correlation analysis are provided in table 4-13. Window issues were inversely correlated with mechanical ventilation and year of the school building. The presence of a central mechanical ventilation system and a newer school building were associated with less window issues (broken, inoperable). Buildings with mechanical ventilation were associated with larger square footage of classrooms and lower levels of peak CO_2 measurements. Mean RH measurements were associated with Peak CO_2, the number of CO_2 measurements >1000 ppm, mean CO_2, median CO_2, and weekly CO_2 average. This association was also identified during the evaluation of the daily and weekly plots of CO_2, temperature and RH measurements. Associations were observed between class student number and the CO_2 parameters but they were not statistically significant although a closer investigation showed that a statistical association existed in round 2 (class room student number and CO_2 measurements of 1000 ppm; cc=0.336, p=0.004).

Table 4-12. Building/classroom factors and environmental parameters analyzed

Building/classroom factor	**Environmental parameter**
Window issues	Peak CO_2
Poverty/SES	Number of CO_2 measurements > 1000 ppm
Mechanical Ventilation	Mean CO_2
Building Year	Median CO_2
Classroom area (square footage)	Weekly CO_2 Average
Maintenance issues	Mean Temperature, Maximum Temperature, Mean RH
Class size (number of students)	

Table 4-13. Correlational analysis between building/classroom factors and environmental parameters.

		Window Issues	Poverty / SES	Mechan. Vent	Building Year	Class area	Mainten issues	Class size	Peak CO_2	>1000	Mean CO_2	Median CO_2	Week AVG	Mean Temp	Max Temp	Mean RH
Window Issues	CC	1	-0.033	-.303**	-.231*	0.005	0.092	0.11	0.072	0.067	0.081	0.05	0.056	0.193	0.136	0.031
	Sig.	.	0.758	0.004	0.029	0.962	0.393	0.312	0.5	0.535	0.452	0.642	0.6	0.07	0.205	0.77
Poverty/SES	CC	-0.033	1	-0.073	0.132	-0.102	0.032	0.084	0.044	-0.049	-0.065	-0.079	-0.172	-0.071	-0.021	.298**
	Sig.	0.758	.	0.496	0.218	0.34	0.767	0.441	0.683	0.646	0.546	0.459	0.106	0.506	0.847	0.005
Mechan. Vent	CC	-.303**	-0.073	1	.838**	.317**	-0.005	-0.194	-.255*	-.210*	-0.172	-0.19	-0.1	-0.188	-0.195	-0.039
	Sig.	0.004	0.496	.	0	0.002	0.961	0.072	0.016	0.049	0.108	0.075	0.353	0.078	0.068	0.717
Building Year	CC	-.231*	0.132	.838**	1	.292**	0.03	-0.173	-0.064	-0.037	0.003	0.011	0.056	-.213*	-0.208	-0.003
	Sig.	0.029	0.218	0	.	0.005	0.779	0.11	0.55	0.73	0.978	0.92	0.604	0.045	0.051	0.976
Class area	CC	0.005	-0.102	.317**	.292**	1	-0.005	0.139	-0.133	-0.133	-0.118	-0.128	-0.083	-0.151	-0.159	0.072
	Sig.	0.962	0.34	0.002	0.005	.	0.963	0.199	0.215	0.214	0.27	0.23	0.44	0.159	0.137	0.503
Mainten. Issues	CC	0.092	0.032	-0.005	0.03	-0.005	1	-0.033	-0.092	0.01	0.018	0.039	-0.005	0.13	0.167	0.045
	Sig.	0.393	0.767	0.961	0.779	0.963	.	0.763	0.39	0.923	0.865	0.714	0.96	0.226	0.118	0.673
Class size	CC	0.11	0.084	-0.194	-0.173	0.139	-0.033	1	0.154	0.15	0.155	0.132	0.049	0.076	0.069	0.163
	Sig.	0.312	0.441	0.072	0.11	0.199	0.763	.	0.154	0.165	0.152	0.222	0.655	0.486	0.524	0.132
Peak CO_2	CC	0.072	0.044	-.255*	-0.064	-0.133	-0.092	0.154	1	.843**	.890**	.781**	.840**	-0.101	-0.077	.288**
	Sig.	0.5	0.683	0.016	0.55	0.215	0.39	0.154	.	0	0	0	0	0.344	0.473	0.006
>1000	CC	0.067	-0.049	-.210*	-0.037	-0.133	0.01	0.15	.843**	1	.938**	.955**	.900**	-0.065	-0.063	.368**
	Sig.	0.535	0.646	0.049	0.73	0.214	0.923	0.165	0	.	0	0	0	0.546	0.557	0
Mean CO_2	CC	0.081	-0.065	-0.172	0.003	-0.118	0.018	0.155	.890**	.938**	1	.917**	.938**	-0.096	-0.112	.333**
	Sig.	0.452	0.546	0.108	0.978	0.27	0.865	0.152	0	0	.	0	0	0.373	0.298	0.001
Median	CC	0.05	-0.079	-0.19	0.011	-0.128	0.039	0.132	.781**	.955**	.917**	1	.896**	-0.098	-0.13	.356**
	Sig.	0.642	0.459	0.075	0.92	0.23	0.714	0.222	0	0	0	.	0	0.361	0.224	0.001
Week AVG	CC	0.056	-0.172	-0.1	0.056	-0.083	-0.005	0.049	.840**	.900**	.938**	.896**	1	-0.115	-0.124	.283**
	Sig.	0.6	0.106	0.353	0.604	0.44	0.96	0.655	0	0	0	0	.	0.285	0.246	0.007
Mean Temp	CC	0.193	-0.071	-0.188	-.213*	-0.151	0.13	0.076	-0.101	-0.065	-0.096	-0.098	-0.115	1	.899**	-.255*
	Sig.	0.07	0.506	0.078	0.045	0.159	0.226	0.486	0.344	0.546	0.373	0.361	0.285	.	0	0.016
Max Temp	CC	0.136	-0.021	-0.195	-0.208	-0.159	0.167	0.069	-0.077	-0.063	-0.112	-0.13	-0.124	.899**	1	-0.204
	Sig.	0.205	0.847	0.068	0.051	0.137	0.118	0.524	0.473	0.557	0.298	0.224	0.246	0	.	0.055
Mean RH	CC	0.031	.298**	-0.039	-0.003	0.072	0.045	0.163	.288**	.368**	.333**	.356**	.283**	-.255*	-0.204	1
	Sig.	0.77	0.005	0.717	0.976	0.503	0.673	0.132	0.006	0	0.001	0.001	0.007	0.016	0.055	.

*=significant at the 0.05 level (2-tailed); **= significant at the 0.01 level (2-tailed)

4.5 Association of CO_2 and Perception of Air Quality and Well being

4.5.1 Correlational Analysis of Health Symptoms

A correlation analysis of the health symptoms using the Spearman chi square test showed that the health symptoms were correlated with each other and with self-reported stress levels. Table 4-14 shows the results of the correlation analysis. Among the health symptoms headache and fatigue had the highest correlation (0.405 $p<0.000$). Stress level was correlated with all reported health symptoms except for drowsiness.

Table 4-14. Round 1 correlation analysis of health symptoms and stress level

		Headache	Fatigue	Drowsiness	Difficulty concentrating	Teachers' stress level
Headache	CC	1.000	.405**	.318**	.316**	.426**
	Sig.	.	.000	.002	.003	.000
Fatigue	CC	.405**	1.000	.428**	.330**	.346**
	Sig.	.000	.	.000	.002	.001
Drowsiness	CC	.318**	.428**	1.000	.346**	.182
	Sig.	.002	.000	.	.001	.088
Difficulty concentrating	CC	.316**	.330**	.346**	1.000	.410**
	Sig.	.003	.002	.001	.	.000
Teachers' stress level	CC	.426**	.346**	.182	.410**	1.000
	Sig.	.000	.001	.088	.000	.

CC=Correlation coefficient
*=significant at the 0.05 level (2-tailed)
**= significant at the 0.01 level (2-tailed)

The correlation analysis of the health symptoms was performed for round 2 results using the same methodology. Table 4-15 provides the results of the round 2 correlation analysis. The health symptoms were correlated with each other and self reported stress, supporting the round 1 results. Headache and fatigue had the highest correlation (0.611 $p<0.000$) followed by headache and difficulty concentrating (0.516 $p<0.000$). Stress level was correlated with all four reported health symptoms but more with fatigue and difficulty concentrating (0.417 $p<0.000$) and (0.427 $p<0.000$) respectively. A number of correlations were greater in round 2, for example headache and fatigue had correlations in round 2 and in round 1 of 0.611 and 0.405, respectively.

Table 4-15. Round 2 correlation analysis of health symptoms and stress level

		Headache	Fatigue	Drowsiness	Difficulty concentrating	Teachers' stress level
Headache	CC	1.000	.611**	.304*	.516**	.257*
	Sig.	.	.000	.010	.000	.032
Fatigue	CC	.611**	1.000	.427**	.495**	.417**
	Sig.	.000	.	.000	.000	.000
Drowsiness	CC	.304*	.427**	1.000	.271*	.268*
	Sig.	.010	.000	.	.022	.025
Difficulty concentrating	CC	.516**	.495**	.271*	1.000	.427**
	Sig.	.000	.000	.022	.	.000
Teachers' stress level	CC	.257*	.417**	.268*	.427**	1.000
	Sig.	.032	.000	.025	.000	.

CC=Correlation coefficient
*=significant at the 0.05 level (2-tailed)
**= significant at the 0.01 level (2-tailed)

4.5.2 Carbon Dioxide and Perception of Air Quality

Round 1

Question 20 in the questionnaire asked teachers about their perception of air quality inside the classroom. A correlation analysis was conducted to evaluate the association of teachers' perception of air quality and the number of CO_2 measurements above 1000 ppm. A significant association was identified between the number of measurements exceeding 1000 ppm and the number of teachers reporting that the afternoon, they feel the air in the classroom becoming more stuffy (CC=0.304; p=0.004). Another indicator of perception of air quality was observed in teachers that reported the need to open windows to introduce more outdoor air. An association was observed with an increase in the number of measurements above 1000 ppm and the need for the teacher to open windows (CC= 0.231; p=030). Table 4-16 presents the results of the correlation analysis.

Table 4-16. Correlation analysis of perception of air quality and the number of CO_2 measurements >1000 ppm; the need to open windows and the number of CO_2 measurements >1000 ppm (round 1)

		CO_2 measurements Over 1000 ppm	Open windows in my classroom to let fresh air in.	In the afternoon, I can feel the air in the classroom becoming more stuffy
CO_2 measurements Over 1000 ppm	Correlation Coefficient	1.000	.231*	.304**
	Sig.	.	.030	.004
	N	89	89	89
Open windows in my classroom to let fresh air in.	Correlation Coefficient	.231*	1.000	.025
	Sig. (2-tailed)	.030	.	.819
	N	89	89	89
In the afternoon, I can feel the air in the classroom becoming more stuffy	Correlation Coefficient	.304**	.025	1.000
	Sig. (2-tailed)	.004	.819	.
	N	89	89	89

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

A logistic regression analysis was performed between the number of measurements exceeding 1000 ppm and teacher's perceiving their classroom becoming stuffy as the day progressed. Mean temperature and mean RH were controlled for in the model (see Appendix 6.1). The results showed slightly increased odds of perceiving the air to be stuffy for teachers with increased number of CO_2 measurements above 1000 ppm.

4.5.3 Carbon Dioxide and Teachers' Wellbeing

Multilevel regression analysis was conducted to evaluate the association between higher CO_2 levels and increased reporting of health symptoms (including headache, fatigue, drowsiness and difficulty concentrating) to take into consideration individual level factors and school level factors. A multiple regression model was also utilized to control for possible confounders including temperature and RH. An association was not identified from round 1 or round 2 data or the combined data set. Some of the results of this analysis are provide in Appendix 6.1. Possible justifications for not observing an association between higher CO_2 levels and health symptoms will be discussed in the following section.

Chapter 5. Conclusions, Discussion and Evaluation

5.1 Overview of the Dissertation

This study investigated the association between CO_2 levels and teachers' perception of air quality and well being. This was the first study to collect continuous air monitoring data within NYC public school classrooms for approximately one week, at two different points during the school year. Teachers from all five boroughs were included in the study. A marked finding in the study is that 77% of the teachers reported a work related symptom. This is similar to the results reported by Muscatiello et al. where approximately 74% of teachers reported a work related symptom. The results also revealed that the majority of teachers were exposed to CO_2 TWA levels above 1000 ppm with a number of peak CO_2 readings reaching 5000 ppm. These peak levels of 5000 ppm were only observed momentarily and declined rapidly. Overall, the CO_2 levels were not statistically different in round 1 and round 2 although some seasonal differences were noted with respect to CO_2. Classrooms from four schools had a significant decrease in CO_2 levels from the heating season to the non-heating season. Significant differences were observed in temperature and relative humidity measurements between round 1 and round 2. This shows that schools and classrooms had a challenge maintaining consistent thermal conditions.

This study also investigated school and classroom factors and their association with CO_2 levels and health outcomes. The type of ventilation system was found to be important as well as the age of the building in impacting CO_2 levels. Newer buildings with mechanical HVAC systems were associated with lower CO_2 levels. Maximum temperature was correlated with reported headaches indicating a possible confounding effect.

Carbon dioxide levels were correlated with relative humidity. This can be explained by the fact that students are the principal source of CO_2 and in addition to CO_2, their exhalation consists of water vapor. Rising RH levels in the classroom may provide a clue that CO_2 levels are increasing as well. Skon et al. attempted to model CO_2 levels based on knowing the temperature and RH. Their rationale was that measuring CO_2 is expensive and utilizes a significant amount of energy. The researchers collected environmental measurements, every 10 seconds (CO_2 temperature and RH), from eight apartments in one building. The results show that predicting CO_2 concentration based on RH and temperature measurements, is difficult.[93]

5.2 Summary of Findings and Discussion

The results of the study yielded several significant conclusions:

1. The majority of teachers had CO_2 TWA full shift exposures above 1000 ppm.
2. Some peak CO_2 levels were at or above 5000 ppm;
3. Peak CO_2 levels were mostly observed on Tuesdays or Thursdays with two peaks: one before noon and another peak in the middle of the afternoon or close 3pm.
4. Approximately 74% of teachers' reported experiencing work related neurophysiological symptoms;
5. The health symptoms were correlated with each other and with teachers' self reported stress. Stress may be acting as a mediator;
6. Overall the CO_2 monitoring results were not statistically different between the two rounds;
7. School staff could help manage air monitoring equipment.
8. An association of teachers' perception of air quality with the number of CO_2 measurements exceeding 1000 ppm was identified.

9. An association of higher CO_2 measurements and reported health effects was not identified.

5.2.1 Teachers' Exposures

The study was successful in monitoring and characterizing NYC public school teachers' full shift exposure to CO_2. More than 30,000 hours of monitoring data were collected over the course of the study providing substantial baseline exposure data for teachers and classrooms throughout the five boroughs. The results indicated that 88 of 160 (55%) of the full shift TWA exposures (Worst case scenario day) exceeded 1000 ppm, and 60 of 160 (37.5%) of the weekly average exposures exceeded 1000 ppm. Very high peak CO_2 levels were also identified, reaching 5000 ppm, the datalogger upper detection limit and also the OSHA PEL (for full shift exposures). Peak CO_2 levels were observed mostly in the afternoon corresponding to a build up of CO_2 from continued student occupancy. Being aware that CO_2 levels build up in the afternoon can allow teachers and custodial staff to be proactive by taking actions early in the afternoon or even early in the day to prevent the CO_2 concentrations from rising. Overall, significant differences in CO_2 levels were not observed between the heating season and non-heating season. It was hypothesized that CO_2 levels would be higher in the heating season less (cold) outdoor air would be brought into the classroom and the classrooms would be more sealed to prevent cold air from entering. Classrooms from four schools did show a reduction in CO_2 levels indicating that conditions of each school and classroom need to be examined more closely.

5.2.2 Evaluation of School Coordinators

The results of this evaluation confirmed the hypothesis that school staff with some information and training can manage air quality monitoring equipment inside their classrooms and school.

These findings are significant since in the future we can rely on school staff to proactively monitor the air quality in classrooms and to implement certain actions to reduce CO_2 levels including opening windows and alerting maintenance staff to increase the ventilation flow rates or the amount of fresh air. The school coordinators were not informed ahead of time that they would be evaluated on the performance of their given tasks. All of the school coordinators were very eager to help in monitoring the air quality in their school and equally eager to know the results. In some schools the coordinators were the school sustainability coordinators whom had a lighter class load than the regular teachers who served as coordinators. The sustainability coordinators had more flexibility in completing the tasks required for the study. In the future non teacher coordinators would be preferable to manage air monitoring equipment or assist in a research study.

Prior to the start of the study, there was a concern that some of the air monitoring devices could be lost or stolen during the environmental testing. At the conclusion of the study none of the equipment was lost nor stolen. The HOBO MX1102 data loggers have built in Bluetooth technology with a signal strength of about 100 feet. In the event the datalogger is misplaced inside a classroom or placed into a desk drawer or taken to the adjacent classroom, the device has a tracking feature and could be located using Bluetooth. Another benefit of Bluetooth technology is that the data could also be viewed and downloaded wirelessly from a distance.

5.2.3 Evaluation of Building and Classroom Factors

In investigating the association of building/classroom factors with CO_2 levels, several significant findings were identified. The number of window issues inside classrooms were inversely correlated with mechanical ventilation and year of the school building. Older buildings utilize windows for their supply air, which is managed mostly by the teacher. Newer school buildings provide supply air through central/mechanical HVAC systems reducing the need for the teacher to open windows. Buildings with mechanical ventilation were associated with larger square footage of classrooms and lower levels of peak CO_2 measurements. This finding indicates that buildings with mechanical ventilation systems may be able to better control rising CO_2 levels. Newer school buildings may utilize CO_2 sensors to control airflow to classrooms. Mean RH measurements were associated with Peak CO_2, the number of CO_2 measurements >1000 ppm, mean CO_2, median CO_2, and weekly CO_2 Average. Increasing RH levels may provide another clue that CO_2 levels are rising as well. Associations were observed between class student number and the CO_2 parameters but they were not statistically significant although a closer investigation showed that a statistical association existed in round 2 (class room student number and CO_2 measurements of 1000 ppm; cc=0.336, p=0.004). Even though the average class size was approximately 23 students some schools had classrooms with very few students because they dealt with special needs students. There were also some teachers that dealt with multiple class sizes and may not have reported an accurate class size. An association between median household income and CO_2 was not identified. Maybe a larger sample size of schools was needed to observe a relationship since only 19 schools were evaluated. Another explanation could be that higher CO_2 levels are pervasive across all SES levels. In New York City individuals from a variety of SES groups are exposed to the same outdoor air pollution including PM_{10} and ozone.[94]

5.2.4 Higher CO_2 Levels and Teachers' Perception of Air Quality and Well Being

An increase in teachers perceiving the air in their classrooms becoming stuffy and the number of CO_2 measurements exceeding 1000 ppm was observed. This finding indicates that teachers can perceive subtle changes in air quality. An association with teachers reporting a need to open windows and increasing number of CO_2 measurements above 1000 ppm was observed providing another indication that teachers can perceive subtle changes in air quality.

A significant association between health symptoms including headache, fatigue, drowsiness, difficulty concentrating and higher levels of CO_2 was not identified. This may be due the existence of other confounders or biases. One possible bias is selection bias since the schools and classrooms were not selected randomly. The study used a convenience sample consisting of schools and teachers who volunteered to participate in the study. It is possible that principals and teachers in older buildings were more likely to volunteer to have their school's air quality checked. This explanation can be possible especially since about 63% of the school building were constructed prior to 1940. However school buildings constructed prior to 1940 represent about 30% of the schools in the NYC public school system. Regression analysis showed that building age and ventilation system were associated with reports of headache. In other words teachers in older schools also reported experiencing more headaches than teachers in newer schools. This may provide some insight into possible biases due to preconceived notions that working in an older school is associated with poor air quality. Older school buildings and classrooms also had on occasion high temperature measurements (above the acceptable criteria) and lower or higher RH levels (outside the recommended criteria. Headaches were found to be associated with higher mean temperatures.

5.3 Strengths

The main strength of this study was the extensive air quality monitoring conducted inside the classrooms to evaluate the teachers' exposure to CO_2. Approximately 30,000 hours of continuous CO_2, temperature and RH measurements were collected during the study (including nights and weekends) providing a large database of exposure levels. Measurements were collected during two different time periods within the school year to evaluate any differences between the heating and non-heating seasons. Few studies have examined seasonal differences in teachers' environmental exposures. There was also a wide range of measurements. The number of environmental exposure records linked to teacher questionnaires combined for round 1 and round 2 was 160. This number of exposure records could be viewed as a strength since the study conducted by Muscatiello et al. monitored 64 teachers/classrooms.

A wider range of CO_2 exposures were observed in the study and the findings from the NYC public school system should be generalizable to other urban schools. The findings may be less generalizable to rural schools which may have different characteristics including smaller class sizes. Selection bias could be a concern if the teachers that volunteer to take part have a different vulnerability to the effects of CO_2 than the teachers who did not volunteer to participate. However, this is unlikely. Nevertheless, the demographics of the teachers who participated were compared to the demographics of the teachers in the entire NYC public school system and determined to be similar. Lahtinen et al. highlights the importance of the impact of psychosocial factors on the wellbeing of occupants. Psychosocial factors such as stress due to heavy work load, if not assessed, could be a confounder and can lower the validity of a questionnaire.[95] Teachers' stress levels were assessed via the questionnaire.

5.4 Limitations

Limitations of questionnaires

Researchers conducting IEQ studies often use questionnaires to collect information that can provide insight into environmental exposures, health symptoms and the subjects general well being.[96] Specific questions and scales are included to elicit specific types of information. The current study adopted a questionnaire used in a similar study conducted by Muscatiello et al. Since the current study was focused on the association between higher CO_2 and teachers' perception of air quality and cognition, questions regarding other symptoms such as asthma or allergic responses were eliminated from the questionnaire. Questionnaires can help disentangle confounders such as other environmental agents (VOCs, mold, temperature) by asking teachers about their perceptions of the environment without having the need to conduct environmental monitoring. However there is a level of subjectivity when self reporting health symptoms and perceptions of air quality. Individuals have different opinions on what constitutes acceptable or poor air quality. Construct validity has been demonstrated in some IEQ questionnaires. Jung et al.[68] administered a questionnaire to evaluate symptoms and conducted 11 non invasive clinical tests that are indicators of sick building syndrome. IEQ testing was also conducted to describe airborne contaminant levels. There was a significant correlation between self reported of symptoms and positive clinical results showing that the questionnaire instrument could be utilized to assess occupant well being. Kajtar et al. reported that more mental effort is exerted under conditions of elevated CO_2 with participants describing feeling more tired after performing mental tasks at 5000 ppm CO_2 than at 600 ppm. A scale assessing fatigue/tiredness was included to collect data on this health outcome.

Recall bias could be a factor particularly if the teachers' recall is impacted by the possible high levels of CO_2 when they are completing the questionnaire inside the classroom. However, the teachers most likely responded to the questionnaires during their lunch hour or break when the CO_2 levels should hypothetically lower since the classroom will not have students.

Limitations of air monitoring

It is unclear to the extent these exposures are representative of classroom CO_2 status for the entire year. Concentrations of airborne contaminants tend to be highly variable.[97] However, this study collected CO_2 continuously for about one week during the heating season and non-heating season to evaluate any variability and seasonal effects.

Other limitations

The sample size may also be a limitation. A larger sample size of teachers would have been preferable. However, since we are collecting primary data, resources including time and funding are limited. Some classrooms within the same school may be served by the same ventilation system which would not make them independent. However, clustering of exposures is unlikely to affect the relation of exposure to outcome. These schools level effects could be evaluated through multilevel regression analysis.

This study focused on the New York City public school system, which is a very specific type of urban and multiracial setting. Replication of the study could be limited by that factor. However, problems with school building condition, as mentioned earlier, are national in scope. Similar results would be expected in other urban settings.

Selection bias could also be a concern. If the teachers who volunteered to participate had a preconceived notion that their classroom air quality was poor and that this study would help improve it. While teachers who may be satisfied with their air quality would be less inclined to participate in the study. To address this in future studies, schools and classrooms will need to be selected randomly.

5.5 Policy Recommendations and Future Directions

This type of study has been conducted in schools elsewhere in New York State but did not utilize school personnel for exposure data collection. The current research project assessed if teachers and/school staff can effectively utilize air monitoring equipment to determine if actions are needed to improve air quality. School staff were able effectively manage the air monitoring equipment. The results of this study may lead to the use of CO_2 sensors in the classroom that would indicate high CO_2 levels as well as communicating with the HVAC systems to increase ventilation. The results of the research may lead to revised guidelines which include specific CO_2 criteria and the development of an enforceable IEQ standard for schools including acceptable CO_2 limits.

Policy Recommendation #1

Utilize the results from this study; particularly the building and classroom level factors associated with increased CO_2 levels, to help identify other school buildings and classrooms with potential high CO_2 levels. School and classroom factors would include: age of school building, type of HVAC system, maintenance issues, window issues, number of students and class room square footage. By selectively targeting at risk schools and classrooms, a tremendous amount of time and financial resources will be saved.

Policy Recommendation #2

Since this study determined that school staff can manage air monitoring equipment, provide classrooms, where teachers and students are at risk of high CO_2 levels, with CO_2 monitors similar to the devices used during the study, to be able to know the CO_2 levels in their classroom. When the levels exceed a predetermined set point it would alert the teacher or school staff to take specific actions to ensure CO_2 levels are controlled. The specific actions could include introducing additional outdoor air by opening the windows or turning on air conditioners or turning on the central air systems. The identification of higher CO_2 levels could also prompt the custodial staff to address any needed repairs to the HVAC systems.

Policy Recommendation #3

Provide school custodial staff with additional training on the ventilation operations and maintenance. The training could include the principles of ventilation, IEQ and environmental sustainability. A version of this training could be also provided for school management as well as teachers to be more informed and aware of potential IEQ issues and the relationship with ventilation. During the study I spoke with some school custodians whom were not aware of the Minimum Efficiency Reporting Value (MERV) rating of the filters used in the school HVAC systems. Some teachers did not know where the exhaust vent was located in their classrooms. An example is a teacher who was not aware that the exhaust was located in the coat closet and was storing books almost completely blocking the intake and restricting air flow. Another teacher kept all the coat closet doors closed at all times except for the beginning and at the conclusion of the school day. Providing information and training could prevent any IEQ issues and help improve the health of teachers.

Policy Recommendation #4

Develop and implement pilot intervention project in older school buildings to install a mechanical ventilation with CO_2 sensors. The feasibility of the intervention could be evaluated based on several factors including return on investment taking into consideration improved well being and academic performance of teachers and students. I recently visited a newly constructed public school in Glastonbury Connecticut classified as a green school based on meeting certain energy efficiency criteria. The mechanical ventilation system installed in the school is considered a "smart" system based on measuring CO_2 in classrooms and providing fresh air based on specific parameters. When the CO_2 measurements are low or similar to background levels the system infers that the classroom is unoccupied and air flow to the classroom is prevented to save energy. When CO_2 levels rise and are detected above the set criteria, fresh air is provided. Each classroom does not have its own CO_2 sensor and instead the air is drawn through tubing to centrally located CO_2 sensors. These centrally located sensors can measure the air from multiple classrooms and switch between different samples of air. The advantages of this design are:

1) There are less sensors to calibrate than if each classroom had its own sensor, especially since the sensors require period calibration or they will not be accurate or reliable.
2) Initial and operational costs should be lower since there are much less sensors to purchase and install as well to maintain and manage.

This type of system, also known as Demand-Controlled Ventilation (DCV). can be used with new construction or can be installed in existing school buildings depending on their mechanical ventilation systems.[60] Improved IEQ can be achieved when the fresh air supply rate responds to the load imposed by the number of occupants and by their activity in the room. The potential for energy savings is substantial, especially in premises such as classrooms where there is considerable variation between high occupancy and when there are few or no occupants.

Policy Recommendation #5

Develop and implement a program to conduct comprehensive IEQ evaluations of schools and classrooms to help identify and prevent IEQ issues from escalating. The NYC DOE DSF already conducts periodic inspections of school buildings focusing on architectural, electrical and mechanical aspects. A greater emphasis needs to be placed on IEQ and optimizing the learning environment. The program would include full shift CO_2 monitoring to identify classrooms with high CO_2 levels. Interventions could be implemented to reduce CO_2 levels as much as possible. The UFT currently conducts limited IEQ assessments usually in response to a complaint collecting a few measurements for CO_2 to quickly check whether the ventilation systems are functioning effectively.

Policy Recommendation #6

School buildings with mechanical ventilation need to increase their air flow to ensure CO_2 are maintained as low as possible (around 700 ppm). The cost benefit analysis supports increased rather than decreased ventilation rates. Energy use for heating, ventilating and cooling buildings often represents more than half of their total primary energy use. The relationship between building ventilation and energy use is complex. It is impacted by a large number of variables related to the climate, the characteristics of the building envelope and the features of the mechanical HVAC systems. Santos and Leal determined that each 1 L s-1 (2.12 CFM) per person increase in ventilation would increase annual energy consumption by 1.2, 1.5 and 2.0

kWh per square meter in Lisbon, Paris, and Helsinki, respectively. The annual per occupant cost is $2.1, $2.7 and $3.5 for the three cities. Increases range from a few dollars to about 10 dollars per person.[90] For reference, comparing to US per student annual spending of $10.3K while NYC per student spending is about $17K.[43]

Future Directions

Since this study established a tremendous amount of baseline air monitoring data, a logical next step would be to obtain classroom academic scores on standardized tests to evaluate any associations between higher CO_2 levels and academic performance or cognitive skills. Intervention studies could be conducted where a mechanical ventilation system would be installed. Carbon dioxide concentrations, temperature, RH, health outcomes and academic performance before and after the intervention would be assessed. A cost benefit analysis would be performed. Based on existing research it is theorized that the benefits of retrofitting an existing school building will outweigh the costs in terms of perceived air quality, less absences, improved academic performance.

Successful interventions to decrease CO_2 levels in schools have been implemented. Norbak et al. utilized a CO_2 controlled ventilation system in computer classrooms (with CO_2 sensors), to demonstrate that reducing elevated levels of CO_2 significantly reduced headache (p=.003) and tiredness (p=.007) and improved satisfaction with the air quality.[98] Wargocki et al. installed CO_2 sensors in classrooms with natural ventilation to provide a visual indicator when air quality was deteriorating. Green diodes signified CO_2 levels below 1000 ppm, yellow denoted that it was in the range from 1000 to 1600 ppm, and red diodes indicated that the levels exceeded 1600 ppm.

Yellow and red indicators prompted teachers to open windows to reduce CO_2 levels. Opening windows maintained CO_2 concentrations below 1000 ppm and increased energy use for heating while reduced the cooling requirement in summertime.[99] Rosbach et al. demonstrated that classrooms with natural ventilation can be retrofitted with a portable mechanical ventilation system to supply more outside air and reduce CO_2 levels. The systems were CO_2 controlled, using a real-time, self-calibrating CO_2 sensor to regulate the amount of outdoor air supplied, and achieve a target steady-state CO_2 concentration in the classroom. A mean decrease of 491 ppm was achieved from a baseline mean of 1335 ppm (range: 763–2000 ppm).[100]

Since self-reported symptoms are subjective and the perception of air quality varies across individuals[101], another possible direction for future research could include obtaining diagnostic (medical) indicators from teachers to support self reported symptoms when conducting exposure monitoring for CO_2. During the initial stages of designing the current study, the possibility of collecting real-time diagnostic health data was considered especially since it is easier than ever to monitor heart rate/pulse or blood oxygen levels. One challenge was the limited budget available to purchase the diagnostic equipment since resources were already being used to acquire the air monitoring devices. However, these devices are becoming less expensive and can be integrated with smart phones or smart watches. Diagnostic data is objective and could provide a more accurate connection between the effects of CO_2 on teachers' health.

Chapter 6. Appendix

6.1 Additional Analytical Results

Higher CO_2 and Perceptions of Air Quality

```
LOGISTIC REGRESSION VARIABLES q0020_0001
  /METHOD=ENTER Mean_Temp Mean_RH
  /METHOD=ENTER Over_1000
  /SAVE=PRED COOK
  /CRITERIA=PIN(0.05) POUT(0.10) ITERATE(20) CUT(0.5).
```

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Mean_Temp	.032	.055	.345	1	.557	1.033
	Mean_RH	.010	.011	.904	1	.342	1.011
	Constant	-3.334	4.125	.653	1	.419	.036

a. Variable(s) entered on step 1: Mean_Temp, Mean_RH.

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Mean_Temp	.045	.056	.630	1	.427	1.046
	Mean_RH	.012	.011	1.048	1	.306	1.012
	Over_1000	.005	.002	6.106	1	.013	1.005
	Constant	-4.939	4.308	1.314	1	.252	.007

a. Variable(s) entered on step 1: Over_1000.

Block 1: Method = Enter

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	8.751	3	.033
	Block	8.751	3	.033
	Model	8.751	3	.033

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	114.528[a]	.094	.125

a. Estimation terminated at iteration number 4 because parameter estimates changed by less than .001.

Classification Table[a]

Observed			Predicted Headache .00	Predicted Headache Yes	Percentage Correct
Step 1	Headache	.00	22	21	51.2
		Yes	12	34	73.9
	Overall Percentage				62.9

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	What is your gender?	-.097	.747	.017	1	.897	.908
	Building_Age	.033	.012	7.504	1	.006	1.034
	Mechanical_Vent	-1.948	.895	4.739	1	.029	.143
	Constant	-63.440	23.304	7.411	1	.006	.000

a. Variable(s) entered on step 1: What is your gender?, Building_Age, Mechanical_Vent.

Block 2: Method = Enter

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	1.938	1	.164
	Block	1.938	1	.164
	Model	10.689	4	.030

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	112.590[a]	.113	.151

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

Classification Table[a]

Observed			Predicted Headache .00	Predicted Headache Yes	Predicted Percentage Correct
Step 1	Headache	.00	23	20	53.5
		Yes	10	36	78.3
	Overall Percentage				66.3

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	What is your gender?	-.177	.772	.052	1	.819	.838
	Building_Age	.037	.013	7.773	1	.005	1.038
	Mechanical_Vent	-2.268	.967	5.497	1	.019	.104
	Week_AVG	-.001	.001	1.837	1	.175	.999
	Constant	-69.640	25.300	7.577	1	.006	.000

a. Variable(s) entered on step 1: Week_AVG.

Block 3: Method = Enter

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	3.991	2	.136
	Block	3.991	2	.136
	Model	14.680	6	.023

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	108.599[a]	.152	.203

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

Classification Table[a]

Observed			Predicted: Headache .00	Predicted: Headache Yes	Percentage Correct
Step 1	Headache	.00	22	21	51.2
		Yes	10	36	78.3
	Overall Percentage				65.2

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	What is your gender?	-.253	.808	.098	1	.755	.777
	Building_Age	.039	.014	7.877	1	.005	1.040
	Mechanical_Vent	-2.241	.997	5.049	1	.025	.106
	Week_AVG	-.001	.001	1.393	1	.238	.999
	Max_Temp	.121	.065	3.536	1	.060	1.129
	Mean_RH	.022	.028	.590	1	.442	1.022
	Constant	-83.992	27.895	9.066	1	.003	.000

a. Variable(s) entered on step 1: Max_Temp, Mean_RH.

6.2 Summary of Deleterious Effects of High CO_2 exposure

Table 1. Deleterious Effects of High CO_2 Exposure[a]

function	CO_2 level	observed effects	detailed observations	references
acid/base balance	acute hypercapnia (min to few days)	acute acidosis	low extracellular pH and inorganic phosphorus plasma concentration	6
			increase of the calcium and HCO_3^- ions plasma concentrations	
			renal compensation with excretion of NH_3 and acidic substances (low pH) and increase urine inorganic phosphorus	
			compensation within days (10 or 15%) or weeks (1.5 or 3%)	
	chronic hypercapnia (days to months)	chronic acidosis	normal extracellular pH	10−15
			elevated plasma calcium and low level of inorganic phosphorus	
	chronic intermittent hypercapnia	chronic acidosis	increase in urine volume and pH (increase in organic acids and NH_3)	16,17
			slower renal compensation than for constant exposure	
cellular metabolism	1−5%	enhanced glycolysis and respiration	in vitro	18−20
	10−20%	reduction of respiration	in vitro	20
	1.5 to 3%	body weight loss	first 25 to 35 days then partial recover, guinea pigs	25
	3% 7 days	liver function changes	depletion of glycogen vacuoles and increase of fat vacuoles	25
respiratory function	10 to 30%	loss of consciousness	observed in 1 min with 30%, 5−10 min with 10%	33
	from 1%	enhanced respiratory rate	increased respiratory minute volume	34
			increased respiratory amplitude and frequency	
		alteration of cell substructure	decrease in the airway conductance	35,36,24
	3−15% for days	hyaline membranes	elevation of $PaCO_2$	24,38
	10% for 1 h	lung inflammation	changes in the structure of type II alveolar pneumocytes	37,9
			hyperplasia and hypertrophia (increased activity?)	36
			decreased gas exchange	
cardiovascular function	from 5%	increased heart rate	cardiac frequency and arterial pressure, peripheral vasodilatation	34
	1.5 to 15%	no evidence of damage	histopathological analysis	25
CNS function	1 to 4%	low to mild effects	headaches, reduction of stereoactuity and ability to detect motion	33,40−42
	10 to 15% (min)	excitability	eye flickering, psychomotor excitation and myoclonus...	43,6
reproductive function	2.5 to 10% (hours)	testes degeneration	reversible tubular disturbance and degenerative changes in rats	44,25
			decrease in the number of mature spermatozoids	
development	6%	teratogenic	enhanced frequency of skeletal and cardiac malformations of the pups	45
	10%		retinopathy of prematurity (rats)	46,47
	10−13%		vertebral malformations (rabbits)	48
	8% chronic intermit.		body weight loss and alterations of lung maturation (rabbits)	49
cell fate and proliferation	6−30%	alteration of in vitro cell fate	retardation of cell division, alteration of the division process	51,52
	8−12%		potentialization of nicotine and NKK mitogenics effects (PNE cells)	53,54
	10%		stimulation of SCLC proliferation with MAP kinase activation	55
	0.03 to 0.1%	carcinogenic	exacerbation of H_2O_2 toxicity, aggravation of DNA damages (*E. coli*)	56
	45 to 100%		enhanced incidence of cancer and metastases (mice)	20,58−60

[a] Definitions: HCO_3^-, bicarbonates ions; NH_3, ammonia ions; $PaCO_2$, CO_2 tension in arterial blood; PNE cells, pulmonary neuroendocrine cells; SCLC, small cell lung cancer; MAP, mitogen-activated-proteins; NNK, nitrosamine 4-(methylnitrosamino)-l-(3-pyridyl)-l-butanone; *E. coli*, *Escherichia coli*.

Table 2. Described Mechanisms of Action of Carbon Dioxide or Bicarbonate Ion[a]

target	actor	direct consequences	indirect regulation	references
acetyl-CoA carboxylase	HCO_3^-	formation of malonyl-CoA	formation of fatty acids for the cell membranes	21
pyruvate carboxylase	HCO_3^-	conversion of pyruvate to PEP during glucogenesis		21,23
carbamoyl phosphate synthetase I	HCO_3^-	synthesis of carbamoyl phosphate	urea cycle and regulation of pyrimidine biosynthesis	21,22
extracellular pH (uncompensated acidosis)	CO_2	increased plasma levels of GOT and GPT increased activities of LDH, MDH, isocitrate dehydrogenase, and cholinesterase	inhibition of lipolysis	25–27
central chemoreceptors	CO_2	regulation of cardiovascular system, lung ventilation, olfaction, cerebral circulation		21,32,61,62
PP2A/NFkB pathway	CO_2	activation of PP2A phosphatase activity causing the nuclear translocation of NFkB, not correlated with extracellular pH changes	secretion of the pro-inflammatory cytokines (TNF- α, IL- 8, IL- 6, Mip1-α) and mucin 5AC	36
MAP kinase pathway	CO_2	activation of MAP kinases, increase of the secretion of serotonin	CO_2 is a messenger molecule stimulating PNE cell proliferation	54,55

[a] Definitions: HCO_3^-, bicarbonates; CoA, coenzyme A; PEP, phosphoenolpyruvate; GOT, glutamic oxaloacetic transaminase; GPT, glutamic pyruvic transaminase; LDH, lactate dehydrogenase, MDH, malate dehydrogenase; PP2A, protein phosphatase 2A; NF-κB, nuclear factor kappa-light-chain-enhancer of activated B cells; IL, interleukin; MAP, mitogen-activated-proteins.

6.3 Questionnaire

Carbon Dioxide and Teachers' Health

This questionnaire is part of a study investigating the association of carbon dioxide levels and perceived air quality and the health of teachers. You responses should cover the time frame of the current school year only. Please answer honestly and to the best of your ability. All responses will be de-identified and remain confidential and secure.

1. What is your school?

2. What is your classroom number?

3. What is your gender?

- Female
- Male

4. What is your age?

- 17 or younger
- 18-20
- 21-29
- 30-39
- 40-49
- 50-59
- 60 or older

5. Please describe your race/ethnicity.

6. In what ZIP code is your home located? (enter 5-digit ZIP code; for example, 00544 or 94305)

7. Year you began teaching at current school:

8. Grades taught in the current year:

- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7

9. Approximately how many students are enrolled in your class this year?

10. Which of the following symptoms have you experienced during the workday today or during the last few workdays? (Check all that apply)

	Yes	No	Unsure	Worsens as Workday progresses	Worsens as Week progresses	Improves overnight or on Weekends or on vacation
Headache	☐	☐	☐	☐	☐	☐
Fatigue	☐	☐	☐	☐	☐	☐
Drowsiness	☐	☐	☐	☐	☐	☐
Difficulty concentrating	☐	☐	☐	☐	☐	☐
None	☐	☐	☐	☐	☐	☐

Other (please specify)

11. Over the past school year have any of these above mentioned symptoms affected your teaching?

- ◯ yes
- ◯ no
- ◯ unsure
- ◯ Not Applicable

12. How many different classrooms do you teach in at your school?

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4

13. During this school year, have you noticed any odors or fumes from the following: (Check all that apply)

- [ ] Mold
- [ ] Diesel Fumes
- [ ] Pesticides
- [ ] Arts/crafts supplies
- [ ] Whiteboard Markers
- [ ] Air freshness or perfumes
- [ ] Paint
- [ ] Construction or renovation
- [ ] Cleaning chemicals
- [ ] None

Other (please specify)

14. Have you observed any of the following conditions in the classroom you spend most time (Check all that apply)?

- [ ] Visible Mold
- [ ] Moisture Problems
- [ ] Dust
- [ ] Construction (during school hours)
- [ ] Dust reservoirs (blinds, curtains, pillows, upholstered furniture, chalkboard)
- [ ] Roaches/rodents
- [ ] Second hand smoke
- [ ] Noise (If yes - please list the noise source in comment box below)
- [ ] Not Applicable

Other (please specify)

15. The windows in my classroom:

- [ ] cannot be opened
- [ ] remain opened during the day
- [ ] I open sometimes to let fresh air in
- [ ] There are no windows
- [ ] Some windows are broken
- [ ] Other (please specify)

16. Is your desk located near the window(s)? (<5ft)

- ○ Yes
- ○ No
- ○ There are no windows in my classroom

17. Are you able to control the air conditioning/heating in your classroom?

- [ ] yes
- [ ] no
- [ ] unsure
- [ ] Not Applicable

18. Are any objects blocking the mechanical air vent grilles?

- [ ] yes
- [ ] no
- [ ] unsure
- [ ] Not Applicable

19. Do you feel the air quality in your classroom is acceptable:

- [ ] Most of the time
- [ ] Some of the time
- [ ] Rarely or never
- [ ] No and it affects my teaching
- [ ] No and the students complain

20. Which best describes the air quality in your classroom? (check all that apply)

- [ ] In the afternoon, I can feel the air in the classroom becoming more stuffy
- [ ] The air in the classroom is stuffy all the time
- [ ] I have previously complained about the air quality in this classroom
- [ ] The air quality is better in the morning than the afternoon
- [ ] The air quality is better in the afternoon than the morning
- [ ] None
- [ ] Other (please specify)

21. Do you feel like there is enough fresh air in your classroom?

- [ ] Most of the time
- [ ] Some of the time
- [ ] Rarely or never
- [ ] No and it affects my teaching
- [ ] No and the students complain

22. Do you feel like the air in your classroom is too dry?

- [ ] Most of the time
- [ ] Some of the time
- [ ] Rarely or never
- [ ] No and it affects my teaching
- [ ] No and the students complain

23. Do you feel like the air in your classroom is too humid?

- [ ] Most of the time
- [ ] Some of the time
- [ ] Rarely or never
- [ ] No and it affects my teaching
- [ ] No and the students complain

24. Do you feel like temperature in your classroom is too hot?

- [ ] Most of the time
- [ ] Some of the time
- [ ] Rarely or never
- [ ] No and it affects my teaching
- [ ] No and the students complain

25. Do you feel like temperature in your classroom is too cold?

- [ ] Most of the time
- [ ] Some of the time
- [ ] Rarely or never
- [ ] No and it affects my teaching
- [ ] No and the students complain

26. Are you able to control the temperature in your classroom?

- [ ] with a thermostat
- [ ] by opening windows
- [ ] not sure
- [ ] I cannot control the temperature in my classroom
- [ ] Other (please specify)

27. How would you rate your current stress level?

1 (minimal stress) 4 (average) 7 (high stress)

28. If you feel that there is an indoor air quality problem, does the problem occur more frequently during specific seasons of the year?

- Yes
- No
- Don't know
- Not Applicable

29. If you answered yes, rank each season from on to four as follows: 1 - season least likely to be associated with indoor air quality problems and 4- season most likely to be associated with indoor air quality problems.

- [ ] Winter (Dec-Feb)
- [ ] Spring (Mar-May)
- [ ] Summer (June- Aug)
- [ ] Fall (Sept-Nov)

30. Please check all the medications that you are taking:

- [ ] Pain relievers
- [ ] Decongestant
- [ ] Antidepressants
- [ ] Antihistamines
- [ ] None
- [ ] Other (please specify)

31. How many hours do you sleep each night?

- ○ 4 or fewer hours
- ○ About 5-6 hours
- ○ About 7-8 hours
- ○ 9 or more hours

32. Do you currently smoke cigarettes, or not?

- ○ Yes, I do
- ○ No, I do not

33. Does anyone in your household currently smoke cigarettes, or not?

- ○ Yes, someone does
- ○ No, no one does
- ○ Not sure

6.4 Technical Specifications

ONSET

HOBO® MX1102 Logger

Bluetooth Smart-enabled CO_2, temperature and relative humidity data logger

Onset's HOBO MX1102 CO_2 logger makes it more convenient than ever to measure and record CO_2 in buildings and other non-condensing environments. It measures CO_2 from 0 – 5,000 parts per million (ppm) – and our free HOBOmobile app allows you to access data right from your mobile phone or tablet within a 100-foot range.

The MX1102 also features a USB port so it can be used with a computer running HOBOware Pro graphing and analysis software.

Supported Measurements:
CO_2, Temperature, Relative Humidity, Dew Point

Key Advantages:

- Wireless communication via Bluetooth Low Energy (BLE)
- Six-month battery life at 5-minute CO_2 logging rate
- Easy to deploy and offload using free HOBOmobile App
- Visual and audible high & low alarm thresholds
- Self-calibrating CO_2 sensor technology ensures optimal accuracy at lower maintenance costs

Minimum System Requirements:

HOBO

HOBOmobile

Mobile device

Download on the App Store

ANDROID APP ON Google play

*iOS 8.3, 8.4 & 9.0, or Android 4.4, 5.0, 5.1
and Bluetooth 4.0 or later

For complete information and accessories, please visit: **www.onsetcomp.com**

Part number	MX1102
Memory	84,650 Measurements
Logging Rate	1 second to 18 hours
Battery Life	6 months, typical with logging and sampling intervals of 5 minutes or slower; 6 months or less with logging and sampling intervals faster than 5 minutes while logging CO_2, user replaceable, 4AA
Dimensions	7.62 x 12.95 x 4.78 cm (3.0 x 5.1 x 1.88 inches)
	CO_2
Range	0 to 5,000 ppm
Accuracy	±50 ppm ±5% of reading at 25°C (77°F), less than 70% RH and 1,013 mbar
Warm-up Time	15 seconds
Calibration	Auto or manual to 400 ppm
Non-linearity	<1% of FS
	Temperature
Range	0° to 50°C (32° to 122°F)
Accuracy	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F)
Resolution	0.024°C at 25°C (0.04°F at 77°F)
Response Time	12 minutes to 90% in airflow of 1 m/s (2.2 mph)
	Relative Humidity
Range	1% - 90%RH, non-condensing
Accuracy	±2.0% from 20%RH to 80%RH typical to a maximum of ±4.5% including hysteresis at 25°C (77°F); below 20%RH and above 80%RH ±6% typical
Hysteresis	±2%RH
Resolution	0.01%RH
Drift	<1%RH per year typical
Response Time	CO_2: 1 minute to 90% in airflow of 1 m/s (2.2 mph), **Temp**: 12 minutes to 90% in airflow of 1 m/s (2.2 mph), **RH**: 1 minute to 90% in airflow of 1 m/s (2.2 mph)
CE compliant	Yes

Note: Temp & RH NIST certification services available for this product. Please visit onsetcomp.com, or call us at 1-800-564-4377.

Contact Us

Sales (8am to 5pm ET, Monday through Friday)
- Email sales@onsetcomp.com
- Call 1-508-759-9500
- In U.S. toll free 1-800-564-4377
- Fax 1-508-759-9100

Technical Support (8am to 8pm ET, Monday through Friday)
- Contact Product Support onsetcomp.com/support/contact
- Call 1-508-759-9500
- In U.S. toll free 1-877-564-4377

Chapter 7. Bibliography

1. Pachauri RK, Meyer L, Van Ypersele J-P, et al. *Climate Change 2014 Synthesis Report*.; 2014.
2. Epa U. *A Standardized Epa Protocol for Characterizing Indoor Air Quality in Large Office Buildings*.; 2003. https://www.epa.gov/sites/production/files/2016-04/documents/standardized_iaq_base_protocol_for_characterizing_iaq_in_large_buildings-pdf.pdfSTANDARDIZED+EPA+PROTOCOL+FOR+CHARACTERIZING+INDOOR+AIR+QUALITY+IN+LARGE+OFFICE+BUILDINGS#7.
3. Gall ET, Cheung T, Luhung I, Schiavon S, Nazaroff WW. Real-time monitoring of personal exposures to carbon dioxide. *Build Environ*. 2016;104:59-67. doi:10.1016/j.buildenv.2016.04.021
4. Peretti C, Schiavon S. Indoor environmental quality surveys. A brief literature review. *12th Int Conf Indoor Air Qual Clim 2011*. 2011:1331-1336. http://www.scopus.com/inward/record.url?eid=2-s2.0-84880524160&partnerID=40&md5=21033d9ace5debc13fccdb1858847ae5.
5. Seppänen O a, Fisk WJ, Mendell MJ. Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air*. 1999;9(4):226-252. doi:10.1111/j.1600-0668.1999.00003.x
6. Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environ Health Perspect*. 2015;Online 26(October). doi:10.1289/ehp.1510037
7. Satish U, Mendell MJ, Shekhar K, et al. Is CO2 an indoor pollutant? direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environ Health Perspect*. 2012;120(12):1671-1677. doi:10.1289/ehp.1104789
8. Kajtár L, Herczeg L. Influence of carbon-dioxide concentration on human well-being and intensity of mental work. *Idojaras*. 2012;116(2):145-169.

9. Muscatiello N, Mccarthy A, Kielb C, Hsu WH, Hwang SA, Lin S. Classroom conditions and CO2 concentrations and teacher health symptom reporting in 10 New York State Schools. *Indoor Air*. 2015;25(2):157-167. doi:10.1111/ina.12136

10. NYC Department of Education. DOE DATA AT A Glance. https://www.schools.nyc.gov/about-us/reports/doe-data-at-a-glance. Published 2018.

11. NYC DOE. NYC DOE Division of School Facilities About Page. website. https://www.opt-osfns.org/nycdsf/dsf.aspx#page=aboutus. Published 2019.

12. NYC DOE. About NYC DOE School Construction Authority History Web Page. http://www.nycsca.org/Quick-Links-Home/About-the-SCA/History. Published 2019.

13. Suzanne Spellen. Walkabout: C.B.J. Snyder: New York City's Master School Builder. *Brownstoner*. https://www.brownstoner.com/architecture/brooklyn-school-buildings-of-architect-c-b-j-snyder/. Published September 10, 2015.

14. Lewis L, Alexander D, Ralph J. *Condition of America ' s Public School Facilities : 2012-13*. Washington, DC.; 2014. http://nces.ed.gov/pubs2014/2014022.pdf.

15. Haimson L. *Space Crunch in NYC Schools*. New York; 2015. www.classsizematters.org.

16. Petty S. *Summary of Ashrae'S Position on Carbon Dioxide Co2 Levels in Spaces*.; 2002.

17. Almeida RMSF, Pinto M, Pinho PG, de Lemos LT. Natural ventilation and indoor air quality in educational buildings: experimental assessment and improvement strategies. *Energy Effic*. 2017;10(4):839-854. doi:10.1007/s12053-016-9485-0

18. ANSI/ASHRAE. *ANSI/ASHRAE Standard 62.1-2016 Ventilation for Acceptable Indoor Air Quality*. US; 2016.

19. Daisey JM, Angell WJ, Apte MG. Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Indoor Air*. 2003;13(1):53-64. doi:10.1034/j.1600-0668.2003.00153.x

20. Miller J, Semple S, Turner S. High carbon dioxide concentrations in the classroom: the need for research on the effects of children's exposure to poor indoor air quality at school. *Occup Environ Med*. 2010;67(11):799. doi:10.1136/oem.2010.057471

21. Chatzidiakou L, Mumovic D, Summerfield A. Is CO2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants. *Build Serv Eng Res Technol*. 2015;36(2):129-161. doi:10.1177/0143624414566244

22. NYC Department of Buildings. *2014 NYC Mechanical Code*. USA; 2014. https://www1.nyc.gov/assets/buildings/apps/pdf_viewer/viewer.html?file=2014CC_MC_Chapter4_Ventilation.pdf&section=conscode_2014.
23. Buildings ND of. *NYC Building Code 1203 Ventilation*.; 2014. https://www1.nyc.gov/assets/buildings/apps/pdf_viewer/viewer.html?file=2014CC_BC_Chapter_12_Interior_Environment.pdf&section=conscode_2014.
24. Montgomery JF, Storey S, Bartlett K. Comparison of the indoor air quality in an office operating with natural or mechanical ventilation using short-term intensive pollutant monitoring. *Indoor Built Environ* . 2014;0(0):1-11. doi:10.1177/1420326X14530999
25. Sundell J, Levin H, Nazaroff WW, et al. Ventilation rates and health: Multidisciplinary review of the scientific literature. *Indoor Air*. 2011;21(3):191-204. doi:10.1111/j.1600-0668.2010.00703.x
26. (ACGIH) AC of GIH. *Industrial Ventilation: A Manual of Recommended Practice for Design, 29th Edition*. 29th ed.; 2016.
27. Yalçin N, Balta D, Özmen A. A modeling and simulation study about CO2 amount with web-based indoor air quality monitoring. *Turkish J Electr Eng Comput Sci*. 2018;26(3):139-01402. doi:10.3906/elk-1612-57
28. David H. Mudarri. *Building Codes and Indoor Air Quality*.; 2010. There is significant political and institutional momentum toward energy conservation in buildings which has led to building codes devoted solely to energy conservation, and resulted in the tightening of building envelopes and reduced air infiltration and.
29. Wyon DP. The effects of indoor air quality on performance and productivity. *Indoor Air*. 2004;14 Suppl 7(Suppl 7):92-101. doi:10.1111/j.1600-0668.2004.00278.x
30. Baker L. A History of School Design and Its Indoor Environmental Standards, 1900 to Today. *Natl Clear Educ Facil*. 2012;(January). http://pitt.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSDQzTTVPMk4FHX5unmpoBHQsMCknWhokpppamFkmoayoRCrN3YQYmFLzRBlk3FxDnD10QRMW8QWQMxfiXV1MjS1BR52IMfAmgtZ-55WA94ilAACxrhwx.
31. Gray C. Streetscapes/Charles B. J. Snyder; Architect Who Taught a Lesson in School Design. *New York Times*. https://www.nytimes.com/1999/11/21/realestate/streetscapes-charles-b-j-snyder-architect-who-taught-a-lesson-in-school-design.html. Published 1999.

32. Stein B. *Building Technology: Mechanical and Electrical Systems*. New York City: Wiley; 1997.

33. NYC.GOV. Mayor de Blasio, Chancellor Fariña and City Council Announce Every Classroom Will Have Air Conditioning by 2022. https://www1.nyc.gov/office-of-the-mayor/news/261-17/mayor-de-blasio-chancellor-fari-a-city-council-every-classroom-will-have-air. Published 2017.

34. Allen JG, MacNaughton P, Cedeno-Laurent JG, et al. Airplane pilot flight performance on 21 maneuvers in a flight simulator under varying carbon dioxide concentrations. *J Expo Sci Environ Epidemiol*. 2018. doi:10.1038/s41370-018-0055-8

35. Mirabelli MC, Wing S, Marshall SW, et al. Air pollution around schools is linked to poorer student health and academic performance. *Environ Health Perspect*. 2016;13(5):852-862. doi:10.1002/MSJ

36. Nuss HJ, Hester LL, Perry MA, Stewart-Briley C, Reagon VM, Collins P. Applying the Social Ecological Model to Creating Asthma-Friendly Schools in Louisiana. *J Sch Health*. 2016;86(3):225-232. doi:10.1111/josh.12369

37. Occupational Safety and Health Administration. Indoor Air Quality. https://www.osha.gov/SLTC/indoorairquality/faqs.html. Accessed September 5, 2019.

38. Kats G. Greening America’ s Schools - Costs and Benefits. 2006;(October):20. www.cap-e.com.

39. Clements-Croome DJ, Awbi HB, Bakó-Biró Z, Kochhar N, Williams M. Ventilation rates in schools. *Build Environ*. 2008;43(3):362-367. doi:16/j.buildenv.2006.03.018

40. Rebell M. CFE v. New York State: Past, Present and Future. *Gov Law Policy J*. 2011;13(1):24-30. http://schoolfunding.info/wp-content/uploads/2011/07/CFE-Past-Present-and-Future.pdf.

41. Service Employees Union International. *Falling Further Apart*.; 2015.

42. SCA N. *FY 2015 – 2019 PROPOSED FIVE - YEAR CAPITAL PLAN AMENDMENT*. New York City; 2017.

43. NYC DOE. *Annual Financial Statements*.; 2018.

44. Amin R. As New York City starts collecting data on inequities in PTA fundraising, the search is on for potential solutions. *Chackbeat*. https://www.chalkbeat.org/posts/ny/2018/11/02/as-city-starts-collecting-data-on-

inequities-in-pta-fundraising-the-search-is-on-for-potential-solutions/. Published 2018.

45. NY Department of Education. Demographic Snapshot of NYC Schools 2011-2015. http://schools.nyc.gov/Accountability/data/default.htm. Published 2016.

46. Hemphill BC, Mader N. Are Schools Segregated Because Housing Is ? It Ain ' t Necessarily So. http://www.centernyc.org/schoolsegregation. Published 2015. Accessed November 7, 2016.

47. Bernstein T. *Healthier Schools: A Review of State Policies for Improving Indoor Air Quality. Research Report.*; 2002.

48. Brody L. New York City Schools Plagued by Overcrowding. *Wall Street Journal*. http://www.wsj.com/articles/new-york-city-schools-plagued-by-overcrowding-1425432802. Published March 3, 2015.

49. Haimson, L, Spitz S (Class SM. *School Overcrowding & Class Size Citywide*.; 2018.

50. School Construction Authority. Building Condition Assessment Surveys. https://survey.nycsca.org/bcas/. Published 2019.

51. Education NYCD of. New York City Department of Education School Facilities Summary Website. http://schools.nyc.gov/community/facilities/BFIS/default.htm. Published 2016. Accessed January 8, 2016.

52. Wargocki P, Wyon D. The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257). *HVAC&R Res*. 2007;13(2). doi:10.1080/10789669.2008.10391012

53. Sanna E, Cuccheddu T, Serra M, Concas A, Biggio G. Carbon dioxide inhalation reduces the function of GABAA receptors in the rat brain. *Eur J Pharmacol*. 1992;216(3):457-458. doi:10.1016/0014-2999(92)90447-C

54. Chivers DP, Mccormick MI, Nilsson GE, et al. Impaired learning of predators and lower prey survival under elevated CO2: A consequence of neurotransmitter interference. *Glob Chang Biol*. 2014;20(2):515-522. doi:10.1111/gcb.12291

55. Organization World Health. *Strategic Approaches to Indoor Air Policy-Making*.; 1999. http://www.euro.who.int/document/e65523.pdf.

56. Kriebel D, Tickner J, Epstein P, et al. The precautionary principle in environmental science. *Environ Health Perspect*. 2001;109(9):871-876. doi:10.1289/ehp.01109871

57. Rosner D, Markowitz G. Industry challenges to the principle of prevention in public

health: The precautionary principle in historical perspective. *Public Health Rep*. 2002;117(6):501-512. doi:10.1016/S0033-3549(04)50195-4

58. EEA. *Late Lessons from Early Warnings: The Precautionary Principle 1896–2000*. Vol 59.; 2001. doi:10.1136/oem.59.11.789-a

59. Kielb C, Lin S, Muscatiello N, Hord W, Rogers-Harrington J, Healy J. Building-related health symptoms and classroom indoor air quality: A survey of school teachers in New York State. *Indoor Air*. 2015;25(4):371-380. doi:10.1111/ina.12154

60. Persily A. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. *Build Environ*. 2015;91:61-69. doi:10.1016/j.buildenv.2015.02.026

61. Haverinen-Shaughnessy U, Shaughnessy RJ, Cole EC, Toyinbo O, Moschandreas DJ. An assessment of indoor environmental quality in schools and its association with health and performance. *Build Environ*. 2015;93(P1):35-40. doi:10.1016/j.buildenv.2015.03.006

62. Population Division of the UN Department of Economic and Social Affairs. 68% of the world population projected to live in urban areas by 2050, says UN. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. Published 2019.

63. Edenhofer O, Pichs-Madrga R, Sokona Y, Seyboth K. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation Summary for Policymakers. *Intergov Panel Clim Chang*. 2011;(May 2011):1-24.

64. Jiang C, Rojas A, Wang R, Wang X. CO2central chemosensitivity: Why are there so many sensing molecules? *Respir Physiol Neurobiol*. 2005;145(2-3):115-126. doi:10.1016/j.resp.2004.07.005

65. Diaper A, Nutt DJ, Munafò MR, White JL, Farmer EW, Bailey JE. The effects of 7.5% carbon dioxide inhalation on task performance in healthy volunteers. *J Psychopharmacol*. 2012;26(4):487-496. doi:10.1177/0269881111415729

66. Guais A, Brand G, Jacquot L, et al. Toxicity of carbon dioxide: A review. *Chem Res Toxicol*. 2011;24(12):2061-2070. doi:10.1021/tx200220r

67. Battisti-Charbonney A, Fisher J, Duffin J. The cerebrovascular response to carbon dioxide in humans. *J Physiol*. 2011;589(Pt 12):3039-3048. doi:10.1113/jphysiol.2011.206052

68. Jung CC, Liang HH, Lee HL, Hsu NY, Su HJ. Allostatic load model associated with

indoor environmental quality and sick building syndrome among office workers. *PLoS One*. 2014;9(4):2-8. doi:10.1371/journal.pone.0095791

69. McEwen BS. Stressed or stressed out: What is the difference? *J Psychiatry Neurosci*. 2005;30(5):315-318.
70. Lu et al. Oxidative DNA damage estimated by urinary 8-hydroxydeoxyguanosine and indoor air pollution among non-smoking office employees. *Environ Res*. 2007;103(3):331-337.
71. Kiray M, Sisman A, Camsari U, et al. Effects of carbon dioxide exposure on early brain development in rats. *Biotech Histochem*. 2014;89(5):371-383. doi:10.3109/10520295.2013.872298
72. (ACGIH) American Conference of Governmental Industrial Hygienists. *TLV Documentation for Carbon Dioxide*.; 2001.
73. Xu F, Uh J, Brier MR, et al. The influence of carbon dioxide on brain activity and metabolism in conscious humans. *J Cereb Blood Flow Metab*. 2011;31(1):58-67. doi:10.1038/jcbfm.2010.153
74. Law J et al. Relationship between carbon dioxide levels and reported headaches on the international space station. *J Occup Env Med*. 2014;56(38):477-483.
75. Maddalena R, et al. Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making. *Indoor Air*. 2015;25:362-370.
76. Vehvilainen T y, Lindholm H, Rintamaki H, et al. High indoor CO2 concentrations in an office environment increases the transcutaneous CO2 level and sleepiness during cognitive work. *J Occup Environ Hyg*. 2016;13(1):19-29. doi:10.1080/15459624.2015.1076160
77. Zhang X, Wargocki P, Lian Z. Effects of Exposure to Carbon Dioxide and Human Bioeffluents on Cognitive Performance. *Procedia Eng*. 2015;121:138-142. doi:10.1016/j.proeng.2015.08.1040
78. Zhang X, Wargocki P, Lian Z, Thyregod C. Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance. *Indoor Air*. 2017;27(1):47-64. doi:10.1111/ina.12284
79. Haverinen-Shaughnessy U, Moschandreas DJ, Shaughnessy RJ. Association between

substandard classroom ventilation rates and students' academic achievement. *Indoor Air*. 2011;21(2):121-131. doi:10.1111/j.1600-0668.2010.00686.x

80. Twardella D, Matzen W, Lahrz T, et al. Effect of classroom air quality on students' concentration: Results of a cluster-randomized cross-over experimental study. *Indoor Air*. 2012;22(5):378-387. doi:10.1111/j.1600-0668.2012.00774.x
81. Sidorin DI. Dynamics of carbon dioxide concentrations in the air and its effect on the cognitive ability of school students. *Izv Atmos Ocean Phys*. 2015;51(8):871-879. doi:10.1134/S000143381508006X
82. Gaihre S, Semple S, Miller J, Fielding S, Turner S. Classroom carbon dioxide concentration, school attendance, and educational attainment. *J Sch Health*. 2014;84(9):569-574. doi:10.1111/josh.12183
83. Riham Jaber A, Dejan M, Marcella U. The Effect of Indoor Temperature and CO2Levels on Cognitive Performance of Adult Females in a University Building in Saudi Arabia. *Energy Procedia*. 2017;122:451-456. doi:10.1016/j.egypro.2017.07.378
84. U.S. Department of Labor Occupational Safety and Health Administration O. *TABLE Z-1 LIMITS FOR AIR CONTAMINANTS*. U.S. https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9992.
85. NYC. SUBCHAPTER 12 LIGHT, HEAT, VENTILATION, AND NOISE CONTROL. http://www.nyc.gov/html/dob/downloads/bldgs_code/bc27s12.pdf.
86. European Committee for Standardization (CEN). *1752, CEN - CR Environment, Ventilation for Buildings - Design Criteria for the Indoor*.; 1998:1-76.
87. Health Canada. *Exposure Guidelines for Residential Indoor Air Quality: A Report of the Federal-Provincial Advisory Committee on Environmental and Occupational Health. Ottawa*.; 1995. www.hcsc. gc.ca/hecssesc/air_quality/pdf/tr-156.pdf.
88. Waters M, Mckernan L, Maier A, et al. Exposure Estimation and Interpretation of Occupational Risk : Enhanced Information for the Occupational Risk Manager Exposure Estimation and Interpretation of Occupational Risk : Enhanced Information for the Occupational Risk Manager. *J Occup Environ Hyg*. 2015;12. doi:10.1080/15459624.2015.1084421
89. Faria NA, Wai K, Version D. *Building Certification Schemes and the Quality of Indoor*

Environment.; 2015.

90. Fisk W. The ventilation problem in schools: literature review. *Indoor Air J*. 2017. doi:10.1111/ina.12403

91. Madureira J, Paci??ncia I, Rufo J, et al. Indoor air quality in schools and its relationship with children's respiratory symptoms. *Atmos Environ*. 2015;118:145-156. doi:10.1016/j.atmosenv.2015.07.028

92. School Construction Authority. *DOE Building Space Usage*.; 2019. https://data.cityofnewyork.us/Education/DOE-Building-Space-Usage/wavz-fkw8.

93. Skön J, Johansson, Raatikainen M, Leiviskä K, Kolehmainen M. Modelling Indoor Air Carbon Dioxide (CO2) Concentration using Neural Network. *World Acad Sci Eng Technol Int Sci Index*. 2012;6(1):737-741. http://waset.org/Publication/modelling-indoor-air-carbon-dioxide-co2-concentration-using-neural-network/11723.

94. Savitz DA, Bobb JF, Carr JL, et al. Ambient fine particulate matter, nitrogen dioxide, and term birth weight in new york, new york. *Am J Epidemiol*. 2014;179(4):457-466. doi:10.1093/aje/kwt268

95. Lahtinen M. Psychosocial work environment and indoor air problems: a questionnaire as a means of problem diagnosis. *Occup Environ Med*. 2004;61(2):143-149. doi:10.1136/oem.2002.005835

96. Bowling A. Mode of questionnaire administration can have serious effects on data quality. *J Public Health (Bangkok)*. 2005;27(3):281-291. doi:10.1093/pubmed/fdi031

97. Wong LT, Mui KW, Hui PS. A statistical model for characterizing common air pollutants in air-conditioned offices. *Atmos Environ*. 2006;40:4246–4257.

98. Norbäck D, Nordström K, Zhao Z. Carbon dioxide (CO2) demand-controlled ventilation in university computer classrooms and possible effects on headache, fatigue and perceived indoor environment: An intervention study. *Int Arch Occup Environ Health*. 2013;86(2):199-209. doi:10.1007/s00420-012-0756-6

99. Wargocki P, Da Silva NAF. Use of visual CO2 feedback as a retrofit solution for improving classroom air quality. *Indoor Air*. 2015;25(1):105-114. doi:10.1111/ina.12119

100. Rosbach JTM, Vonk M, Duijm F, van Ginkel JT, Gehring U, Brunekreef B. A ventilation intervention study in classrooms to improve indoor air quality: the FRESH study. *Environ Health*. 2013;12:110. doi:10.1186/1476-069X-12-110

101. Gay JL, Evenson KR, Smith J. Developing measures on the perceptions of the built environment for physical activity: a confirmatory analysis. *Int J Behav Nutr Phys Act*. 2010;7(1):72. doi:10.1186/1479-5868-7-72