Opportunities and Challenges in Monitoring the Thermal Performance of Passive Buildings in India

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ABSTRACT

In the context of climate change, reduction in operational energy of buildings has gained a prominent focus amongst researchers and practitioners. India and the U.S. have both used design strategies to provide comfortable indoor environments with no or marginal reliance on conventional energy sources, but often with significant differences in their approaches and historical context. In particular, certain locations in both countries offer opportunities to design and operate buildings that are naturally ventilated or mixed-mode (combining operable windows and mechanical cooling). Historical or vernacular case studies have provided empirical evidence of climate responsiveness, however the lessons learned have not been deployed in the mainstream. Absence of rigorous performance evaluation might be one of the reasons behind the lack of large scale deployment of such design strategies.

This paper documents the challenges and lessons learned from an extensive monitoring study undertaken in India. It forms a part of a larger project that aims at formulating a set of protocols of such field monitoring activity and evaluating the performance of selected passive strategies. Observations were made for each stage of monitoring, from building selection to data quality assurance. We found that many buildings were not necessarily constructed or operated as originally designed vis-à-vis the passive strategies we were studying. In some cases the physical components of a passive strategies were not maintained properly. Our experience also emphasizes the importance of having a local champion in the building being monitored. We realized the significance of understanding the trade-offs between the quality and extent of instrumentation as well as the value of allowing flexibility in the monitoring plan to make real-time changes on site.

Introduction

India is the world's fourth largest carbon emitter and is also highly vulnerable to the adverse impacts of climate change (Government of India 2015). Construction of new buildings in India has experienced an expenditure growth of 7% in 2013, and this addition of new floor space also led to a significant rise in energy consumption. A majority of new construction is in the urban areas where 37% of Indian population lives. Of this, 50% lives either in warm and humid and hot and dry climate zones (Census Organization of India 2011). Compared to business-as-usual buildings, climate responsive building design can increase the amount of comfort hours without the use of active cooling systems, and can help reduce the installed capacity of cooling systems and overall cooling energy consumption.

India has five distinct climate zones – hot and dry, warm and humid, composite, moderate and cold. Each climate zone offers the opportunity to operate buildings in natural ventilation (NV) mode or mixed-mode (MM) that combine both natural ventilation and low-energy mechanical systems. In a very significant step towards reducing energy consumption in buildings without compromising on thermal comfort and productivity, the Bureau of Indian Standards (BIS) has included an adaptive thermal comfort approach as part of the upcoming revision of the National Building Code (Bureau of Indian Standards 2005), based on an India-specific model for adaptive thermal comfort (Manu et al. 2016). By expanding the otherwise narrow band of temperatures that are considered comfortable, buildings designed to comply with the adaptive thermal comfort model will be more energy efficient. Energy simulation based studies suggest that 5-6% of EPI savings may be accrued over a degree increase in thermostat set-point temperature (Manu et al. 2011).

Recent advances in building envelope material and construction technology, low energy cooling systems, building performance simulation technology, and ‘easy to use’ graphical user interfaces (GUI), have all helped stakeholders involved in building design and operation to evaluate energy and comfort performance of buildings at the design stage (Clarke 2015). Despite this extensive body of knowledge within the scientific community, it has not had a widespread, transformative effect on the contemporary building stock, and so the mainstreaming of climate responsive architecture has remained a distant reality. Only a fraction of architectural practices in the last couple of decades have relied on ‘common sense’ approaches to designing low-energy climate responsive buildings.

When designing for low energy, the highest priorities should be to reduce both internal and external loads. External loads should be addressed through good envelope design, along with climate-responsive strategies for passive heating and cooling (McGregor, Roberts, and Cousins 2012). Yet, there has been limited assessment of the potential for passive strategies to impact energy use in the commercial building stock compared to residential. There is also a need for more field assessments of how these passive strategies impact the indoor thermal environments and resulting comfort conditions. One example of a project that compared various field studies in mechanically-conditioned office buildings in the U.S. found that buildings are often overcooled, creating problems with both thermal comfort and poor indoor air quality, as well as significant wasted energy (Mendell and Mirer 2009). But such post-occupancy evaluations (POEs) in both the U.S. and India are rare in the building industry, and particularly for climate-responsive buildings. While even one-time or occasional POE’s have led to building owners making design or operational changes in existing buildings, there clearly remains a critical need to create more frequent, ongoing feedback about the impacts of building design on indoor thermal performance to help building designers, owners, and operators make more informed decisions.

There are many barriers to why we are not seeing more of these essential feedback loops for building performance (Brown and Arens 2012). The most common method for ongoing assessment of indoor thermal conditions in a commercial building would be through the building management system (BMS), which generally monitors and controls the heating and cooling mechanical systems. We are starting to see some promising experimentation in buildings with dashboard-based systems for gathering more frequent, real-time feedback from occupants and linking that to the BMS, but this remains in the early stages. But in passive buildings, unless they are hybrid or mixed-mode (combining both operable windows and mechanical cooling), a BMS might not even exist.

The U.S.-India Joint Center for Building Energy Research and Development (CBERD), is a collaboration between five organizations in the U.S. (led by LBNL), and six in India (led by CEPT University). The work described in this paper is part of Task 6: Climate Responsive Design, whose broad purpose is to better understand the performance of climate responsive buildings in terms of their indoor thermal environments. This project provides an opportunity for a unique collaboration between academic researchers in both the U.S. and India with combined backgrounds in architecture, mechanical engineering, and building physics. This paper documents some of the opportunities and challenges revealed by a part of this project - an extensive monitoring study being undertaken in India to understand the performance of selected prominent climate responsive buildings.

Description of Buildings

In selecting buildings for monitoring, we tried to capture the varied passive design strategies used in the different climatic, geographical and cultural contexts of the Indian subcontinent. Owing to the vast and varied geographical area that the country covers, India has an extensive range of climatic conditions. The National Building Code (NBC) of India (Bureau of Indian Standards 2005) refers to five-zone classification, which was used for this study (Figure 1). We have conducted long-term monitoring in seven buildings in the warm/humid climate of Auroville, and in six buildings in broader Indian climate zones to document a wide range of climate responsive strategies.

The seven buildings (W1-W7) being monitored in the broader climate zones are all commercial (office) buildings, and are complex in their energy efficiency strategies, including being mixed-mode (combination of operable windows and mechanical cooling). In these buildings, extensive instrumentation has typically been distributed throughout the buildings for more whole-building monitoring of indoor thermal conditions. The seven buildings in Auroville (C1-C7) are smaller in size, ranging from individual and shared residences to light commercial, and are all naturally ventilated. Due to limitations in available instrumentation, in some cases monitoring often focused on documenting specific components of the building. The climate-responsive characteristics of these buildings, as well as the periods of time over which we monitored are summarized below in Table 1.

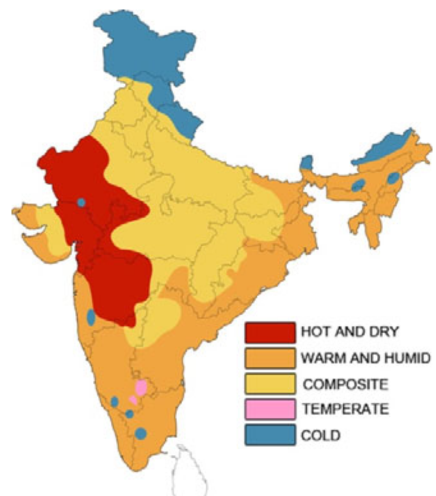


Figure 1 Climate zone map of India

Table 1 List of buildings being monitored

Code	Type	Climate zone (City)	Area (m^2)	Strategy	Monitoring period	No. of sensors
W1	Institutional	Warm & humid (Pune)	18670	Detached façade, shaded courtyard, stack ventilation	Sep 2014 to Aug 2015	42
W2	Office (Public)	Composite (Chandigarh)	5100	Solar chimney (stack ventilation), evaporative cooling Stack effect	Mar 2014 to Apr 2015	96
W3	Institutional	Hot & dry (Ahmedabad)	2500	Wall and roof cavity, thermal mass, cross ventilation	Jun 2014 to May 2015	33
W4	Institutional	Composite (Delhi)	4310	Radiant cooling, cool roof, shading	Feb 2015 to Feb 2016	130
W5	Institutional	Hot & Dry (Ahmedabad)	1200	Stratification, cross ventilation, thermal Mass	Feb 2015 to Feb 2016	51
W6	Office (Private)	Hot & Dry (Anand)	320	Stratification, earth berm	Jun 2015 to present	38
W7	Institutional	Temperate (Bangalore)	3526	Solar Chimney, Stratification, Coffer Slab	Feb 2016 to present	61

Code	Type	Climate zone (City)	Area (m^2)	Strategy	Monitoring period	No. of sensors
C1	Dormitory	Warm & Humid	2324	Ventilated roof, cavity walls, cross ventilation	Sep 2014 to Oct 2015	49
C2	Residential	Warm & Humid	276	Composite walls, insulated roof, shading, thermal mass with night ventilation	Aug 2013 to Oct 2014	22
C3	Residential	Warm & Humid	220	Thermal mass, stack ventilation	Aug 2013 to Feb 2015	29
C4	Residential	Warm & Humid	1813	Cavity wall, cross ventilation	Sep 2013 to Oct 2014	15
C5	Hospitality	Warm & Humid	414	Shading, double roof, micro climate	Aug 2013 to Apr 2015	14
C6	Community	Warm & Humid	1700	Solar chimney (stack ventilation)	Jan 2014 to Mar 2015	4
C7	Institutional	Warm & Humid	388	Thermal mass, courtyard	Nov 2013 to Feb 2015	8

Challenges and lessons learned

Building selection

Our primary criterion for building selection was to find ones that were designed intentionally to operate as climate responsive buildings in a way that that the strategies were a recognizable architectural feature, and there was an opportunity for their performance to be quantified. For example, a building may be optimized in terms of its orientation but it is not possible to quantify the relative impact of this strategy unless we monitor a building that is exactly the same except with a different orientation. In contrast, the relative impact of a solar chimney can be quantified by looking at the days when it is or is not in operation, or how it operates in different climatic conditions throughout a year. Institutional/ commercial buildings that fulfilled this criteria were very limited. Historically, building construction, primarily of residences, has been a part of the traditional wisdom passed on from one generation to others where the environmental, cultural, social and economic aspects merged and become one to inform the design. During the late 20th century these layers became more distinct, particularly the environmental dimension. With the advent of glazing and air-conditioning, from an integral aspect of design ‘sustainability’ became an ‘add-on’ feature. From 1980’s architects have been designing such buildings using initial trial and error and learning by doing. This approach is easier to deploy in small scale buildings such as residences compared to more complex functions such as offices and institutional buildings.

There are other reasons that impact original design intentions. Rising thermal comfort expectations have led to air conditioning (AC) retrofits in buildings that were originally designed to operate exclusively in passive, or free-running mode. Or in some of these buildings, the passive features did not functioning properly because of lack of maintenance, which is an important issue in a dusty and humid outdoor conditions in India. A very common example is windows for natural ventilation. There were instances where the windows were poorly maintained and eventually became inoperable. Many contemporary buildings simply install AC in buildings with inefficient envelopes because that is easier than going through the process of designing, building and operating it as a passive building. The architect may not have the technical knowledge and skills to implement passive design strategies. As such, they may decide not to consider climate or other contextual factors that impact thermal performance, and simply hand over the responsibilities for environmental conditioning to the design and operations engineers.

There is extensive written material that celebrates the traditional wisdom of Indian architecture and the many buildings that have been designed based on a sensitivity of the climatic, social and cultural context. These buildings are widely acclaimed for their architectural design and are often used as case studies as part of the architectural curricula. Most of this documentation, however, is limited to the conceptual idea and the design process. Whether these buildings continue to operate as designed and meet comfort expectation is a question that is often missing from the architectural debate. During the process of building recruitment for this project, we found that many of these buildings were documented incorrectly. The climate responsive strategies that were attributed to some of these buildings were either missing from the real building or were not working effectively. In multiple cases, the architectural feature had become dysfunctional and the strategy wasn't operational. In others, the buildings were retrofitted with AC, so strategies such as cross ventilation became redundant for most part of the year.

Intent, design and execution

Figure 2 Solar chimneys on the façade and misters in the courtyard in building W2

In many of the buildings we investigated, we found a gap in the design intent and its execution in the actual building. This gap may have been a result of lack of technical knowledge at the design stage where the architect or the designer did not know how to translate a strategy into a functional architectural element. It is also possible that the design was technically correct but changes were made during the construction. As one example, building W2 uses solar chimneys for stack ventilation. It has five chimneys on the façade and two in the courtyard, all facing south. The chimneys on the façade are covered with high performance glazing as shown in **Error! Reference source not found.**. The intent of a solar chimney is that the solar radiation would heat up the air, creating a strong buoyancy-driven upward flow, which would then draw air in from the indoor spaces and serve as an exhaust. But this façade also has horizontal projections at multiple levels that serve as overhangs to reduce solar gain from the façade. While this would be very effective if they were protecting an interior space, they are instead protecting the chimneys, where the direct radiation was an essential part of their operation, now making them less effective. From this case study we realized that style and aesthetics sometimes take precedence over climate responsiveness in building design resulting in buildings that may be celebrated for their design intent rather than correct technical execution of a climate responsive strategy.

Access and privacy

One of the objectives of the monitoring activity was to understand the performance of the building with changing outdoor conditions. We wanted to monitor these buildings over a long term period and gather data for all seasons. It was important to get continued access to the buildings to make sure the loggers could be installed for a period of one year. What we realized, however, was that getting access to buildings for installing sensors was not enough. We also had to find a local champion who would agree to partner with us on this activity on an ongoing basis, especially for buildings that were located in other cities. It was important for the local contact to have a technical understanding of monitoring as well as a commitment to follow up with the research team located in a different city. As one example, we were not able to find any local help for building W2 located in Chandigarh. That made it difficult to download data from the loggers as frequently as needed. We had to send a researcher from Ahmedabad to retrieve data every three months, as compared to other buildings where the download intervals were less than one month. Frequent site visits also help ensure logger and data safety.

In building C2, which was a residential building in Auroville, the occupants were not willing to install loggers in their bedroom because they were of the opinion that the loggers would generate harmonics, similar to many powered systems and they said this would disturb their meditation and sleep. As much as we tried to convince them that this wouldn’t be a problem, we could not install the loggers in that room during the first round of installation. After a few weeks, when they did not experience any disturbances from other loggers installed at their residence, they let us install loggers in their bedroom.

In building W3 we wanted to understand the performance of the roof and wall cavity on the top floor which was exposed to solar radiation. Most of this floor was a dormitory. We installed the loggers, but every time we went to the site to download the data we either found the loggers were moved elsewhere or missing altogether. The dormitory housed workshop participants so the occupancy was transient and the occupants changed every so often. Whenever a new group of occupants came, they felt that the loggers invaded their privacy, perhaps because they were unaware of the objectives of this monitoring work. Uninformed occupants in this case led to frequent logger tampering which resulted in data loss.

Monitoring design

Once a building was identified for monitoring and the permissions were in place, we would use the drawings to develop the monitoring plan. For each building, we developed a set of research questions pertaining to the specific climate responsive strategies deployed in the building. An example of a research question for building W2 (Figure 2): “How does the air temperature inside the solar chimney and in the room adjacent to the chimney vary with the air temperature outdoors?” Then an instrumentation plan was developed by identifying potential logger positions on the plans. The objective of this exercise was to record as much data as possible to help answer the research questions. The environmental parameters that were monitored extensively were air temperature and relative humidity. Globe temperature was monitored in selected spaces to understand the impact of radiant surfaces, wherever they were present. Air speed was measured in few buildings using hand-held instruments for selected days during the one-year long monitoring. It is important to note here that the monitored parameters remained the same for all passive strategies. The difference was in the way the data was analyzed to answer the specific research questions.

In field studies, it is near impossible to isolate the impact of one strategy from other variables that affect its performance. One example is building W2, where the courtyard had a series of misters that were used for evaporative cooling during summer and the courtyard and façade had solar chimneys to enable stack ventilation (Figure 2). Rooms that were served by the chimneys were also open to the courtyard and consequently affected by both strategies. So while the research questions were specific and detailed, it was difficult to separately quantify the impact of a specific strategy. In buildings that are designed to operate in passive mode throughout the year, a combination of passive strategies are deployed to take advantage of all opportunities available on site and maximize comfort.

There are always trade-offs between instrumentation and cost. We could not monitor every point of interest. Instead we had to optimize the instrumentation to make sure we had enough data to quantify the performance of the climate responsive strategies. This also enabled us to monitor multiple buildings concurrently.

We could not identify any cost-effective way of accurately monitoring air speed at the low speeds that exist indoors, and this remains a widespread problem in both the industry and academia. Instruments that are able to log low air speed were expensive and the project budget did not allow us to procure them. At multiple places, we used a proxy environmental parameter in place of air speed to understand and evaluate the impact of ventilation strategies. For example, in instances where we wanted to study stack ventilation, which occurs due to temperature and pressure differentials in a building, we looked at stratification instead and measured air temperature at multiple heights. Similarly, in absence of a flux meter to measure the performance of an insulated or cavity wall, we measured internal and external surface temperatures, the results of which are indicated in Figure 3 for building W3.

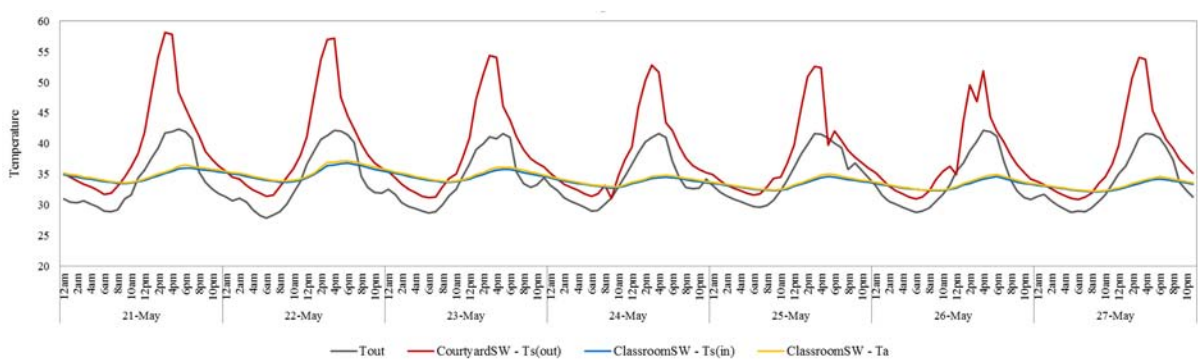
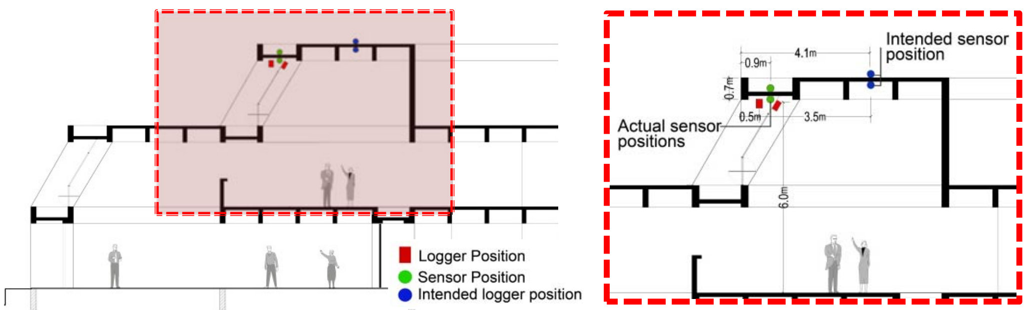


Figure 3 Hourly variation of unshaded cavity wall surface temperatures during the 'warm week' in building W3

Instrumentation

The quality and reliability of instrumentation is perhaps the most important part of monitoring. In a majority of the cases, the pre-determined monitoring plan had to be changed on site at the time of installation of loggers. The degree of change depended on the quality and detail of documentation that was provided to us by the building managers or owners. In many cases, the drawings we received were either incomplete or erroneous. Then there were cases where the drawings were outdated and the actual building was different. In such cases we were either not able to design a detailed monitoring plan prior to the installation or had to alter it significantly on site. But even in cases where we had all the requisite documentation, minor alterations in the monitoring plan were made because we realized that we could not install a logger at the location we had identified in the drawings for multiple reasons - it would be exposed to direct solar radiation or rainfall; there was a chance of tampering; it would be too visible and become an eyesore in terms of aesthetics; the logger would not be easily accessible if installed at that location.

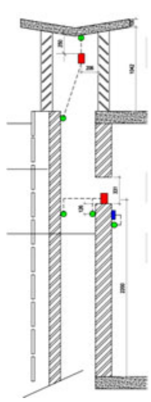
There were times when we installed loggers at points where accessibility to the logger would have been difficult because installation is a one-time effort. But access to such loggers was challenging for researchers when they had to connect their laptop to the logger to download the data every month. Figure 4 shows a set of sensors installed in building W5 to monitor external and internal roof surface temperatures. The sensors were connected to the logger by an external channel. The height of the logger was 6m from the finished floor level making it difficult to download data monthly. To minimize the effort, we started downloading the data once in every two months. The same figure also shows the intended location of the surface temperature sensors. Since the length of the connector cable (between the sensor and the logger) is restricted to 2m, we had to adjust the sensor location.

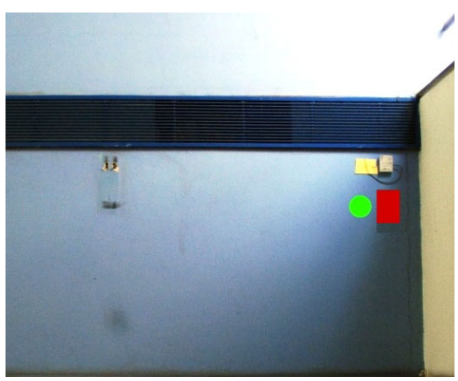


(a) Cross-sections showing 'intended' and actual logger positions


(b) Interior photo of the space in (a)

Figure 4 Roof surface temperature monitoring in building W5


(a) cavity wall and solar chimney cross-section


(b) Interior photo of the solar chimney-cavity wall showing the logger positions


(c) Photo showing logger positions inside solar chimney

Figure 5 Wall cavity monitoring in building W7

In building W7 we wanted to monitor the performance of the 'punctuated' cavity in the south wall. The cavity did not run across the length of the wall but was punctuated by a solid wall at fixed intervals, mimicking a solar chimney of sorts (Figure 5a). The south wall also had a vent on the terrace but this vent was in the spaces adjoining the south wall and disconnected from the cavity. In order to install loggers inside the cavity space, we had to get the blue grill in Figure 5b removed.

Documentation

Documentation of the monitoring plan and logger positions was done through a combination of drawings, photographs and tables. We learned the value of documenting the logger positions on site at the time of installation after the first few case studies. Any delays in this process often makes it difficult to remember the exact sensor and logger positions forcing the researchers to fill those gaps from their memory. We realized that spending half a day on site after installation for documentation and correction of drawings is an exercise that saves a lot of time later.

Templates for documenting logger positions and tracking sheets were prepared for each building to go with the drawings and the photographs. It included details such as the logger number and position, date of installation and checking, battery and memory status and the condition of the logger. It assisted in keeping track of loggers that were missing, fallen or tampered in any way that was visually evident. The data was usually downloaded once in every 15 days for the first two months and every 30 days thereafter. This documentation was very useful when new team members took over from their colleagues. It also helped share a complex monitoring plan with the building owners and local contact with ease.

Data quality assurance

Due to extensive tampering of the loggers, considerably large sets of data was either missing or deemed erroneous. A simple quality assurance of the data was done to identify isolated instances of missing and erroneous data points. First, after all the data was merged into one spreadsheet, an identifier code (“*”) was inserted for missing data, and an inventory sheet summarized the dates of all missing data for each space. Finally a summary of the erroneous and missing data was prepared to quantify data loss (see example in Table 2). For the first stage of quality assurance, we identified acceptable ranges for each environmental parameter:

- Air temperature: 0 to 60°C
- Globe temperature: 0 to 60°C
- Surface temperature: 0 to 60°C
- Relative humidity: 5 to 100%
- Light levels: 0 to 1100 lux

Data points that were not within these ranges were highlighted. All erroneous data points occurring as a continuous series were removed and marked with an ‘N/A’ identifier, and again an inventory sheet summarized the dates for each space. Erroneous data points occurring in isolated instances was removed and replaced with interpolated values. An example is presented in Table 3.

Meteorological data was requisitioned from an online weather source (http://www.worldweatheronline.com/) for locations where we did not have our own weather station data (locations other than Ahmedabad). Hourly outdoor data for air temperature, relative humidity, and wind speed available online had a time stamp that was off by 30-minutes compared to the indoor monitoring data. This means that while the building monitoring data was recorded at 9:00 am and then 10:00 am, the outdoor data we had was for the hours of 8:30 am, 9:30 am and 10:30 am, for example. In order to align the outdoor data with the indoor data, we interpolated the former by taking an average of the two hourly values to get a value for the intermediate time step.

Table 2 A sample of missing and erroneous data summary

Parameter	*Incorrect data (%)*	*Missing data (%)*	*Total data loss (%)*
ClassroomSE - Ta	0.1	0	0.1
Courtyard - RH	0.1	30.2	30.3
CourtyardSW - Ts(out)	2.7	30.2	32.9
Passage - lux	0.3	41.9	42.2

Table 3 A sample of the erroneous data QA and corrections sheet for building W3

Date	*Time*	*Erroneous data*	*Interpolated data*
Admin - Tg			
13-08-2014	16:00:00	138.7	30.12
16-08-2014	07:00:00	-94.8	29.49
16-08-2014	08:00:00	98.4	29.09
AdminNE – Ts(in)			
13-08-2014	16:00:00	163.0	30.21
16-08-2014	08:00:00	162.3	29.14

Discussion

Our study focuses on climate responsive buildings to evaluate the impact of specific passive design strategies on the indoor thermal environment. The monitoring is on-going, and future publications will speak more to the performance of these strategies. In this paper we have discussed the challenges of monitoring passive buildings in the cooling dominated climate zones of India. We have also tried to articulate our learnings on the ways to address some of these challenges.

It was difficult to find commercial buildings that relied exclusively on passive strategies. One reason is that it is relatively easier to design a building and simply use AC to cool it; designing a building to operate in passive mode is more difficult and requires a lot of technical knowledge in design and execution. Formal channels for disseminating this knowledge were found to be missing in academics and research and this realization formed the genesis of this study. In the long run, our industry requires a much larger set of field studies that uses a common set of protocols (instrumentation kits, data acquisition, quality assurance, data visualization, etc.) and analytical frameworks for assessing the performance of passive buildings. Our study hopes to contribute to that effort by sharing our own experiences, and providing guidance for future researchers towards their monitoring projects.

The importance of collaboration in long-term field monitoring cannot be exaggerated. A researcher interacts with multiple stakeholders during various stages of the study. Personal and professional relationships help obtaining access and monitoring permissions. Local contact helps champion the cause and coordinates with the off-site research team for periodic logging of the data, tracking the loggers and replacing them if needed. It is very important to talk to the building owners and occupants about the monitoring work and explain its importance so they can become an active stakeholder in the process. This can be done through briefing meetings and sending graphical mailers that explain the objectives of the research work without being excessively technical. The most important message to the occupants is the assurance that the monitoring will be unobtrusive and will not affect their health and privacy.

We also realised the importance of preparing a detailed monitoring plan before the instrumentation on site. This includes identifying the research questions, parameters to be monitoring and the sensor and logger positions. This helps save time and resources (number of loggers). But more importantly, researchers must visit the site before preparing the plan because drawings rarely capture all the details that become critical during installation. The plan should be flexible enough to enable minor changes on site at the time of installation. It should also be address issues that may not be apparent at the time but may surface during the monitoring period, such as tampering, theft, extreme outdoor conditions (storm and torrential rains), damage done by animals (monkeys and rats).

There are a few technological challenges that may be solved by research-industry collaboration. Currently, ‘stand-alone’ sensors are the most cost-effective way to log environmental data. They are easy to install; they are wireless so do not affect the aesthetics of the building. But they require manual data download periodically and may need a change of batteries. Wired loggers, on the other hand, do not need manual download but are difficult to install because of all the wiring. The other challenge has to do with not being able to monitor air velocity and heat flux in a cost-effective way using compact instrumentation.

Conclusion

This paper uses an ongoing monitoring study being undertaken in India to identify some of the opportunities and challenges associated with trying to understand the indoor environments of climate responsive buildings that collectively incorporate a wide range of passive strategies. Thirteen buildings are being monitored, each over a 1-year period. They include seven buildings in the warm/humid climate of Auroville, and six buildings in broader Indian climate zones.

We found that many of these buildings were not necessarily constructed or operated as originally designed. In some cases, the details in the design drawings simply did not exist in the actual building, or had been altered significantly, perhaps suggesting that the builders did not have sufficient technical knowledge. Some buildings appear to have been constructed properly, but were later retrofitted with air conditioning to meet changing thermal comfort expectations, or because of the increase in internal loads associated with the rise in computer use. In other examples, some of the climate responsive features weren’t getting maintained properly and stopped working as effectively. These examples suggest the importance of clear and ongoing communication between the architect, contractor, building owner and operator, and occupants.

Having a local champion in a building you want to monitor, particularly if you are planning to collect data over a long period, is critically important. This is not only for getting the initial access, but also for assistance with checking the status of the sensors, and to help download data. That person can also be an important liaison to the occupants of the building, to help educate them about the purpose of the study, and to ask that they not tamper with the equipment – which was often a problem in some of the circumstances.

As is likely a challenge for many researchers, there is always a trade-off between the quality and extent of instrumentation one would like to utilize in a study, and the money that is available. Preliminary spot measurements can sometimes help to identify how much a particularly parameter might change throughout the building, thus leading to a decision to use fewer sensors (for example temperature vs. humidity). Air speed represents the most challenging variable to measure, as there are limited cost-effective ways of measuring the low velocities that typically exist indoors. Developments in sensor technology in this area would be tremendous boon for our industry.

Flexibility is a required trait for field researchers! Regardless of how detailed one’s preliminary monitoring plan is, one needs to always be prepared for making real-time changes on site, either because of differences between the drawings and the actual building, and challenges in accessibility, or installing sensors where they would not be intrusive or prone to tampering.

While this paper was written from our own personal experiences doing monitoring in India, not all of the lessons learned are unique to this country, or in fact to developing countries in general. It is our hope that this information is helpful to other field researchers, particularly those who are junior and may be doing this for the first time. This is an on-going project, and future publications will focus on the performance of these climate-responsive strategies, and provide guidance for what features were most successful.

References

Brown, Karl, and Edward Arens. 2012. "Broken Information Feedback Loops Prevent Good Building Energy Performance – Integrated Technological and Sociological Fixes Are Needed." In *Proceedings, 2012 ACEEE Summer Study on Energy Efficiency in Buildings*, 59–70. Monterey, California: American Council for an Energy-Efficient Economy. http://aceee.org/files/proceedings/2012/data/papers/0193-000391.pdf.

Bureau of Indian Standards. 2005. *National Building Code of India 2005*. Edited by Mazdoor Kisan, Shakti Sangathan, Jawaharlal Nehru, and Satyanarayan Gangaram Pitroda. New Delhi: Bureau of Indian Standards.

Census Organization of India. 2011. "City Census 2011." *Census 2011*. http://www.census2011.co.in/city.php.

Clarke, Joe. 2015. "A Vision for Building Performance Simulation: A Position Paper Prepared on Behalf of the IBPSA Board." *Journal of Building Performance Simulation* 8 (2): 39–43. doi:10.1080/19401493.2015.1007699.

Government of India. 2015. "India's Intended Nationally Determined Contribution." http://www4.unfccc.int/submissions/INDC/Published Documents/India/1/INDIA INDC TO UNFCCC.pdf.

Manu, Sanyogita, Yash Shukla, Rajan Rawal, Leena E. Thomas, and Richard de Dear. 2016. "Field Studies of Thermal Comfort across Multiple Climate Zones for the Subcontinent: India Model for Adaptive Comfort (IMAC)." *Building and Environment* 98 (March): 55–70. doi:10.1016/j.buildenv.2015.12.019.

Manu, Sanyogita, Justin Wong, P. C. Thomas, Satish Kumar, and Aalok Deshmukh. 2011. "An Initial Parametric Evaluation of the Impact of the Energy Conservation Building Code of India on Commercial Building Sector." In *Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, 1571–78. Sydney, Australia: International Building Performance Simulation Association. http://www.ibpsa.org/proceedings/BS2011/P_1530.pdf.

McGregor, Alisdair, Cole Roberts, and Fiona Cousins. 2012. *Two Degrees: The Built Environment and Our Changing Climate*. 1st ed. Routledge.

Mendell, M. J., and A. G. Mirer. 2009. "Indoor Thermal Factors and Symptoms in Office Workers: Findings from the US EPA BASE Study." In *Indoor Air 2009*, 291–302. Singapore. doi:10.1111/j.1600-0668.2009.00592.x.