Cloud Magnet: the ethical imperative for environmental health and restoration

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ABSTRACT: This paper presents data from Cloud Magnet, a research and design project conducted in the summer 2017 within the cloud forest of the Monteverde Biological Reserve in Costa Rica. Cloud Magnet explores the co-dependencies between material, form, energy, and environment. Cloud forests have been rapidly disappearing due to climate change and deforestation. Rising global temperatures and deforestation cause a cloud-lifting effect, raising the cloud cover above the tree canopy and forest ecosystem that depend on constant moisture and humidity to support its life. The impetus for this project is to explore how design can contribute to the stabilization of the atmosphere and the restoration of the forest. In recognition of the mutual and inseparable presence of built and natural contexts, Cloud Magnet suggests that architects bear an ethical responsibility for the health of the environment. As such, priorities of environmental performance might be extended beyond energy efficiency to include aspirations of environmental remediation and ecological healing to reverse the harmful effects of human habitation on the world.

KEYWORDS: ethics, environmental restoration, material performance, phase change material, carbon fiber reinforced polymers

INTRODUCTION

As society contends with rising concerns over the viability of our ecosystems, the convergence of human and ecological priorities is increasingly evident. Architecture bears a long history of prioritizing the needs and desires of human experience, including the provision of shelter, creation of community, and design of conditions for physical comfort and human health. Over the past several decades, architecture has responded to challenges of sustainability, seeking to minimize the overall environmental impact of buildings and establish new metrics of energy performance. These measures increasingly acknowledge the impact of buildings on the biosphere. However, these standards and principles do not yet fully embrace the fundamental alignment of human and natural contexts. We assert that architects bear an ethical responsibility for the health of the atmosphere.

1.0 ETHICS OF ENVIRONMENTAL RESPONSIBILITY

Environmental philosophers began to shift their thinking in the 1960s, placing greater emphasis on “humans-in-the-world” as compared to “humans-apart-from-the-world.” They began to explore the history and evolution of our societies to understand the ways in which our cultures connect us or separate us from nature and its diverse resources through these questions:

> What can I know about the environment in which humanity exists?
> What should I do to both sustain and contribute to this environment?
> What may I hope for regarding the future of this environment?
> What is “humanity” in relationship to this ecosystem?
> What role does nature play in developing our sense of beauty?
> What are the most logical ways of addressing the role of humans in the environment? (Delaney 2014, 8)

For philosophers, these queries expound on the fragility of human existence and its connections to the various ecospheres that sustain our lives – and all life. They serve as a reminder of the similarities that exist between human life and other biota, while also underscoring the distinction of the ethical vantage point that only humans can assume. Unlike other forms of life, humans possess the moral responsibility to preserve and safeguard the environment, while also harnessing the power and ability to harm it.

In consideration of the relationship between the professional ethics of architects and the collective responsibility of society to defend the current and future health of the environment, a number of challenges arise. Tom Russ suggests, “There is a design philosophy at the heart of every design effort” (Russ 2010, 117). The act of design consistently requires the subjective prioritization of certain criteria over others, as well as the resolution of competing and conflicting agendas at the same time. The ethics of professional judgment is an essential aspect of the practice of architecture. Current standards of sustainability focus on energy and resource efficiency and human health, but fall short of identifying the health of the environment as a benchmark criterion. Human acts of making, i.e. objects, buildings, infrastructure, do not simply create a built environment that is separate and apart from the natural. To the contrary, these acts of making can be conceived of as a new natural state. As human health is fundamentally aligned with environmental health, architects bear an ethical responsibility to preserve and improve the condition of the environment. In order to act with ethical responsibility towards this goal, we must expand our understanding of the micro-climatic and macro-climatic effects of constructed objects within the ecosystems of the earth.

1.1. A threatened ecosystem

As scientific evidence continues to intensify confirming the significant and indisputable rise in the temperature of the Earth's atmosphere, some of the most bio-diverse ecosystems such as grasslands, coral reefs, and rainforests are threatened. Among these is the Monteverde Cloud Forest Reserve, a tropical montane cloud forest in Costa Rica that has been subject to well-documented effects of climate change since the early 1990s (Holmes 2000). Moisture levels in the cloud forests depend on the trade winds that carry humid air into the mountains, where it condenses covering large areas of forest in fog. Tropical montane cloud forests have been found to be particularly susceptible to the effects of climate change. Encompassing six Holdridge life zones within its diverse topography, Monteverde is a highly useful place to study climate change as it characteristically experiences wide seasonal variations in temperature, precipitation, and other climatic variables (Holmes 2000). Furthermore, recent simulations of climate change through the year 2100 suggest continued pressures on the ecosystem, projecting an increase of 3.8 °C (6.8 °F) in the mean dry surface air temperature along Costa Rica's Pacific slope, while dry season precipitation is expected to fall by approximately 14% during the same period (Nadkarni 2014). If this comes to pass, the current ecology of the forest would be undoubtedly imperiled.

The cloud forest in Monteverde is located within the Guanacaste-Tilarán Mountains, along the continental divide, a topographic ridge between the Pacific and Atlantic oceans that extends from Canada to Argentina. The highest peak of the forest rises 1,800 meters (5,900 feet) above sea level, with hiking trails located up to 1,250 meters (4,100 feet). The cloud forest plays a vital role in the hydrologic cycle in Monteverde as it captures water as wind-driven mist and fog, protects watersheds from erosion, and reduces runoff. Although reforestation measures within the protected, high-altitude zones of the forest have been initiated over recent decades, research on the broader context of this interconnected landscape has identified two primary causes for the persistent reduction of cloud-covered forest. Firstly, the rising global temperature has caused a rise in the altitude of cloud bases by 25 to 75 meters (Deepak 2006). Secondly, deforestation at lower altitudes for farming and more urbanized land uses have been linked to an estimated 5 to 13% decrease in cloud cover in the forest (Deepak 2006). This fragmented landscape further increases the local temperature of the atmosphere due to the reduction of dense flora that retains moisture and distributes it from the cloud to the ground. Furthermore, fauna depend on the connectivity of the tree canopy between altitudinal gradients for movement and migration.

The removal of forestland continues to jeopardize the native biota at the higher altitudes of the cloud forest by lowering the relative humidity and increasing the temperature of the air that rises over the mountains. Forest clearing also causes soil compaction, reducing the infiltration of rainfall into the ground, decreasing the moisture levels in soils, increasing the runoff within streams and rivers, and decreasing the presence of atmospheric mist (Lawton 2001). These changes have been linked to the disappearance of high altitude flora and fauna, including birds, reptiles, amphibians, and other forms of life that are less closely monitored. The changing climate has also made way for outbreaks of pathogens that thrive within the warming atmosphere, and further threaten native species. The interdependency of forest ecosystems foreshadows ongoing ripple effects in the years to come (Nadkarni 2014).

1.2. A history of conservation of nature

The Monteverde Cloud Forest Reserve was founded on principles of conservation that reflect the ethical obligation of humans to protect the environment. American Quakers who were disillusioned with the war efforts in the United States settled in Monteverde in 1950 drawn to the climate, farming industry, and antiviolence position of the country, which had just abolished its army. Well before the effects of climate change became evident, the tropical montane cloud forest was rapidly disappearing due to deforestation. The Quakers purchased about 1400 hectares (3500 acres) of land in Monteverde for dairy farming, parceling some of the land into lots for their homes, farmland, a school, and a meetinghouse for worship. However, they also protected about a third of their land, entitled the Watershed Property, and agreed to leave this area of forest intact to protect the streams needed to supply water for their community (History of Monteverde).

This Quaker community spurred additional interest from English-speaking visitors, as scientists began to visit the area to study the rare species of fauna, namely the golden toad, now extinct from the forest, and the Resplendent Quetzal that remains an attraction for today's eco-tourists. Twenty years after the first Quakers arrived, biologists George and Harriett Powell visited the area and foresaw the impending threat to this unique ecosystem. Alarmed at the rate of forest removal for farmland, the Powells raised money and purchased as many parcels of primary forest as they could to save the forest. The Powells arranged for the Tropical Science Center, a non-governmental scientific and environmental organization in San José, to care for the newly protected land. With assistance from the World Wildlife Foundation, more properties were purchased and added to the privately owned protected land. In 1974, the Quaker community also leased its land to the Tropical Science Center, increasing the total area of secured property to 2,000 hectares (4,940 acres). With the help of Wolf Guindon, one of the original Quaker settlers, and Eladio Cruz, a native Costa Rican from San Luis, the Reserve continued to expand, including higher altitude forest and land in the Peñas Blancas River valley on the eastern side of the Continental Divide. Today, the Monteverde Cloud Forest Reserve encompasses over 10,500 hectares (26,000 acres) of primarily virgin forestland. Much of this land remains inaccessible to the public, as less than 3% of the reserve is open to visitors through a trail network maintained by the reserve (History of Monteverde).

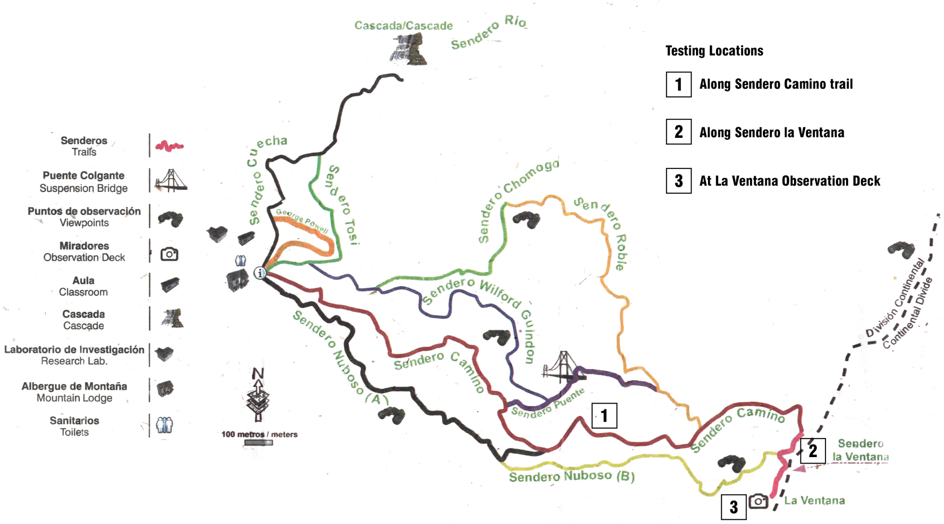


Figure 1: Monteverde Cloud Forest Reserve Trail network (modified) with testing locations (distributed by the Monteverde Cloud Forest Reserve, June 2017)

2.0 A SPECULATIVE PROPOSAL

Cloud Magnet is a research proposal that explores how design might contribute to the restoration of the cloud forest in Monteverde. The initial ideas for the project emerged from a speculative proposal in response to the 2013 d3 Natural Systems Competition, an ideas contest that encouraged the investigation of natural processes that proposed innovative, sustainable, and ecological design solutions to the impending threats associated with climate change. The team's entry, "Cloud Magnet: Restitching the Costa Rican Forest Canopy" proposed a systems strategy to conserve and restore the cloud forest and received a Special Mention for Ecological Systems Enhancement in the competition.

2.1. A systems strategy for forest restoration

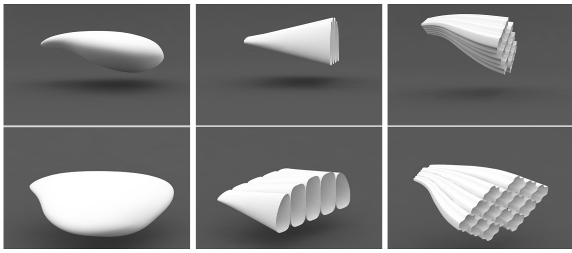
In response to the issue of deforestation, the competition proposed a networked system of structures intended to act as a catalyst by which fragmented patches of forest would begin to be reconnected. The design considered five different site zones from the higher altitude forest through the lower altitude farmland, including the Elfin Forest, the Highland Tree Fall Gap, the Midland Valley, the Lowland along Route 702, and the Lowland Pastureland. Central to this proposal were a series of forest stitching (FS) structures that provide a habitat where native epiphytes, such as mosses and bromeliads, would propagate and grow through the collection of moisture and nutrients from the air. The FS structures were also designed to serve as windbreaks at the vulnerable edges of the forest, providing a continuous biological corridor through a network of flexible epiphyte-covered ropes that span over roadways for the migration of fauna. Capturing and directing water, synthetic dew ponds were proposed along cable zip lines between the structures to provide micro-ecosystems for the habitation of small insects, plants, and amphibians, to aid in the restoration of the forest. The network of structures was designed to provide a transitional zone between the reforming forest and areas of human habitation. In time, the structures are intended to be overgrown by the local flora to reconnect the diverse life zones of the Costa Rican cloud forest. The re-densification of plant life within farmland would also help reduce surface air temperatures within the lowlands, capturing the moisture from the humid air and directing it towards the re-colonization of the forest, with the hope of reversing some of the adverse effects of deforestation that plague the tropical montane cloud forest above.

Figure 2: (Left) Cloud attracting (CA), cloud forming (CF), and forest stitching (FS) structures; (Right, top) Site strategy for the elfin forest using CA kites; (Right, bottom) Site strategy for the Highland tree fall gap using FS structures and CF kites.

In addition to the forest stitching structures, the speculative proposal also proposed the distribution of a series of kites along various elevations within the Guanacaste-Tilarán mountain range. The Cloud Magnet kites were designed to modify airflows in order to stimulate the formation of clouds. Two types of kites were proposed: cloud-forming and cloud-attracting types, which would work through the creation of low pressure zones and the reduction of air temperature, essential environmental conditions for the formation of clouds. The skin of the kites would be fabricated with phase change material (PCM) coated fabric to reduce the temperature of the surrounding air by storing high quantities of latent heat in the change of state from solid to liquid. The forms of the kites were based on scientific principles of airflow and designed to reduce the pressure of the air. Based on Bernoulli's Principle of Pressure, the cloud-forming (CF) kites channeled air through a cluster of venturi tubes, cylindrical forms with a narrow throat that increases the velocity of the air thereby decreasing its pressure. The CF kites were sited in varying densities within the lower to mid altitude site zones. The shape of the cloud-attracting (CA) kite was informed by the sectional profile of an airfoil used within the wing of an airplane. As air circulates around the airfoil shaped kite, a low-pressure zone is created on the top surface due to the increased velocity that occurs on the upper surface of an airfoil. Located in clusters at the highest altitudes of the forest, the cloud-attracting kites were envisioned to mitigate the lifting effect of the clouds off the mountain. Dust particles and pollen within the wind would be funneled through and around the diminutive microclimates of the Cloud Magnet assemblies thereby stimulating the formation of clouds and mist.

3.0 DESIGN AND PROTOTYPING

Following the completion of the ideas competition, we received funding to test ¼ full-scale "proof-of-concept" prototypes of the Cloud Magnet kites in the cloud forest in Costa Rica. The team refined the designs of the cloud-forming kites through digital modeling, computational fluid dynamic (CFD) simulations, material studies, and physical prototyping. The final prototypes were fabricated in Philadelphia, shipped by airfreight to Costa Rica, and then assembled at the Monteverde Cloud Forest Reserve prior to testing along the trails of the forest. One of the primary design considerations was to utilize a form that reduced the pressure of the air flowing through and/or around the kites. We evaluated both the speculative designs of the CF and CA kites for their potential for further refinement and future prototyping. Based on our initial CFD studies, the venturi tube form of the CF kite seemed to have a greater potential to modify the pressure differential of the air and was therefore selected for further development. We explored several iterations of the designs, including a series of bundled venturi tubes similar to that of the initial proposal and a hybrid design that combines the form of the venturi tube of the CF kite with the sectional profile of an airfoil utilized in the CA kite design (See Figure 3).



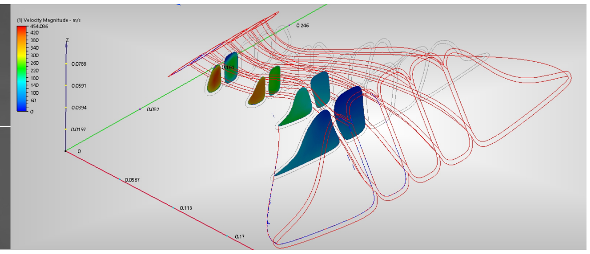


Figure 3: (Left) Formal studies of kites **Figure 4**: (Right) CFD simulation of airflow and velocity showing increased velocity (reduced pressure) in the narrow throat.

As we refined the forms, further CFD simulations were used to analyze flows, pressure change, air velocity, and the overall aerodynamics of the model. As shown in Figure 4, the smaller the circumference of the tube, the greater the velocity of the air, which results in a corresponding decrease in air pressure. These design studies were useful in establishing basic criteria for the movement of air through the kites including ratios of air inlets to air outlets, and served to inform the physical prototyping of the kite frame and skin that followed. Concurrent to the digital studies of form, we also evaluated the movement of air through the forms utilizing 3d printed studies of the forms placed within a smoke tunnel for flow visualization.

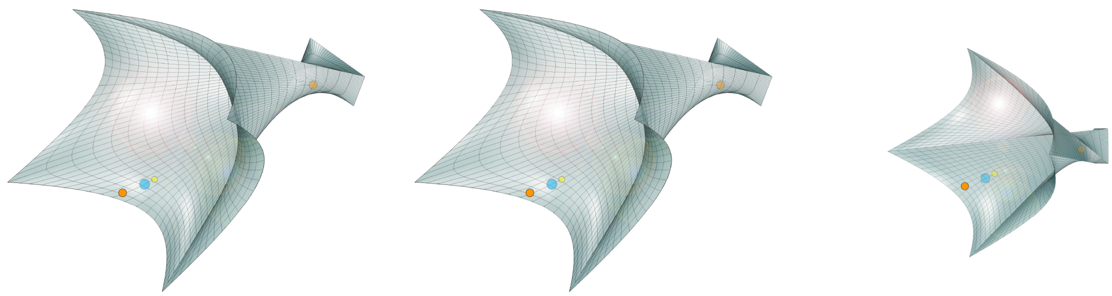
Given the expertise of the project team and the lightweight characteristics of the materials, we prototyped the skin of the kites with Dyneema CT5K.18, a laminated nonwoven ultra-high molecular weight polyethylene (UHMWPE) fabric skin, which was stretched over a flexible pre-impregnated carbon fiber reinforced polymer (CFRP) frame. The Dyneema fabric was coated with a pattern of high performance transfer adhesive tape dusted with Rubitherm PX27, a microencapsulated phase change material (microPCM). Data from the CFD analysis was utilized to create an iterative dialogue between the digital modeling and formal studies and the iterative prototyping of the frames.

Throughout the design process, nearly twenty CFRP frame prototypes were fabricated; each wound in a malleable state then cured in large gas fired kilns. The curing process took approximately four hours of firing at a temperature of 127°C (260°F), with an additional eight hours dedicated to temperature ramp up and down time to achieve its desired structural characteristics. The early frame prototypes attempted to replicate the complex and fluid curvatures of the digital studies. To achieve this, we created a removable core of laser cut cardboard that could withstand the heat of the kiln during firing, and be removed from the cured frame by soaking it in water. Although successful at a small-scale, creating high strength frames and low-cost rapid prototyping, the cored system produced excess waste in the cardboard core, and the rigid form posed problems for shipping. Therefore, this approach was abandoned in favor of a more material-efficient coreless winding process that produced a high level of structural strength while retaining a spring-like elasticity in the frame when compressed. The coreless winding process introduced a logic in which the fabrication process closely informed the final geometry of the frame, rather than attempting to replicate a digitally derived predetermined form. 24k (24,000 strand) CFRP tow, bundled into rovings of carbon fiber that resemble cable or rope, were wound between stainless steel hooks that were bolted to a reconfigurable steel frame which allowed for variation on both ends of the kite as well as in its length. The pattern of hooks on one side created a wide opening as the air inlet; the hooks on the other side were arranged to produce the narrow throat of the kite outlet. Non-stretch, high-temperature cable was wound around the hooks before the CFRP tow was added, creating a predefined formwork of the structure that minimized the chance of CFRP tow slippage during the winding and baking process. The CFRP was wound in a pattern of alternating clockwise and counter clockwise passes. With each successive winding, the CFRP cables were pulled into increased tension creating the desired double curvature in the form.

The reusable cable formwork not only minimized error in during the winding and baking processes, but also minimized the amount of CFRP necessary, providing a more material-efficient, lightweight, and flexible frame. The flexible CFRP wound frames were compressed for shipping efficiency, and then attached to pre-fabricated CFRP perimeter arches and compressive rectangular rings to provide a rigid frame. The final geometry of the kite prototype that was tested in Costa Rica included a 45-degree rotated axis, provided to maximize the efficacy of the microPCM by allowing the kite to rotate its sun facing surface allowing for even heat distribution on all sides of the fabric skin. The Dyneema skin was sculpted to fit the rotated frame through the use of the MPanel tensile fabric modeling software and fabricated from (16) flat panels that achieved a double curvature when fully assembled. The fabric was trimmed and rolled onto a cardboard spool, and each of the (16) panels was printed onto the textile using a wide format ink-jet plotter. The individual patterns for each panel included 1” wide tab extensions that were affixed with Dyneema fabric welding tape to join all the patterns into a fabric sock with openings at both ends. The fabric sock was stretched inside the CFRP framework and pulled into tension. The microPCM was affixed to the interior of the kite, to provide for maximum temperature reduction along the airflow path.

4.0 TESTING AND RESULTS

The team fabricated and tested (2) ¼ full-scale kites and one smaller prototype as indicated in Figure 7. The kites were equipped with programmed microcontrollers with (2) temperature, pressure, and humidity sensors, one located at the air inlet, the other positioned at the air outlet. Kite 01_Yellow was a ¼ full-scale prototype with a CFRP frame and Dyneema fabric skin without microPCM. Kite 02_Blue was the same as Kite 01_Yellow with the addition of microPCM. Kite 03_Red included a 90 degree rotated frame and Dyneema fabric skin with microPCM.



	KITE 1	KITE 2	KITE 3
Size:	Large (30" x 30" x 48")	Large (30" x 30" x 48")	Small (24" x 24" x 36")
Design:	180° Rotation	180° Rotation	90° Rotation
Fabric:	Dyneema CT5K.18 welded w/ CTPSA tape	Dyneema CT5K.18 welded w/ CTPSA tape	Dyneema CT5K.18 welded w/ CTPSA tape
PCM:	None	Rubitherm Microencapsulated PX 27 50% surface area w/ 3M transfer tape	Rubitherm Microencapsulated PX 27 50% surface area w/ 3M transfer tape
Data:	(1) Feather M0 Micro-controller (2) BME280 Temp/Humidity/Pressure (1) RTC_DS3231 Real-time	(1) Feather M0 Micro-controller (2) BME280 Temp/Humidity/Pressure (1) RTC_DS3231 Real-time	(1) Feather M0 Micro-controller (2) BME280 Temp/Humidity/Pressure (1) RTC_DS3231 Real-time

Figure 7: Kites fabricated in Monteverde for testing.

Testing was conducted at several locations with perceptible wind flow along the hiking trails. Many of the trails are located with the forest canopy, beneath the shelter of mature trees with little to no access to the trade winds. Also, some of the trail paths were narrow and steep, and therefore difficult to traverse with the kites and computing equipment in hand. The team identified three locations with steady airflow for the kite testing as indicated in Figure 1; one along the Sendero Camino, another in a clearing along the Sendero la Ventana, and the third situated along the continental divide at the La Ventana lookout. The exposed mountain peak at La Ventana proved to be the best location for testing as it offered the greatest access to the trade winds from the North East. The vegetation in this area consisted of shorter elfinwood trees characteristic of exposed mountain ridges at this altitude, and several viewpoints openings are cleared along the mountain peak that provided adequate space for testing.

When exposed to the open area, Kite 2 performed as expected, increasing the relative humidity of the air at the outlet, and decreasing the temperature of the air. The Figure 8 graph diagrams the performance of Kite 2 for approximately ten minutes of testing at location 3, La Ventana (Data Set 013). The plot charts the change in relative humidity (%) and dry bulb air temperature (°C) between sensor 1 (located at the air inlet) and sensor 2 (located at the air outlet). Plotted values indicate the difference calculated as the variable measured at sensor 2 – sensor 1. The kite was lifted into the air at 10:49:46, just after testing was initiated at 10:59:37.

The initial weather conditions from the outset of testing to approximately 11:02 (+/-) were windy and overcast with high clouds about the mountain peaks. During this time, the airflow stabilized with about a -3 °C temperature change, and an 11% increase in humidity. Then, the sun began to peek through the clouds and the performance of the kite improved, reaching a maximum increase in relative humidity of 18.12%, with a concurrent decrease in temperature of 4.41°C (7.87°F) and decrease in air pressure of 70.67 hPa. When the peak change was observed, the temperature and pressure at sensor 1 (inlet air) was 26.35°C (62.94°F) and 84,732.72 hPa, with the temperature and pressure at sensor 2 (outlet air) of 22.10°C (71.78°F) and

84,662.05 hPa. At approximately 11:04, the wind speeds began to decrease during which time the change in relative humidity steadily declined as indicated in Figure 8. In addition, the data reveal an increase in the performance of the kite when clouds and mist were not observed in the air as compared to conditions when intermittent mist was present in the winds moving upward along the mountain slope. The kite was dismounted at 11:09:11, marked by the distinct shift in the graph where the temperature change and relative humidity change lines cross for the second time.

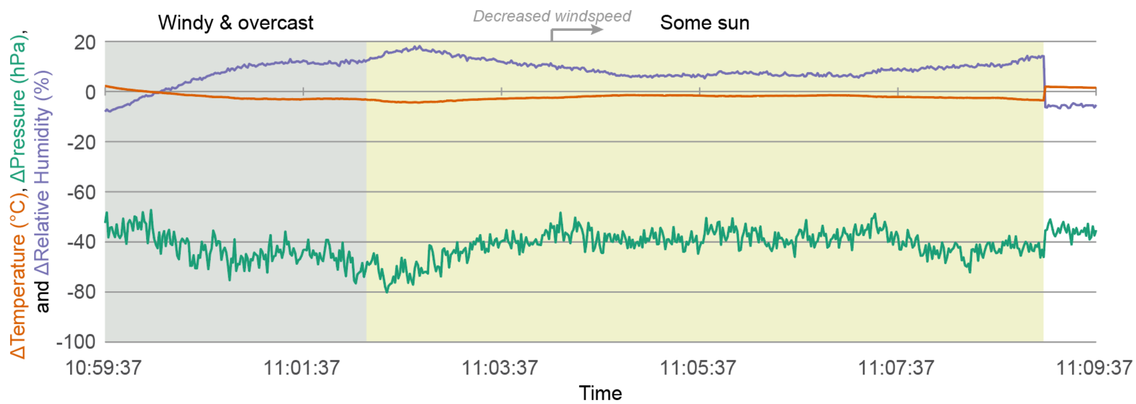


Figure 8: Testing of Kite 2 at Location 3: La Ventana, Data Set 013, June 28, 2017.

For the ten second interval surrounding the peak in humidity change, the mean change in humidity (sensor 2 minus sensor 1) was 16.98% +/- 0.62%; the mean change in temperature was -4.28 +/- 0.10 °C; and the mean pressure change was -72.11 +/- 2.61 hPa. Refer to Figure 9 for absolute values during this interval.

Change: Sensor 2 - Sensor 1	
Δ Humidity	16.98 +/- 0.62 %
Δ Temperature	-4.28 +/- 0.10 C
Δ Pressure	-72.11 +/- 2.61 hPa

Absolute Values: Sensor 1	
Humidity	63.48 +/- 0.49 %
Temperature	26.34 +/- 0.12 °C
Pressure	84730.64 +/- 3.22 hPa

Absolute Values: Sensor 2	
Humidity	80.46 +/- 0.42 %
Temperature	22.06 +/- 0.0272 °C
Pressure	84658.53 +/- 2.17 hPa

Figure 9: Mean and Standard Deviation, 10-second interval at peak humidity change; Kite 2 at Location 3: La Ventana, Data Set 013, June 28, 2017.

Kites 1 and 2 were simultaneously tested on June 27, 2017 at testing location 1 along the Sendero Camino trail during light rain and misty conditions. These kites were identical in form, but Kite 1 did not contain microencapsulated PCM, thereby allowing for comparative results that isolate the performance of the PCM. Unfortunately, some data was lost seemingly due to moisture contact with the microcontrollers. Valid data from Kite 1 was collected for 11 minutes 19 seconds (Data Set 004) producing a mean change in temperature of -0.09 °C, a mean change in pressure of 9.23 hPa, and a mean change in relative humidity of -1.85%. It is notable that the relative humidity decreased from sensor 1 at the inlet air to sensor 2 at the outlet, which is the opposite of the anticipated result. However, the specific relative humidity was high at both sensor locations, with consistent values near 99.5% at sensor 1, which may be attributable to the weather at the time of testing. Perhaps even more significant is the extremely small reduction in temperature of 0.09 °C. At the same location and in similar weather conditions, Kite 2 produced a mean reduction in air temperature of 0.86 °C and a mean change in pressure of 12,235.26 hPa (Data Set 005). The relative humidity at both sensors was 100% during this test. Although further testing is required, these results are positive indicators of the use of PCM in reducing air temperature, as compared to kite forms without PCM.

Testing at location 2 did not perform as expected. After confirming the sensor locations and wiring, we realized that location 2 was located within a “natural” venturi tube within the forest. This testing site was positioned under a dense tree canopy, and along a compressed section of path connecting a viewpoint (with an opening in the forest vegetation) to a wider picnic area along the Sendero la Ventana. Trade winds traveling through the opening on the side of the mountain increased velocity as it traveled through the compressed opening, and air that flowed through the kite produced a decrease in humidity and an increase in temperature between sensors 1 and 2, the opposite of the anticipated results.

Data was not collected from Kite 3 due to the malfunctioning of the sensors after exposure to moisture.

5.0 CONCLUSION

Cloud Magnet seeks to contribute to contemporary design discourse through a research and design project that evaluates the restorative capabilities of performative materials within a localized ecosystem. Specifically, it aims to produce a proof-of-concept prototype of a cloud-producing kite in the cloud forest of Monteverde, Costa Rica. The data supports the design aims as the kites produced a reduction in air temperature and air pressure that corresponded to a maximum increase in relative humidity of 18.12%, a maximum decrease in dry bulb air temperature of 4.41°C (7.87°F), and a maximum decrease in air pressure of 80.2 hPa. We recorded an average increase in relative humidity of 9.42%, an average decrease in temperature of 2.40°C (4.32°F), and an average decrease in air pressure of 61.85 hPa. Furthermore, the results indicated improved performance of the kites in sunny weather conditions, where the natural occurrence of clouds is diminished. These data provide supportive evidence for the potential to modify the microclimate of the Montverde Cloud Forest to stimulate the formation of clouds. However, further research is needed in the following areas: 1) adjustment and evaluation of the melt temperature of the microPCM to maximize its effectiveness in the climate of the cloud forest; 2) improved waterproofing of microPCM coated Dyneema fabric; 3) improved waterproofing of the sensors and micro-controllers; and 4) stabilization of the aerodynamic properties of the kites. Future testing should also be located in open-air locations to avoid natural Venturi tubes and conducted during sunny or partly sunny weather conditions to maximize performance.

Beyond the localized performance of the Cloud Magnet kites within the cloud forest in Monteverde, this project reinforces the notion that the constructed objects produce changes in weather in time that lead to measurable and interdependent micro-climatic and macro-climatic changes over longer periods. Scientists have produced definitive evidence that the current era of rapidly intensifying global climate change is the result of human factors. Current metrics of energy and material efficiency do not go far enough to assess the full impact that buildings have on the environment. Furthermore, if we are to fully embrace the ethical obligation that humans have to all other life forms, we must raise our aspirations beyond the notion of do no harm, and take measured steps to reverse the destructive consequences of our previous (and current) practices.

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