# climate adaptive design strategies

St. Maarten

Architectural Engineering

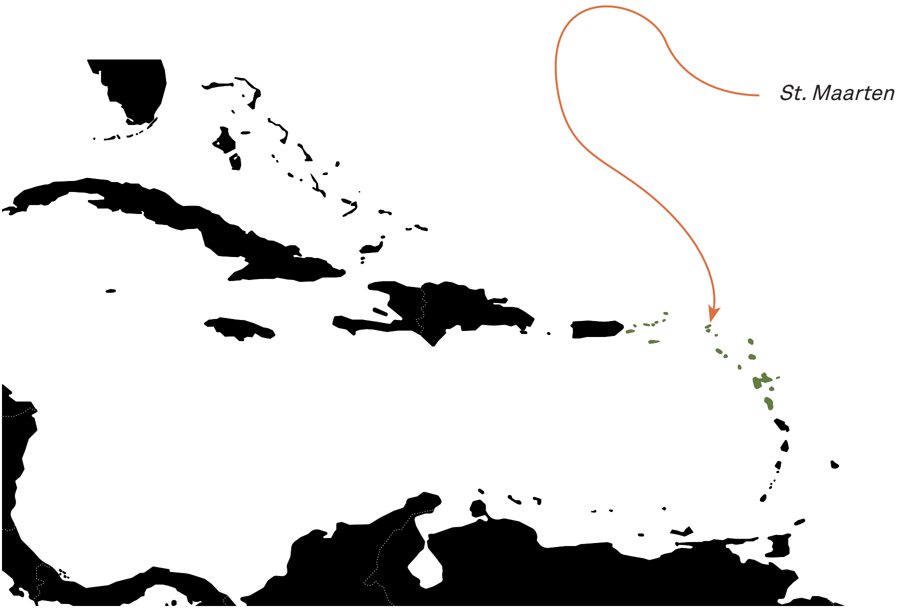
TU Delft

10/01/2020

Bram Rooijakkers//
4137698

# Index


| | |
|---|---|
| Preface | 5 |
| Methodology | 7 |
| A. Climate on St. Maarten | 8 |
| A1. Sun chart | 10 |
| A2. Sun path diagram | 11 |
| A3. Solar radiation | 12 |
| A4. Shading calendar | 13 |
| A5. Wind direction | 14 |
| A6. Wind speed | 15 |
| B. Hurricane resilience | 16 |
| B1. Wind impact on structures | 19 |
| B2. Projected area | 21 |
| B3. Drag coefficient | 25 |
| B4. Wind pressure | 27 |
| Passive Climate Design Strategies Tropical Savannah Climate | 30 |
| 1. Urban scale | 32 |
| 1.1 Topographic microclimates | 34 |
| 1.2 Urban microclimates | 38 |
| 1.3 Urban microclimates: Shading open spaces | 44 |
| 1.4 Urban patterns & ventilation corridors | 48 |
| Recommendations Cluster scale | 56 |
| 2. Building scale | 58 |
| 2.1 Permeability: cross -and stack ventilation | 60 |
| 2.1.1 Cross-ventilation: wing walls | 68 |
| 2.1.2 Cross ventilation: wind catcher | 74 |
| 2.1.3 Stack-ventilation | 82 |
| 2.2 Zoning for cooling | 86 |
| 2.2.1 Zoning: buffer zones | 88 |
| 2.2.2 Zoning: transformations | 100 |
| 2.3. Cooling mass: roof pond | 104 |
| Recommendations Building scale | 110 |
| Reflection | 114 |


St. Maarten

# Preface

The idea for this catalogue started with the problem that is faced by many islands in the Caribbean today. Tropical storms are a constant element of the climate in tropical regions around the equator. The subject of this catalogue is the island of St. Maarten which is part of the Leeward islands in the Caribbean, shown in the image on opposite page.

As a result of the yearly possible threat of destruction, the built environment adjust accordingly. Many homes that were destroyed by previous hurricanes (strongest one recently was hurricane Irma in 2017) are being rebuild with the 'build back stronger' approach to be less vulnerable during these catastrophic events. What that means is that buildings have: heavy foundations, heavy structures and walls (concrete and concrete block work) and few, small openings in the exterior shell. While this fulfills the most important aspect of what a home should represent, namely safety, it has a negative effect on peoples physical and social surroundings. Most aspects of St. Maarten's climate ask for different approaches to design and build comfortable living environments. Using the 'build back stronger' approach the result in most cases means that the indoor climate has to be controlled by mechanical means (ventilation -or air-conditioning units), unsustainable materials are used and the interaction between inside and outside is lessened.

Therefore, the idea to display the ways in which climate appropriate design can be applied while maintaining safety measures in the event of hurricanes was born and displayed in this catalogue. This document is very much a working document which is subject to change and adopts additional information.

*Research question*
How can a passive climate design strategy be developed which deals with the constraints posed by hurricane resilient design to provide sustainable design solutions?

*Literature study*
- What are St.Maarten's climatic aspects that will influence residential building design?
- What is hurricane resilient design?
- Which passive climate design principles are applicable on St. Maarten?

*Reference study*
- How are climate adaptive design aspects applied in practice?
- How are homes currently being designed with regards to the climate on St. Maarten?
- How can hurricane design and passive climate design be combined in a single design strategy?

*Passive Climate Design Catalogue*

# Methodology

This catalogue is part of the research for my graduation project and provides crucial information to strengthen the design of the project. The main question, subquestions and corresponding methods that are used to answer those are shown on opposite page.

The literature study looks at literature that describes design strategies or tools that can be used to design for St. Maarten's "Tropical Savannah climate". Therefore a selection is made of relevant (cooling) design strategies that are gathered from several sources. In addition, research articles are gathered to gain a better understanding of the application of certain strategies in a hot-humid climate like the one on St. Maarten.

The reference study will function as a complementation to the relevant passive climate design strategies and its applicatibility on St. Maarten. Reference projects with a comparable climate are selected and analysed, but also examples of buildings on St. Maarten that apply the strategies are picked. These projects will show how a combination between hurricane design and climate design can be established.

This whole catalogue is meant to be a tool for architects and builders to use in practice and better understand the choices that are made in design with regards to hurricane- and climate design.

# A. Climate on St. Maarten

*Temperature range*
*21 °C - **27 °C** - 31°C*

*Precipitation*
*Avg.*
*83 mm/month*

*Humidity*
*Avg. 77%*

*Wind direction & speed*
*Predominantly east*
*Avg. 4,5 m/s*

Applying passive climate design principles for the design of a home requires a thorough understanding of the climate at hand. Only then can passive climate design fulfill its full potential by using the climate to its advantage and minimize the need for mechanical aid to create a comfortable living environment.

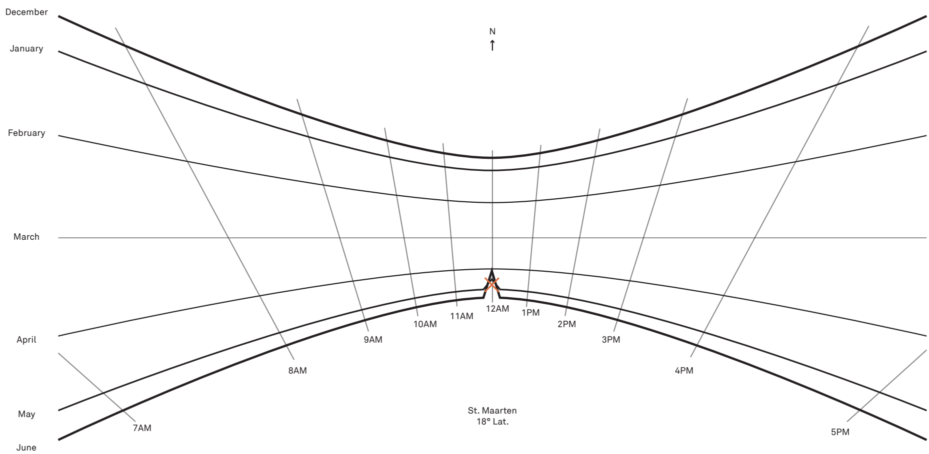
This chapter will therefore analyze the climatic conditions on St. Maarten with the intent to use them in the design process. The climatic aspects are labeled and used to refer back to this chapter when passive climate design strategies are discussed in upcoming chapters.  Ofcourse there are many climatic aspects that can be discussed but for the purpose of this catalogue a selection is made of climatic aspects which have a relation to building design. The gathered information comes from local weather data at the Princess Juliana International Airport which is translated into graphics with the software Climate Consultant (v6.0). These graphics are then partly reinterpretted and adjusted to maintain a consistent layout.

The climate of Sint Maarten is classified as a **Tropical Savannah climate** (Koppen-Geiger classification). Average yearly temperatures lie around 27°C with summer highs of 33°C and winter lows of 21°C. The yearly precipitation is around 83 mm/month with a dry season running from January till June and a wet season from June till December. The wet season is generally associated with the hurricane season. Predictions state that these wet and dry seasons will diverge more from each other (Yokoyama, 2019) which places even more importance on building design.

What is of main importance is comfort. Ensuring that a building stays cool means that the building should be protected from solar radiation to minimize heat gain.

# A1. Sun chart

A1

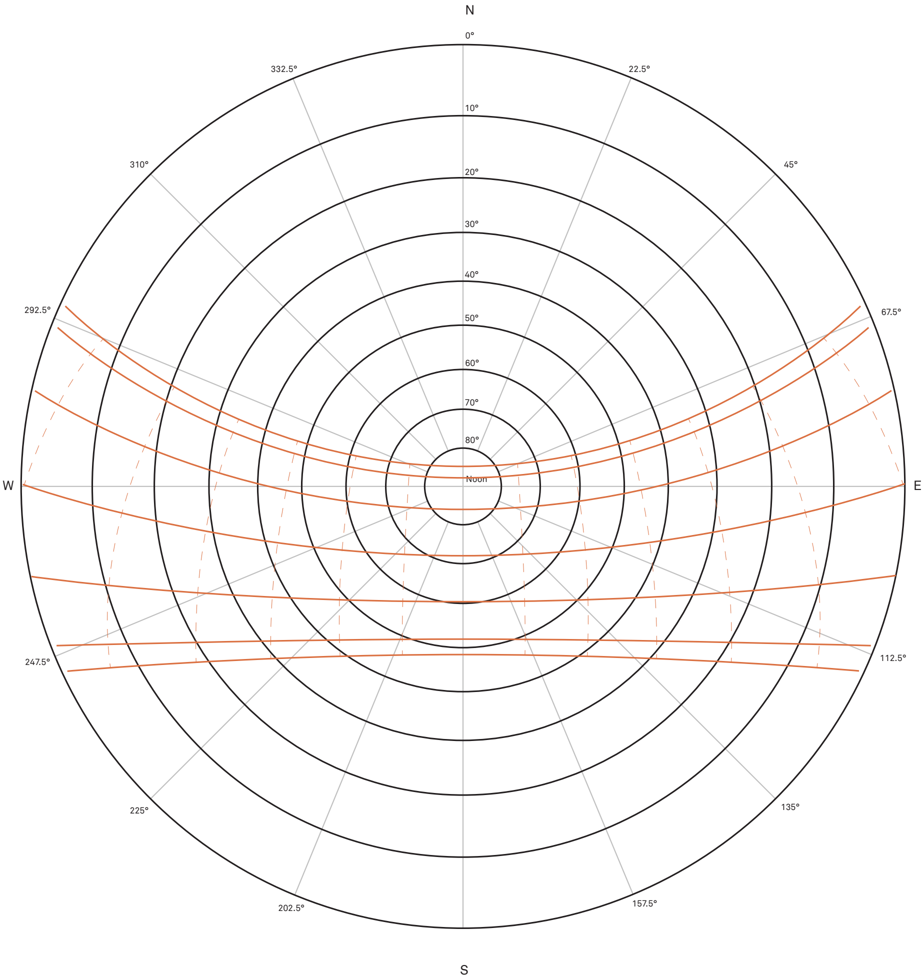



The sun chart, combined with a model simulates the changing positions of the sun with corresponding shade through the day in different months of the year.

The sun path diagram on opposite page can determine when a certain point on a actual site will be shaded by surrounding objects. This will create a shading plot for a specific point.

# A2. Sun path diagram





# A3. Solar radiation

A3

| Hours | Months J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 11 | 24 | 33 | 4 | 0 | 0 | 0 | 0 | 0 |
| 8 | 95 | 167 | 229 | 241 | 167 | 240 | 180 | 162 | 170 | 191 | 178 | 118 |
| 9 | 373 | 459 | 467 | 428 | 326 | 416 | 358 | 322 | 320 | 387 | 411 | 367 |
| 10 | 577 | 638 | 635 | 558 | 425 | 531 | 494 | 467 | 457 | 538 | 547 | 561 |
| 11 | 643 | 723 | 697 | 631 | 505 | 592 | 564 | 550 | 526 | 609 | 603 | 626 |
| 12 | 676 | 745 | 744 | 659 | 569 | 609 | 596 | 577 | 568 | 640 | 633 | 676 |
| 13 | 671 | 729 | 782 | 648 | 602 | 627 | 603 | 581 | 590 | 666 | 639 | 680 |
| 14 | 711 | 727 | 767 | 702 | 632 | 644 | 606 | 629 | 556 | 659 | 630 | 686 |
| 15 | 680 | 694 | 757 | 677 | 579 | 599 | 565 | 595 | 535 | 618 | 608 | 631 |
| 16 | 580 | 693 | 700 | 595 | 494 | 538 | 532 | 538 | 440 | 514 | 490 | 498 |
| 17 | 397 | 468 | 513 | 449 | 323 | 400 | 386 | 371 | 308 | 301 | 250 | 320 |
| 18 | 45 | 151 | 201 | 174 | 118 | 161 | 165 | 132 | 52 | 2 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Low | Medium | High |
|---|---|---|
| < 240 W/m2 | > 240 < 630 W/m2 | > 630 W/m2 |

Solar radiation diagram showing the average hourly radiation (W/m²) on a horizontal surface in St. Maarten.

# A4. Shading calendar



| Time \ Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 25 | 25 | 25 | 26 | 27 | 27 | 27 | 28 | 28 | 27 | 27 | 25 |
| 2 | 25 | 24 | 24 | 26 | 26 | 27 | 27 | 28 | 28 | 27 | 26 | 25 |
| 3 | 25 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 28 | 27 | 26 | 25 |
| 4 | 25 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 28 | 27 | 26 | 25 |
| 5 | 24 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 28 | 26 | 26 | 25 |
| 6 | 24 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 28 | 26 | 26 | 25 |
| 7 | 24 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 28 | 26 | 26 | 25 |
| 8 | 24 | 24 | 25 | 26 | 26 | 28 | 28 | 28 | 28 | 27 | 27 | 25 |
| 9 | 26 | 25 | 26 | 26 | 27 | 28 | 29 | 28 | 29 | 28 | 28 | 26 |
| 10 | 26 | 26 | 27 | 27 | 28 | 29 | 29 | 29 | 30 | 29 | 28 | 27 |
| 1 | 27 | 27 | 27 | 27 | 28 | 29 | 30 | 29 | 30 | 30 | 29 | 27 |
| 12 | 27 | 27 | 28 | 28 | 29 | 29 | 30 | 30 | 30 | 30 | 29 | 28 |
| 13 | 27 | 27 | 28 | 28 | 29 | 30 | 30 | 30 | 30 | 30 | 29 | 28 |
| 14 | 27 | 27 | 28 | 28 | 29 | 30 | 30 | 30 | 30 | 30 | 29 | 28 |
| 15 | 27 | 27 | 28 | 28 | 29 | 30 | 30 | 30 | 30 | 30 | 29 | 28 |
| 16 | 27 | 27 | 28 | 28 | 29 | 30 | 30 | 30 | 30 | 30 | 29 | 27 |
| 17 | 27 | 27 | 27 | 28 | 28 | 29 | 30 | 30 | 30 | 29 | 28 | 27 |
| 18 | 26 | 26 | 27 | 27 | 28 | 29 | 29 | 29 | 29 | 28 | 28 | 26 |
| 19 | 25 | 25 | 26 | 27 | 27 | 28 | 29 | 29 | 29 | 28 | 27 | 26 |
| 20 | 25 | 25 | 25 | 26 | 27 | 28 | 28 | 28 | 29 | 27 | 27 | 26 |
| 21 | 25 | 25 | 25 | 26 | 27 | 28 | 28 | 28 | 28 | 27 | 27 | 25 |
| 22 | 25 | 25 | 25 | 26 | 27 | 28 | 28 | 28 | 28 | 27 | 27 | 26 |
| 23 | 25 | 25 | 25 | 26 | 27 | 28 | 28 | 28 | 28 | 27 | 27 | 25 |
| 24 | 25 | 25 | 25 | 26 | 27 | 27 | 28 | 28 | 28 | 27 | 27 | 25 |
| Average | **26** | **25** | **26** | **26** | **27** | **28** | **28** | **29** | **29** | **28** | **27** | **26** |

Numbers in table are rounded up.

*< 25°C* | *> 25°C < 27°C* | *> 27°C < 29°C* | *>29°C*

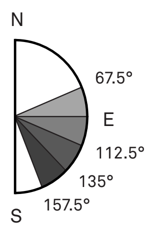
Dry-bulb temperature table showing the hourly average temperature per month in a year. The winter months from Dec untill April are the most comfortable with daily temperatures only just exceeding 28°C. Based on the ASHRAE standard 55 comfort model, the winter comfortable temperatures (with winter clothing) are from 20.5°C to 24°C and the comfortable temperature during the summer months (with summer clothing) are between 24°C to 27°C.

# A5. Wind direction

A5

| Time | Month: J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 106 | 87 | 101 | 88 | 98 | 94 | 85 | 92 | 118 | 132 | 98 | 93 |
| 2 | 97 | 96 | 98 | 93 | 112 | 93 | 95 | 91 | 111 | 135 | 105 | 112 |
| 3 | 106 | 93 | 104 | 106 | 112 | 96 | 93 | 103 | 140 | 119 | 80 | 98 |
| 4 | 100 | 102 | 107 | 102 | 120 | 105 | 83 | 92 | 99 | 133 | 81 | 102 |
| 5 | 125 | 98 | 100 | 99 | 113 | 95 | 92 | 87 | 133 | 130 | 83 | 102 |
| 6 | 94 | 92 | 113 | 97 | 98 | 99 | 93 | 99 | 119 | 135 | 108 | 99 |
| 7 | 98 | 87 | 110 | 99 | 108 | 106 | 81 | 92 | 155 | 130 | 96 | 106 |
| 8 | 113 | 89 | 122 | 94 | 106 | 108 | 85 | 89 | 132 | 134 | 81 | 94 |
| 9 | 116 | 91 | 105 | 106 | 113 | 107 | 98 | 100 | 118 | 130 | 94 | 104 |
| 10 | 121 | 102 | 121 | 105 | 110 | 109 | 103 | 106 | 120 | 139 | 85 | 92 |
| 1 | 126 | 99 | 122 | 110 | 118 | 105 | 111 | 103 | 132 | 134 | 85 | 103 |
| 12 | 120 | 101 | 118 | 113 | 118 | 113 | 96 | 104 | 122 | 133 | 91 | 83 |
| 13 | 116 | 96 | 137 | 112 | 113 | 103 | 101 | 98 | 144 | 137 | 93 | 125 |
| 14 | 126 | 101 | 131 | 111 | 119 | 105 | 101 | 94 | 147 | 145 | 104 | 88 |
| 15 | 139 | 106 | 120 | 113 | 118 | 112 | 100 | 103 | 134 | 133 | 104 | 84 |
| 16 | 118 | 102 | 133 | 116 | 107 | 107 | 108 | 95 | 127 | 134 | 112 | 94 |
| 17 | 129 | 103 | 113 | 106 | 108 | 104 | 96 | 97 | 119 | 131 | 87 | 97 |
| 18 | 123 | 95 | 105 | 106 | 120 | 104 | 96 | 93 | 127 | 126 | 86 | 95 |
| 19 | 121 | 106 | 104 | 98 | 118 | 97 | 87 | 88 | 108 | 122 | 77 | 113 |
| 20 | 98 | 87 | 112 | 92 | 96 | 93 | 89 | 87 | 116 | 123 | 84 | 80 |
| 21 | 100 | 97 | 102 | 95 | 115 | 99 | 94 | 101 | 115 | 114 | 86 | 81 |
| 22 | 100 | 87 | 97 | 92 | 109 | 91 | 80 | 97 | 113 | 138 | 73 | 111 |
| 23 | 111 | 90 | 103 | 97 | 113 | 93 | 84 | 101 | 123 | 125 | 77 | 95 |
| 24 | 110 | 93 | 109 | 92 | 116 | 97 | 85 | 82 | 127 | 125 | 82 | 108 |

Wind direction table showing the average wind dierction every month at a specific hour.



# A6. Wind speed

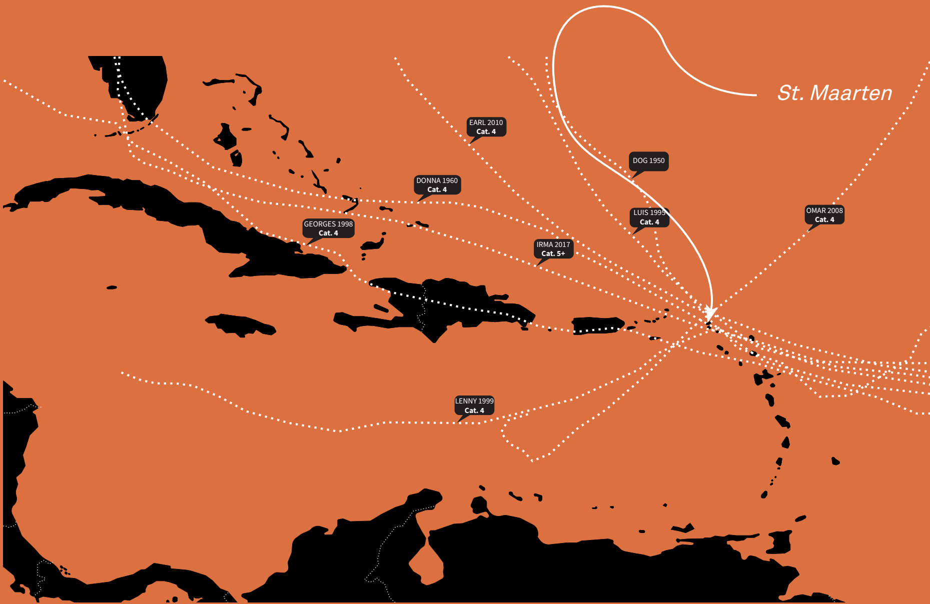


| *Time* \ *Month* | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.5 | 5.1 | 4.3 | 4.4 | 4.1 | 4.9 | 4.9 | 5.2 | 3.9 | 3.7 | 4.1 | 4.3 |
| 2 | 3.8 | 5.1 | 4.0 | 4.4 | 4.3 | 4.7 | 4.7 | 4.8 | 3.6 | 3.5 | 3.9 | 4.2 |
| 3 | 3.6 | 4.9 | 3.9 | 4.4 | 4.2 | 4.7 | 4.5 | 5.0 | 3.5 | 3.6 | 3.8 | 4.3 |
| 4 | 3.6 | 4.8 | 4.0 | 4.3 | 4.5 | 4.8 | 4.6 | 4.9 | 3.6 | 3.6 | 4.0 | 4.1 |
| 5 | 3.8 | 4.8 | 3.9 | 4.4 | 4.2 | 4.9 | 4.5 | 4.8 | 4.0 | 3.3 | 3.8 | 3.8 |
| 6 | 4.1 | 4.7 | 4.0 | 4.5 | 4.0 | 4.6 | 4.4 | 5.0 | 3.9 | 3.2 | 3.8 | 4.0 |
| 7 | 3.6 | 4.6 | 3.9 | 4.4 | 4.1 | 4.8 | 4.6 | 5.2 | 4.1 | 3.6 | 3.9 | 4.0 |
| 8 | 3.8 | 4.9 | 4.1 | 4.6 | 4.2 | 5.1 | 4.7 | 5.6 | 4.2 | 3.3 | 3.7 | 4.2 |
| 9 | 3.6 | 5.2 | 4.4 | 4.8 | 4.8 | 5.4 | 5.6 | 5.9 | 4.7 | 3.9 | 4.0 | 4.6 |
| 10 | 4.3 | 5.7 | 4.8 | 5.1 | 4.9 | 5.7 | 5.8 | 6.1 | 5.0 | 4.2 | 4.8 | 4.7 |
| 1 | 4.5 | 5.7 | 4.9 | 5.4 | 5.1 | 5.9 | 5.4 | 6.4 | 5.1 | 4.4 | 5.0 | 5.1 |
| 12 | 4.6 | 6.2 | 5.2 | 5.6 | 5.2 | 5.9 | 5.6 | 6.5 | 5.3 | 4.5 | 5.1 | 5.2 |
| 13 | 4.7 | 5.9 | 5.1 | 5.4 | 5.2 | 5.8 | 5.6 | 6.4 | 5.0 | 4.7 | 4.7 | 5.2 |
| 14 | 4.5 | 6.0 | 5.2 | 5.4 | 5.1 | 5.8 | 6.0 | 6.3 | 4.7 | 4.7 | 4.6 | 5.4 |
| 15 | 4.6 | 6.2 | 5.0 | 5.2 | 4.9 | 5.9 | 5.7 | 6.1 | 5.1 | 4.2 | 5.0 | 5.3 |
| 16 | 4.3 | 5.8 | 5.0 | 5.0 | 4.8 | 5.7 | 5.6 | 6.3 | 4.8 | 4.2 | 4.8 | 5.1 |
| 17 | 4.1 | 5.5 | 5.0 | 4.9 | 4.8 | 5.5 | 5.7 | 6.0 | 4.9 | 4.2 | 4.6 | 4.9 |
| 18 | 4.0 | 5.5 | 4.9 | 4.8 | 4.6 | 5.8 | 5.6 | 5.9 | 4.6 | 3.9 | 4.4 | 5.0 |
| 19 | 4.0 | 5.5 | 4.7 | 4.4 | 4.5 | 5.1 | 5.4 | 5.4 | 4.8 | 3.7 | 4.3 | 4.7 |
| 20 | 3.9 | 5.0 | 4.5 | 4.2 | 4.6 | 4.9 | 4.9 | 5.4 | 4.1 | 3.9 | 4.1 | 4.4 |
| 21 | 3.6 | 5.2 | 4.4 | 4.2 | 4.7 | 5.1 | 4.9 | 5.3 | 4.0 | 3.9 | 4.1 | 4.3 |
| 22 | 3.7 | 5.1 | 4.4 | 4.3 | 4.6 | 5.0 | 5.0 | 5.3 | 4.1 | 3.7 | 4.1 | 4.5 |
| 23 | 3.9 | 5.0 | 4.6 | 4.3 | 4.5 | 5.0 | 5.1 | 5.3 | 3.9 | 3.7 | 4.0 | 4.6 |
| 24 | 3.9 | 5.4 | 4.5 | 4.3 | 4.6 | 5.1 | 4.7 | 5.2 | 4.2 | 3.8 | 4.2 | 4.4 |

Wind speed table showing the average windspeeds every month at a specific hour.

*>6 m/s* *>5< 6 m/s* *>4<5 m/s* *<4 m/s*

# B. Hurricane resilience




*Caribbean map showing major hurricanes (Cat. 4+) that passed by St. Maarten in the last 70 years.*

In Chinese culture the complex Yin-Yang relational concept states that ‘the meaning of yin and yang is that the universe is governed by a cosmic duality, sets of two opposing and complementing principles or cosmic energies that can be observed in nature’ (Shan, 2019). This description applies to the relationship that St. Maarten has to its climate. Most climate aspects are ‘hot, bright, and positive’ (Yang) while the obvious other is ‘dark, and negative’ (Yin). And a category 5+ hurricane like Irma in 2017 is as negative as it gets.

While resilience or resistance against hurricanes with regards to home design expresses itself in various forms on the island. My research stresses the importance of designing and constructing buildings to fit both the Yin and Yang aspects of St. Maarten’s climate. Many buildings that are being build recently are made to withstand hurricanes which on average occur every 2.69 years (Hurricane City, 2019). Often this means that some sort of concrete bunker is built which might be safe during the day that a hurricane hits or brushes the island, but does not provide a pleasant living environment the other 99% of the time.

This chapter of the research explains a couple of important aspects to account for when designing for hurricane resilience. The information is mainly retrieved from documents produced by Non-governmental organisations such as the Red Cross and Habitat for Humanity. It will form a crucial role when combined with the PCDS’s described in the next chapter.

$$F = A \times P \times Cd$$

**Wind load** — Projected area — Wind pressure — Drag coefficient

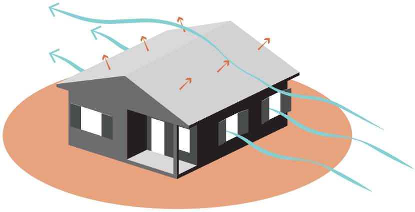
# B1. Wind impact on structures

The essence of understanding what to account for when designing for hurricane resilience is to understand the wind load equation, displayed on opposite page. In general, the wind load is calculated by taking the projected area of an object multiplied by the wind pressure and drag coefficient of the object. In this equation there are two variables that are influenced by the object or building, namely: *the projected area (A) and the drag coefficient (Cd)*.

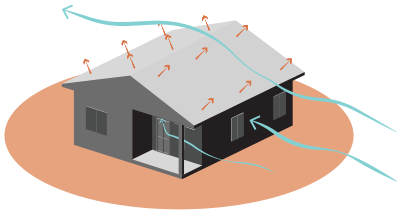
The larger the surface of an object is, the more area there is where wind can apply pressure. Minimizing the surface area results in less wind loads on the total structure. There are several options to minimize surface area such as: breaking up the building into smaller buildings, use permeable materials where the wind cannot apply its pressure, etc. If the option is not available to minimize surface areas of your building, the structural integrity becomes more important. The structure has to be able to transfer the wind load to the foundation without collapsing under the pressure.

The main aspects that determine the drag coefficient of an object are the shape of the building and the roughness of its surface. Taking these aspects into account can also reduce wind loads durring extreme wind pressures.

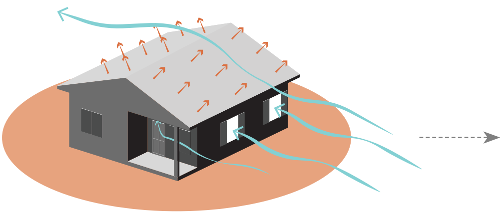
Lastly, the wind pressure can also be influenced, not directly by the building itself but its surroundings. Wind breaks such as vegetation and netting can reduce the strength of the wind and additionally intercept projectiles carried by the wind. Each of these aspects are explained in the coming paragraphs.



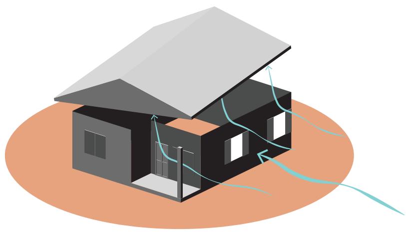
**1. Wind enters and leaves.**
*Less pressure and structure holds up*



**2. Wind cannot enter**
*Structure is strong and holds up*



**3. Wind enters one side**
Pressure build up



**Internal pressure lifts the roof**

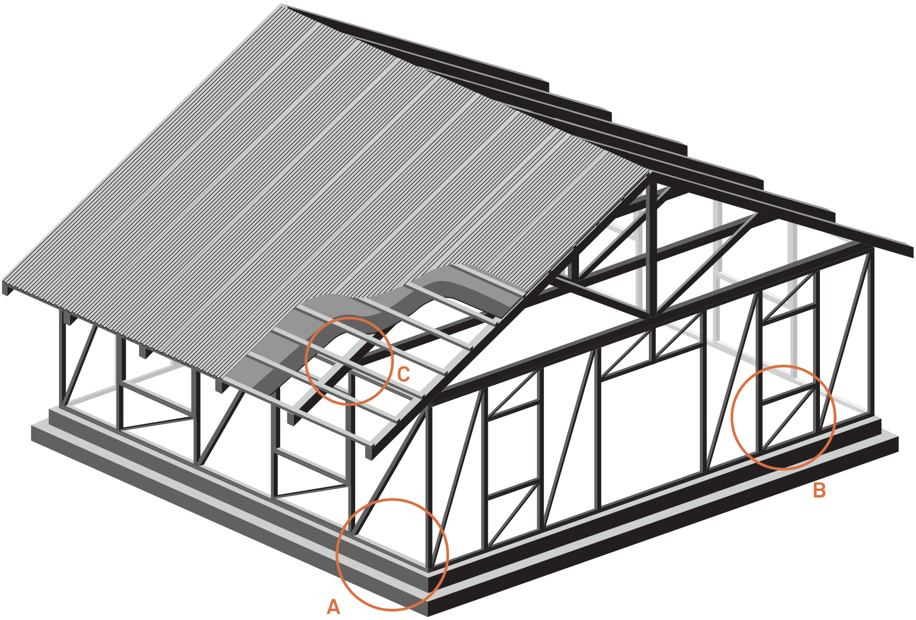
# B2. Projected area

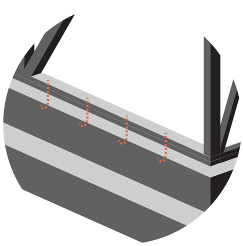
Wind pressure only becomes dangerous once it is applied to an object. Larger objects absorb more pressure simply because they have larger areas. For buildings the two strategies to minimize damage by wind are displayed on opposite page:

1. Minimize surface area (opening windows to facilitate wind flow).
2. Ensure structural integrity when high wind loads are applied on the building (close all openings).

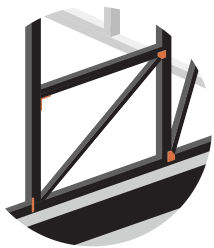
When the third situation  occurs the internal pressure becomes to large for the structure to withstand and as a result the roof is lifted from the building. It goes without saying that a building should be structurally sound and during a hurricane this becomes increasingly important. The Red Cross on St. Maarten provides a manual (2019) to inhabitants which explains how to make your house as safe as possible during the event of a hurriane. It is explained with the construction principles ABC’s, meaning:

- Anchoring, to prevent the building from overturning.
- Bracing, to prevent the building from racking.
- Connecting to prevent the building from sliding and uplifitng.

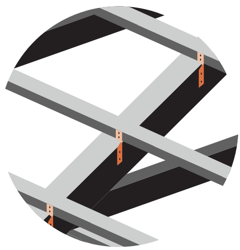


Anchoring



Bracing



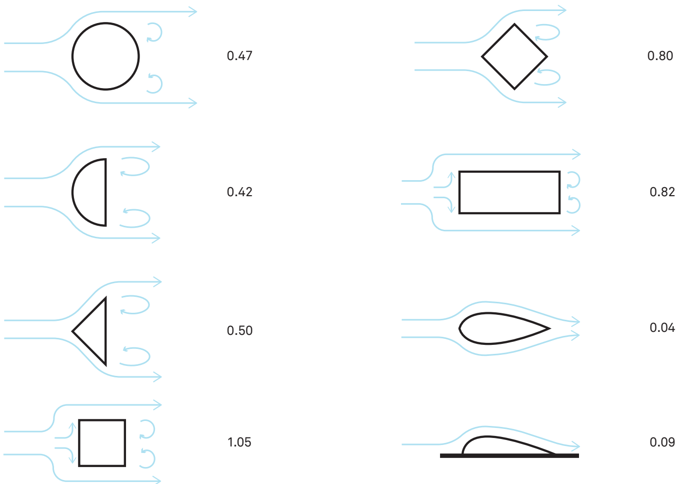
Connecting

**Anchoring**
The first priority for ensuring that your building will withstand a hurricane is that you have a good foundation to prevent *overturning or sliding*. A good foundation typically is heavy and is 'stronger than the wind' meaning that it can withstand the lift forces put on the structure. If the building is made from light materials, this should be compensated with a heavier foundation. Another point that needs attention is that the foundation should be lifted about 90cm (3 feet) to be protected against floods.

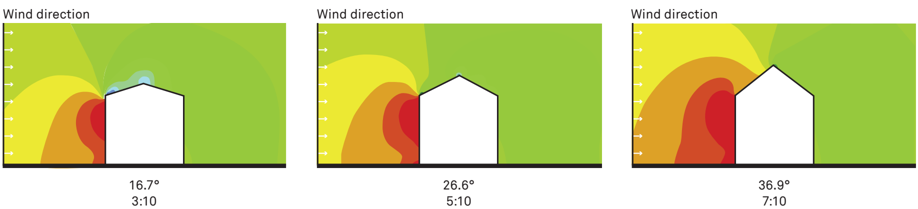
**Bracing**
Regarding the stability of the house all walls and the roof should be braced against to prevent the building from *racking* under heavy wind loads. The braces need to be able to withstand the wind loads. As a general rule, ideally the braces need to be put under a angle of 45º but between 30º and 60º is also good. There are several options to brace wood frame walls, such as thick galvanized steel wire or timber members.

**Connecting**
Connecting all the building elements together is a fundamental part of a safe structure. Every elements should be linked to the next to resist wind loads together. Foundation to walls, walls to roof structure, roof structure to roof finish. Hurricane straps are used to tie the roof rafters to the battens as well as the wall mullions to the transoms. Corrugated roof plates are connected with weather proof screws to the battens.

The information above is a summarization of the manuals released by The Netherlands Red Cross and Habitat for Humanity. More detailed information can be found in their construction manuals (The Netherlands Red Cross, 2019) (Perez, 2018).




*Measured drag coefficients for different shapes.*
*Image altered by author from: https://en.wikipedia.org/wiki/Drag_coefficient*

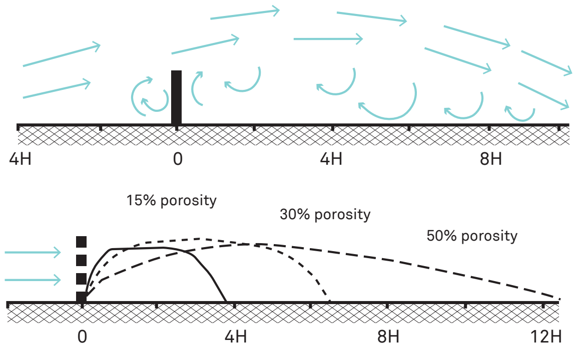



*Static pressure distribution for different roof pitches.*
*Source: Tomanaga, Y et al. (2014).*

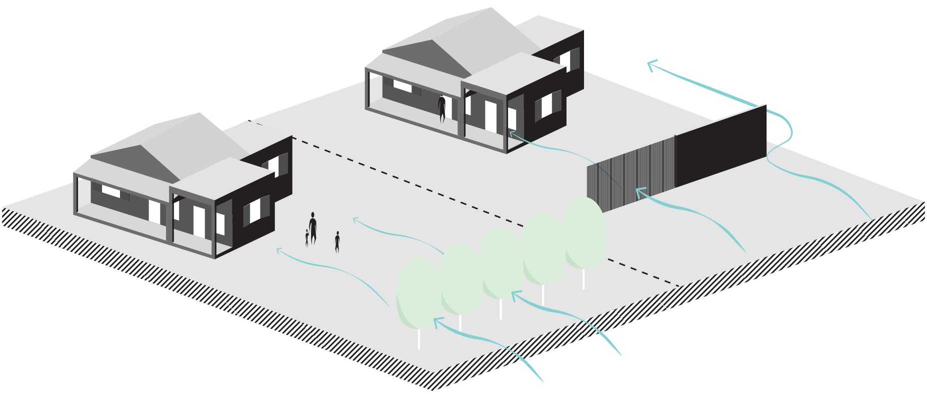
# B3. Drag coefficient

Wind flow design is a important aspect of designing hurricane resilient houses to minimize pressuer put on the structure by wind loads. Futhermore it is used for urban design and ofcourse skyscraper design. The drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment, such as air or water. The two most important aspects that inflience the drag coefficient are the surface friction and shape of the object. For the design of buildings in hurricane regions this is a aspect that cannot be overlooked and should be accounted for in the design. The top image on opposite page shows different shapes with their corresponding drag coefficients. The wing shaped object has the smallest drag coefficient and the square shape the highest.

When air can flow around the object without detachment of the surface, no turbulence is created and therefore less drag. Objects with sharp edges create larger pressure differences and turbulent areas around the object which creates more drag. In building design, the shape of the roof is often the cause of damage during hurricanes due to the pressure differences that are created. The bottom image on opposite page shows how different roof pitches influence pressure differences on the roof. The flattest roof has two areas where negative pressure areas occur and the steepest roof has to endure a significantly higher positive pressure on the windward side of the building. Roof design but also the shape of the building in plan affects how the building will be affected by high windloads.




*Top: schematic of wind flow near a windbreak. Bottom: Influence of porous windbreak materials on performance of the windbreak. Source: (Maraveas, 2019). Image adjusted by author.*



*Natural (left) and manufactured windbreaks (right) to reduce wind nuisance in and around the house. Image by author.*

# B4. Wind pressure

The last variable in the wind load equation is the wind pressure. The wind pressure cannot directly be influinced by the design of the building itself but rather the design of its surroundings. Strategically placed wind breaks produce drag force causing a net loss of energy and therefore disturb the characteristics of flow. The wind moves around the ends or over the top and creates a sheltered area behind it.

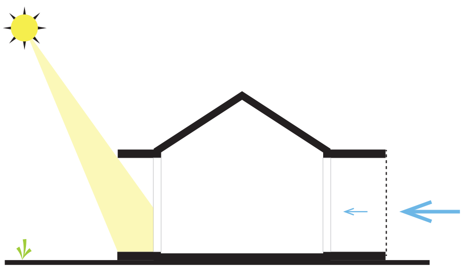
There is the option to use a natural windbreak instead of constructed windbreaks. Choosing for a natural windbreak can provide not only shelter from wind but also other benefits regarding the microclimate it creates. Throughout history, windbreaks have functioned as protection at farmlands for crops and livestock and to control soil erosion. More recently, they have been used for landscaping, visual screening, heat reduction, odor dispersion and noise barrier. The effectiveness of natural windbreaks depends on the height, width, density, porosity, orientation and arrangement of the windbreak. Where the height and width determine the extent of the protected area on the leeward side. Porosity is the most influential to the efficiency of windbreaks and is defined as the percentage of pore space to the space occupied by tree stems, twigs,branches and leaves (Bitog et al., 2011). This affects the degree of wind speed reduction as well as the shelter extent behind the windbreaks as shown on opposite page.

Windbreaks can be applied in various ways to create microclimates that contribute to internal comfort for homes or reduce and protect from high wind speeds (and projectiles) during hurricanes.

# Reference Project
Harunatsu architects - Villa 921
Okinawa, Japan

***Application of wind break***
This house is build on Iriomote-Island, part of Okinawa in the South of Japan.  The interesting aspect of this house and the reason why it is included in this chapter is that it features a possibilty to apply a windbreak net to the facade. The first protection are the wooden sliding doors (Amado) which protect the house against the typhoon, which can last several days. The 'Amado' sliding doors are a special japanese door which translates as 'storm door'. These doors are strong enough to withstand typhoon winds.

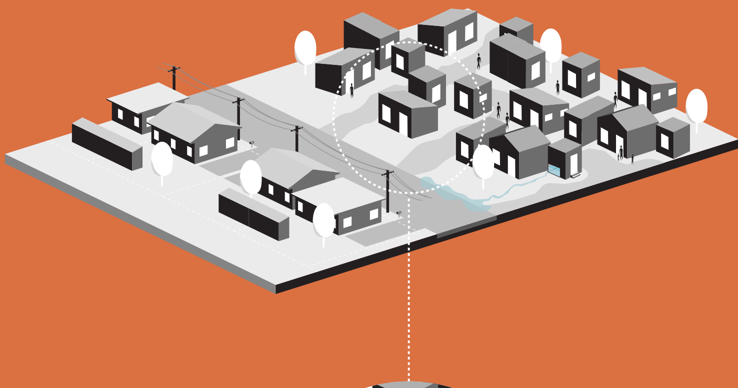
Because of power outages during typhoons, electric air conditioning cannot be used. To be somewhat comfortable inside the house during that time the doors are opened. Wind protection nets are then installed on the eaves to protect the inside against airborn projectiles. The structure itself is constructed out of reinforced concrete which is resistant against high wind loads due to its weight and strength (tensile and compressive).



# Passive Climate Design Strategies

# Tropical Savannah Climate

Cluster

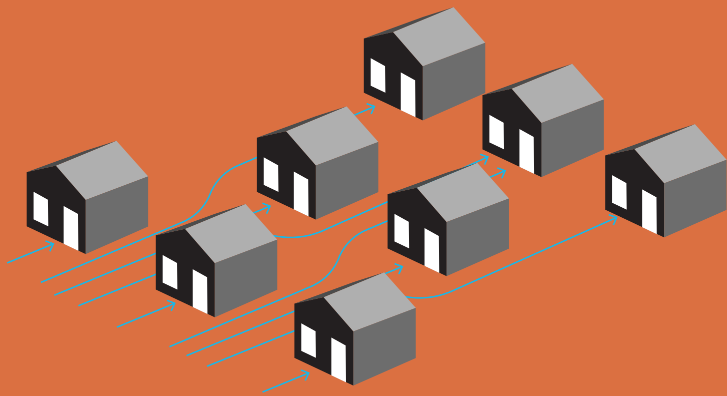


Building

The main body of research consists of passive climate design strategies which can be applied on St. Maarten but also other countries with a Tropical Savannah Climate. There are several literature sources that contain design strategies which are included in this catalogue. The largest part of these strategies is retrieved from the book “Sun, Wind and Light” and the PhD research project “Climate-Responsive Design”. This collection consists of passive design strategies that are applicable in hot arid -and humid climates. These strategies are important for the application on buildings in St. Maarten to make sure the architecture reflects the climate (again).

The additional angle this research provides is that it takes into account that hurricanes are also part of St. Maarten’s natural environment. Already discussed before are the climatic characteristics and what to take into account when designing against hurricanes. Every Passive Climate Design Strategy (PCDS) forms a chapter over 2 different scales: Cluster and Building scale. Every chapter consists of a general discription of the PCDS, a part which describes which climate characteristics on St. Maarten are important when applying the strategy and a part which describes what to take into account when applying the strategy with regards to hurricane design.

# 1. Urban scale



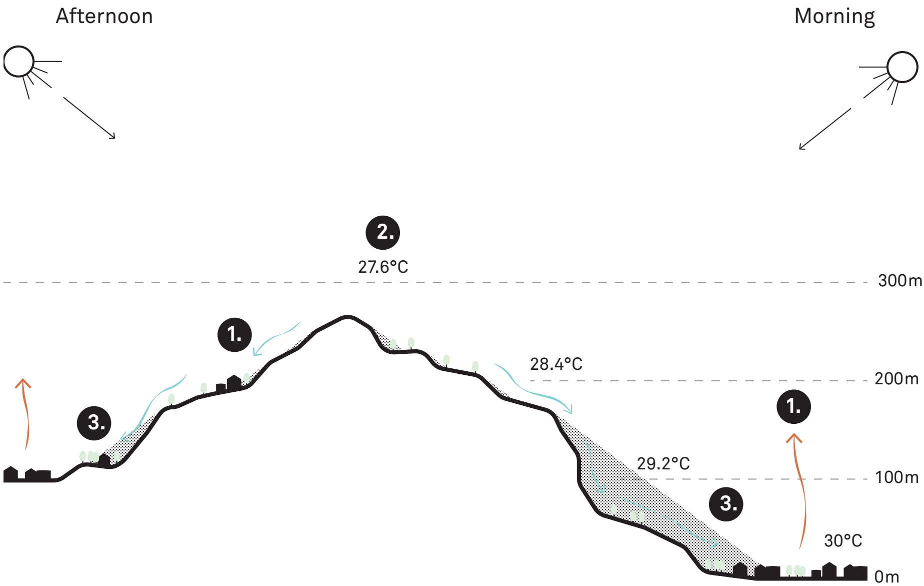
## Contents


| | |
|---|---|
| 1.1 Topographic microclimates | 34 |
| 1.2 Urban microclimates | 38 |
| 1.3 Urban microclimates: Shading open spaces | 44 |
| 1.4 Urban patterns & ventilation corridors | 48 |
| Recommendations Cluster scale | 56 |

The strategies in the Cluster scale section deal with the range of scales that extends beyond the single building to a cluster, block, town or city. The major architectural elements that are addressed are buildings, streets and open spaces, which are the primary pieces that make up building groups. The strategies are mostly concerned with relationships between those pieces, either between buildings or between buildings and open spaces or streets.

Larger scale strategies can be difficult to implement because the designer frequently does not have control over the larger site or urban pattern. However, these strategies are critical to passive design at the building scale because they control access to the site resources of sun, wind and light. Also because they can have a major impact on reducing or magnifying the heating, cooling, and lighting loads to which buildings are subjected. Even though a designer sometimes only controls one building on a site, the form and placement of that building creates a particular set of relationships with the street and with neighboring buildings, configures open space between buildings, and creates distinct microclimates around the building.

# 1.1 Topographic microclimates




*Topographic microclimates on hillsides as explained in-text.*
*Image by author. Source of principles: DeKay and Brown, 2014.*

On a larger scale the topography, solar radiation and wind together produce microclimates that emphasize characteristics of the area's macroclimate. These microclimates can make certain areas within the topography more desirable that others. The principles that can be applied to predict the microclimate on a site are described below.

**1. Air movement is driven by density**
Cool air that is formed at night flows downhill because it is denser than hot air. Higher elevation landforms shed cool air and concave forms collect it.

**2. Temperature varies with elevation**
Higher elevations are cooler than lower elevations. Air moving down a slope will therefore be cooler that the air it replaces below. The cooling rate close to the ground is 0.8 °C for each 100 meters of elevation.

**3. Solar radiation differs per terrain aspect**
The differing terrain aspects are a combination of the slope and orientation towards the sun. Terrains with a face perpendicular to the sun's rays receive more solar radiation than other orientations. South facing slopes receive the most sun, East facing slopes more morning sun and West facing slopes more afternoon sun.

**4. Using water bodies to moderate daily and annual temperature ranges**
Sites near large water bodies like oceans and lakeshave less variations between day and night and summer and winter than inland sites. This effect gives differences in microclimates over relatively short distances, especially within 20 kilometers of sea. St. Maarten being a small island with the longest stretch of land is coast to coast about 13 kilometers will not experience benefits of this principle.

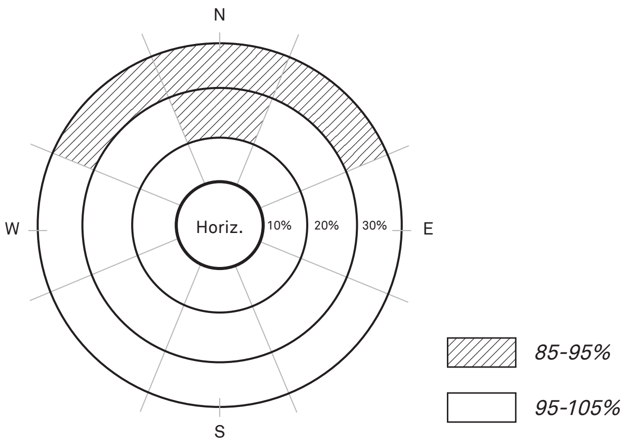


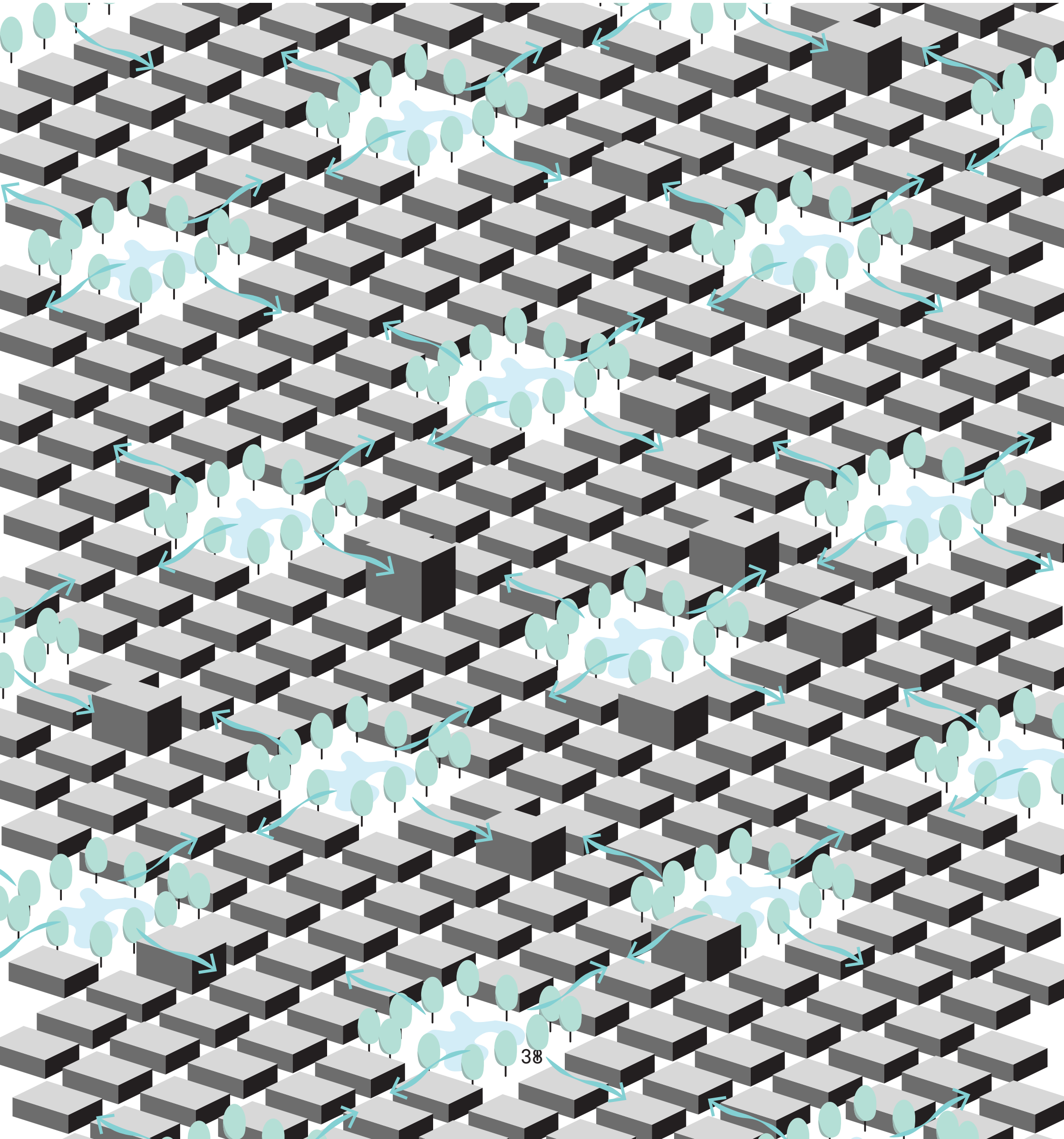

*Diagram showing the combined effect of slope and orientation on the percentage of radiation that falls on a surface in regions of 16° North latitude.*
*Source: DeKay and Brown, 2014.*

St. Maarten has a Tropical Savannah climate with a distinct wet and dry season. Due the the high RH, St. Maarten can be regarded as a hot-humid climate. Thus the following design objectives are important:

- Shade and wind flows need to be maximized.
- The best microclimate location is at the top of a hillside slope for exposure to wind and on East orientations to decrease solar exposure in the afternoons.

The microclimates on St. Maarten that benefit from air movement driven by density **(1)** are at the bottom of a slope during the dry season during the months January till June. The island's highest point is at 424 meters and most hillsides are very steep which makes them hard to build upon making the principle of building on higher elevations difficult **(2)**. The diagram on opposite page shows that North facing slopes of a hill receive less solar radiation than on all other orientations. The slope steepness has little effect. Only few places in St. Maarten are affected by this principle **(3)**. Lastly, the whole island of St. Martin enjoys temperature moderation by the sea and other water bodies **(4)** like the Great Salt Pond and Simpson Bay Lagoon. This shows in a year round stable ambient air temperature with a minimum of 24 C at night and a maximum of 30 C during the day.

# 1.2 Urban microclimates



**Mixed buildings and water bodies & green areas**
It is possible to create microclimates within cities without making use of the topography as discussed in previous chapter. In cities, due to the production of heat by urban structures and absorbance and reflection of solar radiation, Urban Heat Island's (UHI's) are created. Most surfaces in a UHI are non-reflective, water-resistant and have a low percentage of vegetation. Shishegar (2014) concludes that there are three processes that can reduce the UHI effect:

- Evapotranspiration.
- Direct shading on surfaces .
- Influence on air movements and heat exchange.

Temperatures can be reduced to up to 4°C in a treed urban environment. This reduction depends on the size of the park, the amount of trees and grass cover in the park and the choice of species. Trees provide cooling by evapotranpiration and by direct shading on surfaces. Evidence shows that temperatures beneath individual and clusters of trees are lower than temperatures in open areas (during the day) (Shishegar, 2014).

Green areas and water bodies influence temperature differences. Wu and Zhang (2019) found the cooling effect of water bodies in the Suzhou Bay area (31° N latitude) decrease as the distance from the water bodies increases. Water bodies have a greater specific heat capacity compared to other physical objects, meaning that water bodies do not heat up as fast as other materials. This results in a cool island effect in the daytime depending on the size of the water body. Smaller pools just warm up faster than big ones. In the case of Suzhou Bay, a large bay reaching far into the city of Suzhou, the cooling effects are significant in areas within a horizontal distance of 800 meters which show a maximum decrease in temperature of 3.02°C.

*Airplane view of the Villa el Salvador district in Lima, Peru.*
*Source: David Almeida, Flickr.*

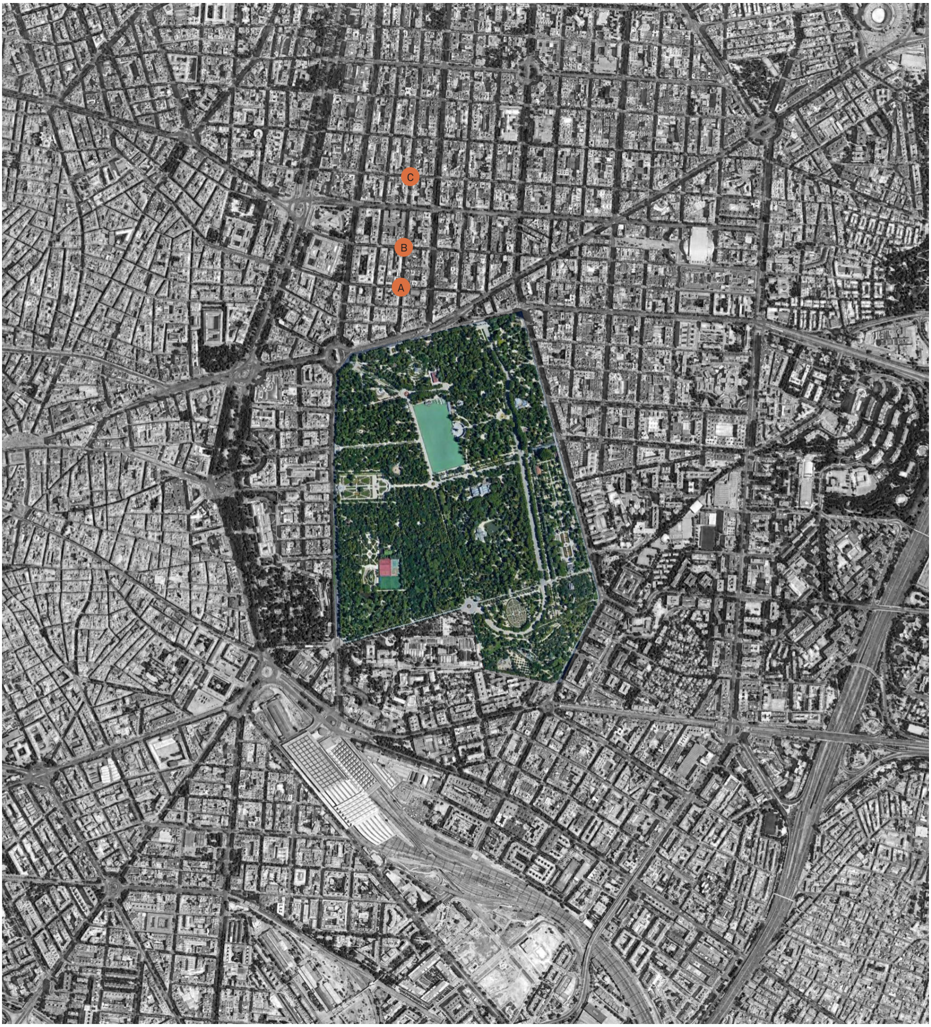
**Green edges**

Instead of mixing green and water areas within the city, it can also be placed at the edges as an alternative. In an arid climate, a tree can transpire up to 380 liters of water a day. In a hot dry climate, this cooling effect equals that of five air conditioning units running for 20 hours (Akbar et al., 1992). This cooling effect is raised by wind and water. Wind exchanges air more rapidly, taking the cool air vapor from trees. When this cool air is then taken to a urban area it can have a significant cooling effect as discussed before in this chapter.

DeKay (2014) discusses the effect in the city of Lima, Peru. The designer of this area placed a vegetated zone between the pacific ocean and the district. Lima is very dry, with almost no annual rainfall. Therefore the already more humid ocean breezes flow through the vegetated area and is further cooled by the trees. For this strategy to be effective, ideally the green edge would have to be 40-60% of the size of the area to be cooled.

# Reference Project

Retiro Park
Madrid, Spain.

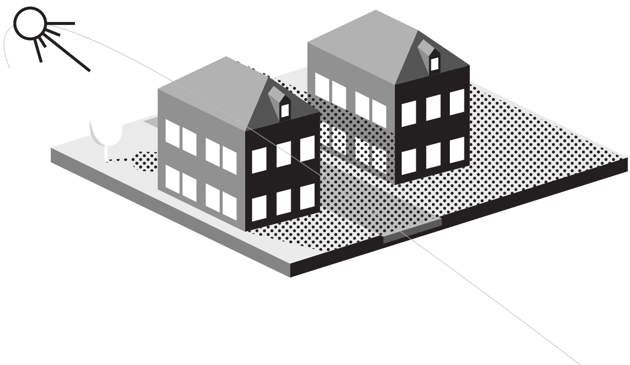


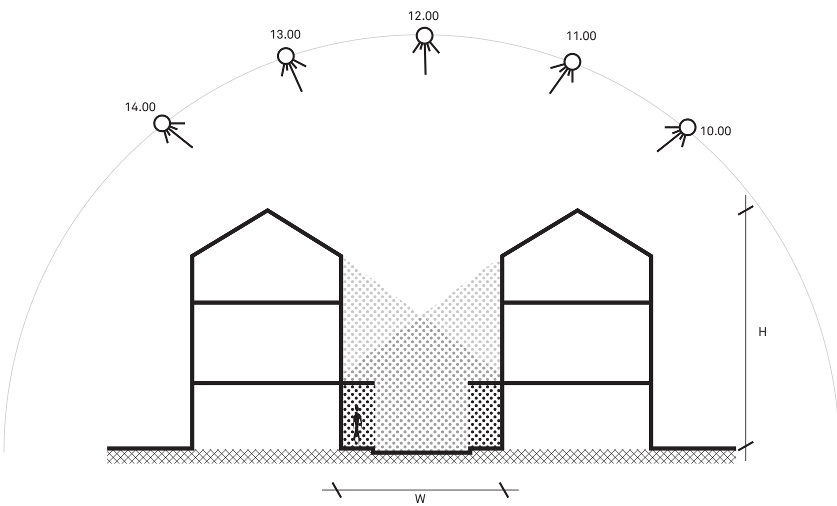

*Retiro park in Madrid, Spain.*
*Source: Google Earth.*

A study was done to investigate the potential of large urban parks in providing urban comfort for citizens living within the park perimeter. The study focused on Retiro park in Madrid and collected data from three different areas, in increasing distance from the park, during six hot summer days. The results show that the park has a cooling effect on its surroundings, especially at distances close to the park (within 380 meters). Point A was set at 150 meters from the park, point B at 380 meters and point C at 665 meters from the park. The biggest difference in temperature between point A and C and was 1.9°C (Aram et al., 2019).

The previous examples show the effect of urban green and water bodies in an urban context. Sint Maarten is a small island and is surrounded by the Atlantic ocean and therefore does not have a typical urban environment such as Madrid or Lima. Due to its high RH, evaporative cooling will not be very effective in Sint Maarten's climate. What can prove effective are large water bodies reducing surrounding temperatures due to their specific heat capacity, such as the Salt Pond. Water absorbs heat at a slower rate than concrete and asphalt which creates a cooler microclimate. Also for villages further away from the coast or Salt Pond, green spaces can provide shaded areas to cool its surroundings. Here, careful design is necessary because vegetation can obstruct the wind flow for buildings. And natural ventilation is of maint importance to passively cool buildings in St. Maarten.

# 1.3 Urban microclimates: Shading open spaces





On urban scale the period of comfort outside as well as inside can be extended by providing shaded areas in combination with good ventilation. One option is to is to share shade from surrounding buildings. In hot arid climates this strategy is often used.
During the day, tops of buildings receive more direct sunlight, meaning that they are absorbing more energy. The streets receive less sunlight, absorbing less energy. Although during the night the tops of buildings lose more of their absorbed heat because they have a larger sky exposure angle than the streets. When the tops of buildings are cooled down, the cooler air cascades down to street level. This process is enhanced when roof's slopes are angled towards the streets.

The temperature difference between air and surface has been tested in Dhaka, Bangladesh and there is a significant difference when deciding the ratio between height of the buildings and width of the street (H/W ratio). A H/W ratio of 1:1 shows to have a daily temperature of 4°C higher than a H/W ratio of 3:1 (Ahmed, 1994). The shared shade strategy using these canyons that are created between building walls and street function best when oriented on the North-South axis. Providing shade to the East and West facades of opposing buildings as well as the street which lies between as shown on opposing page. When the sun is at its highest point, horizontal elements such as porches and overhangs can provide shade.

Depending on the circumstances, shade can be provided by vertical elements such as buildings, by horizontal elements or both. Providing horizontal shading objects is a balance between the shade provided by vertical and horizontal elements.

*Outdoor tent structure which is used for performances and religious services in the neighborhood of Belvedere. These can be found all accross the island.*
*Image from author.*

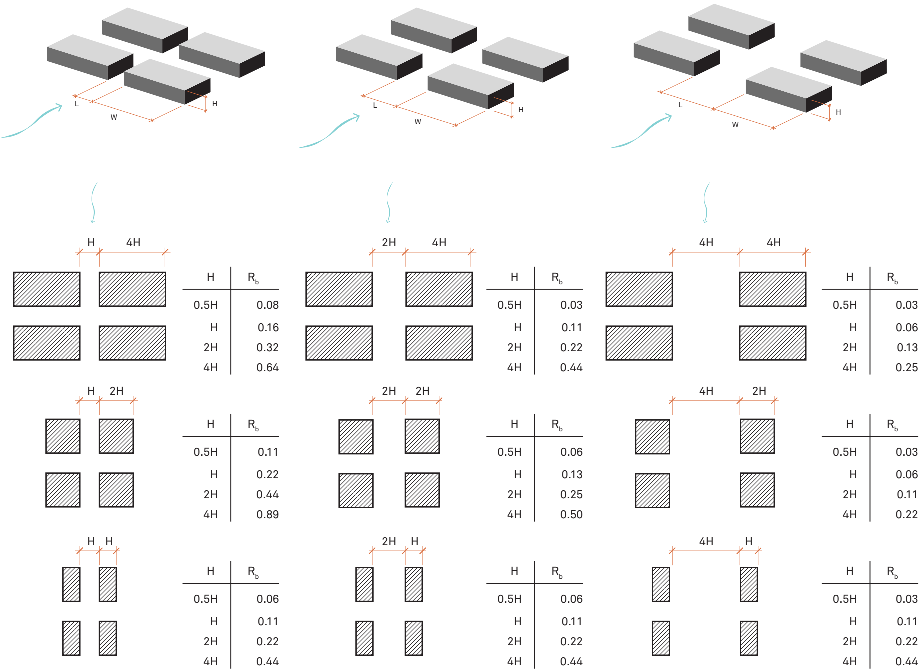
On St. Martin it is a necessity to have shaded spaces when people intend to spend time outside. Climatic analyses A3 and A4 provide information about the average hourly solar radiation and temperature per month through the year. From this information it is evident that most of the time there is a necessity to provide cooling to living spaces. The open tent structure displayed on opposite page is an example of a outdoor gathering place where people come to attend religious services or watch a performance of some sort. Such a structure is ideal for its purpose due to its lightness, openness and it is a structure that can be easily broken down and placed somewhere else.

The temperature table in chapter A4 shows that only in the early mornings and later in the afternoon it is comfortable to be in these spaces without additional cooling. When services are organized in between these moments, additional cooling should be accounted for, especially during the summer months. Often you'll see additional ventilation units underneath the tents because natural ventilation does not provide the necessary comfort. Access to natural ventilation is very important for the location of these tents to minimize the necessity of ventilation units. Focus on the design of urban spaces then becomes very important, to maintain access to natural ventilation, see strategy *Urban patterns & ventilation corridors (1.1)* .

# 1.4 Urban patterns & ventilation corridors

In dense urban areas, the use of ventilation corridors can contribute to the air movement through the city when oriented parallel to the regional wind currents. When these currents are calm, the urban heat island affects hot, less dense air to rise and high density cooler air to move to that low pressure area (centripedal wind patterns). Connecting ventilation corridors to down currents of cool air from higher surrounding areas can provide green cool air in dense areas.
Additionally, because of high density urban patterns the heat tends to accumulate and remain in the dense city. The surrounding countryside cools quicker under the night sky which creates a density difference between the city and countryside. The hot air rises and creates a negative pressure difference to pull in the cooler surrounding air.

Orienting main streets to the prevailing wind direction improves the possibility for effective cross ventilation in buildings. DeKay (2014) writes that the orientation can differ at the most 20-30° from the prevailing wind direction. Especially in humid climates it is important that buildings have access to natural ventilation to take away excess heat from inside. Whereas in arid climates cross ventilation is not always preffered because it can be hot and carry dust. St. Maarten, being a tropical climate, needs the prevailing wind to reach within the urban areas to take away the hot air. This air movement is the only option to attain physiological comfort at high temperatures, because it affects both evaporative and convective heat losses from the human body (Priya and Kaja, 2016).




| H | $R_b$ |
|---|---|
| 0.5H | 0.08 |
| H | 0.16 |
| 2H | 0.32 |
| 4H | 0.64 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.03 |
| H | 0.11 |
| 2H | 0.22 |
| 4H | 0.44 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.03 |
| H | 0.06 |
| 2H | 0.13 |
| 4H | 0.25 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.11 |
| H | 0.22 |
| 2H | 0.44 |
| 4H | 0.89 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.06 |
| H | 0.13 |
| 2H | 0.25 |
| 4H | 0.50 |

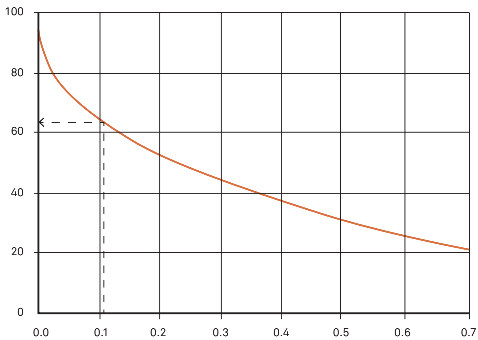
| H | $R_b$ |
|---|---|
| 0.5H | 0.03 |
| H | 0.06 |
| 2H | 0.11 |
| 4H | 0.22 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.06 |
| H | 0.11 |
| 2H | 0.22 |
| 4H | 0.44 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.06 |
| H | 0.11 |
| 2H | 0.22 |
| 4H | 0.44 |

| H | $R_b$ |
|---|---|
| 0.5H | 0.03 |
| H | 0.11 |
| 2H | 0.22 |
| 4H | 0.44 |

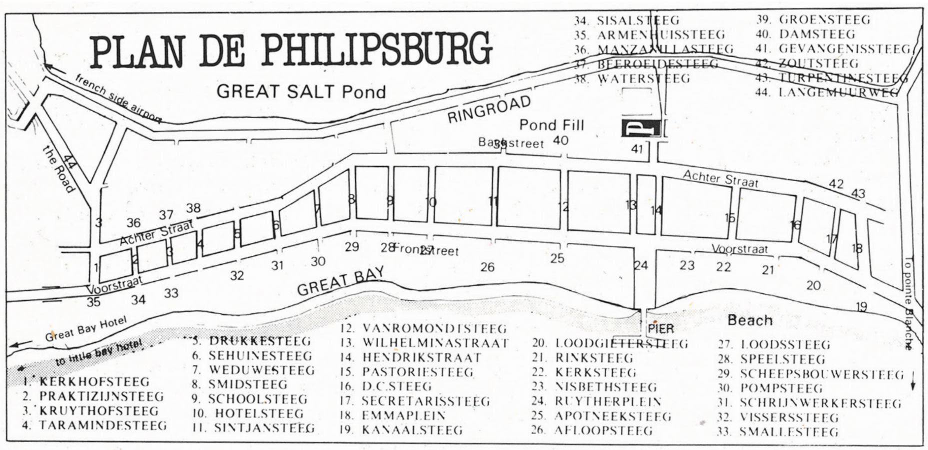
*Building group organizations and dimensions that influence the blockage ratio.*
*Image adjusted by author from source (DeKay, 2014).*



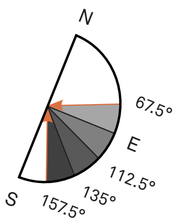

*The percentage of the undisturbed wind speed that is left in the alleyways can be read from the graph as a function of the blockage ratio on the x-axis.*
*Image adjusted by author from source (DeKay, 2014).*

To predict wind velocity in streets, the blockage ratio of a given building group organization is an important number. The blockage ratio is defined as: $R_b$ = (W x H). What this looks like in a certain building group organization is dislpayed on opposite page. Additionally a graph of the wind speed in the streets as a function of the blockage ratio is displayed. These rules of thumb are helpful for determining how a urban plan can function regarding wind flow and as a result the cross ventilation in the buildings.
For example,  if we take a building group with blocks of 7m (H) in height and a width (W) of 28m (4H) with a space between them (L) of 14m (2H). This gives us a blockage ratio (Rb) of 0.11. Looking at the windspeed translation table the windspeed will become only 60% of the undisturbed wind speed.

When designing, these rules of thumb are very important especially in a Tropical Savannah climate like St. Maarten. Even with large spaces between buildings, their height greatly diminishes the windspeed.




*Plan of Philipsburg in 1985.*
*Source: Van Andel, 1985.*

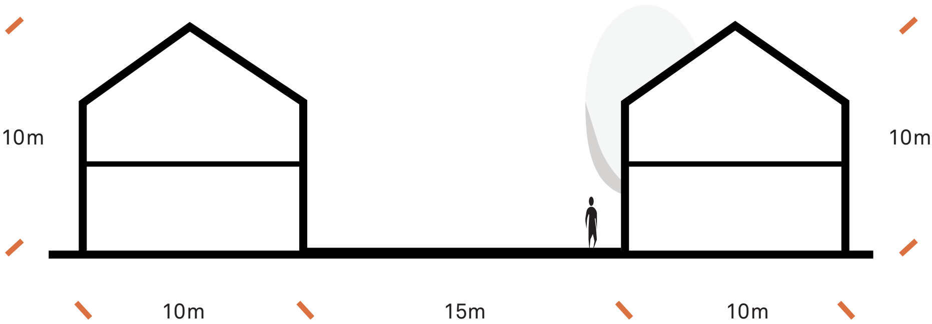



*Wind direction window (yearly).*

**Climate**
Looking at the plan of Philipsburg it seems that the strategy of adding ventilation corridors has played a role in the planning of the city. Before progress and tourism came to St. Maarten, Philipsburg was mainly a residential town with one to two story houses and a lot of vegatation with water on both sides. Ideal conditions for a town in a tropical climate.

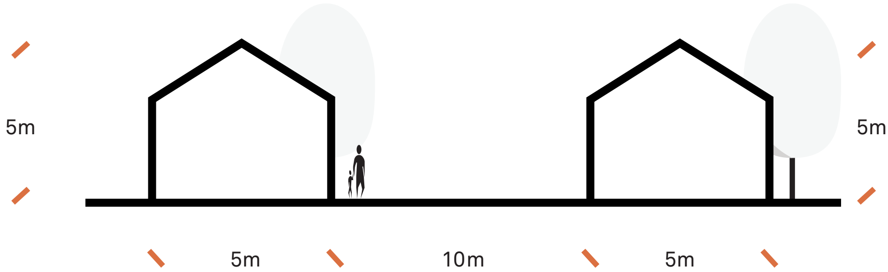
The sand-ridge that Philipsburg is build upon has the advantage that it is a flat piece of land where goods can easily be brought ashore. There are three main traffic roads running parallel in the length of the sand-ridge: Front street, Back street and Ring road (now Walter A. Nisbeth Road) as shown on opposite page. Between these streets there are alley ways, connecting the Great Salt Pond to Great Bay. These alleys made it possible from the beginning to take the salt directly to the beach of the Great Bay where it could be shipped. The city was planned this way for practical reasons, along the coast and build on a rectangular system with its most important street situated on the sea side. Altough it is mentioned by Van Andel (1985) that 'the trade winds coming from the sea blows some coolness through the alleys'.

Chapter A5 shows the average wind direction and speed through the year. The average wind direction is East to East-Southeast with a constant (average) 4 m/s windspeed. This direction is almost perpendicular to the orientation of the main traffic streets in Philipsburg. From the time that people started to live in Philipsburg this would have been a comfortable environment to settle in. This shows in old pictures of Philipsburg where porches were located towards the street and people lived outdoors, shown on the next two pages.




*The buildings in this part of Front Street are about 10m tall, 10 wide and the space between them is 15m. This gives a blockage ratio of 0.11 and similarly to the example a wind speed of about 60%. Sint Maarten has a average wind speed of 4 m/s, leaving only a windspeed of 2.4 m/s on street level.*

*Front Street a few years after picture on opposite page. The first car was introduced to St. Maarten in 1914. Source: Van Andel J.D., 1985.*




*The buildings in this part of Back Street are about 5m tall, 5 wide and the space between them is 10m. This gives a blockage ratio of also 0.11 and a wind speed of about 60%. The blockage ratio is the same in these two instances because of the low buildings and wide street.*



*Back Street in 1897. Source: The Saba Islander.*

# Recommendations
## Cluster scale

As mentioned in the introduction of this chapter, the strategies discussed before are critical to passive design at the building scale because they control access to the site resources of sun and wind. For application on St. Maarten, all of the previously mentioned strategies are applicable, yet some more than others. Due to its climate and position, the ambient air temperature remains a steady 27-30°C during the day and 24-26°C during the night. During the day, this is a uncomfortable temperature, especially in direct sunlight.

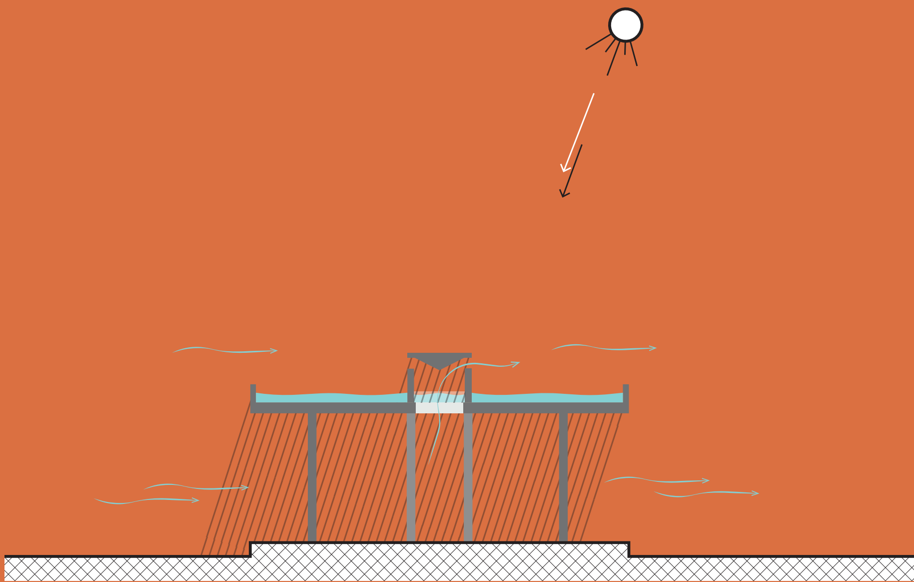
One segment of the strategies revolves around the creation and recognition of microclimates. These are two strategies (1.1 & 1.2) which try to **minimize solar heat gain** on surfaces. Firstly, by recognizing favorable topographic microclimates which are cooler and secondly by creating favorable microclimates with vegetation and water bodies in areas with a higher density of buildings and thus absorb more solar radiation (UHI).

Another segment addresses how to **maximize shading** in public spaces and thereby preventing solar radiation from further heating up surfaces and the environment in general. This is shown in *Shading open spaces* (1.3). The tent structure on St. Maarten shows that it is a necessity to have shading when being outside during the day and also that additional cooling is necessary, which is often provided by ventilation units. This is when access to natural ventilation becomes important.

The design strategy *Urban patterns & ventilation corridors (1.4)* elaborates on the effect of urban density on the wind speed on ground level. Particularly in the climate of St. Maarten does natural ventilation play the most important role with regards to passive cooling. Ventilation or air movement affects both evaporative and convective heat losses from the human body (Priya and Kaja, 2016). Urban design on St. Maarten should therefore, as a matter of main importance, revolve around **access to natural ventilation**, to public spaces and to buildings.

All the discussed strategies can contribute to a cooler urban environment, yet the access to natural ventilation has the biggest impact on comfort levels. This is due to the relatively constant temperatures caused by the tropical-humid-sea climate that St. Maarten has. Allowing ventilation to reach public spaces and buildings affects the comfort levels of the people around and inside those buildings making it the most important tool to use in St. Maarten.

# 2. Building scale



## Contents


2.1 Permeability: cross -and stack ventilation 60
- 2.1.1 Cross-ventilation: wing walls 68
- 2.1.2 Cross ventilation: wind catcher 74
- 2.1.3 Stack-ventilation 82

2.2 Zoning for cooling 86
- 2.2.1 Zoning: buffer zones 88
- 2.2.2 Zoning: transformations 100

2.3. Cooling mass: roof pond 104

Recommendations Building scale 110

The building scale is subdivided in a couple of categories, distinguishing several principles to maximize passive cooling inside homes. The cluster scale strategies ensure that a (passively cooled) wind flow reaches the buildings. The following categories can ensure a cooler interior on the building scale when applied correctly.

- **Permeability** of buildings (cross-ventilation). Ensuring that the natural wind flow can reach all rooms of the house and several options how to facilitate that.
- **Zoning** within the buildings (cooling zones, buffer zones). The effectiveness of design regarding the creation of comfortable zones within the home.
- **Cooling mass**. Strategies that help to provide a cooler interior space using material mass.

On the scale of the building this chapter aims to find the best strategies to provide passive cooling to buildings. As discussed in the Cluster scale chapter, access to natural ventilation is important to ensure comfortability. The design of the urban plan provides the buildings access to natural ventilation and the intent of the strategies in this chapter is to make maximum use of the provided wind flow.

# 2.1 Permeability: cross -and stack ventilation

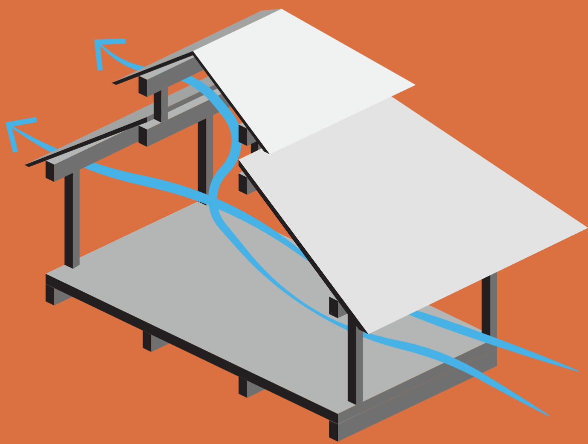
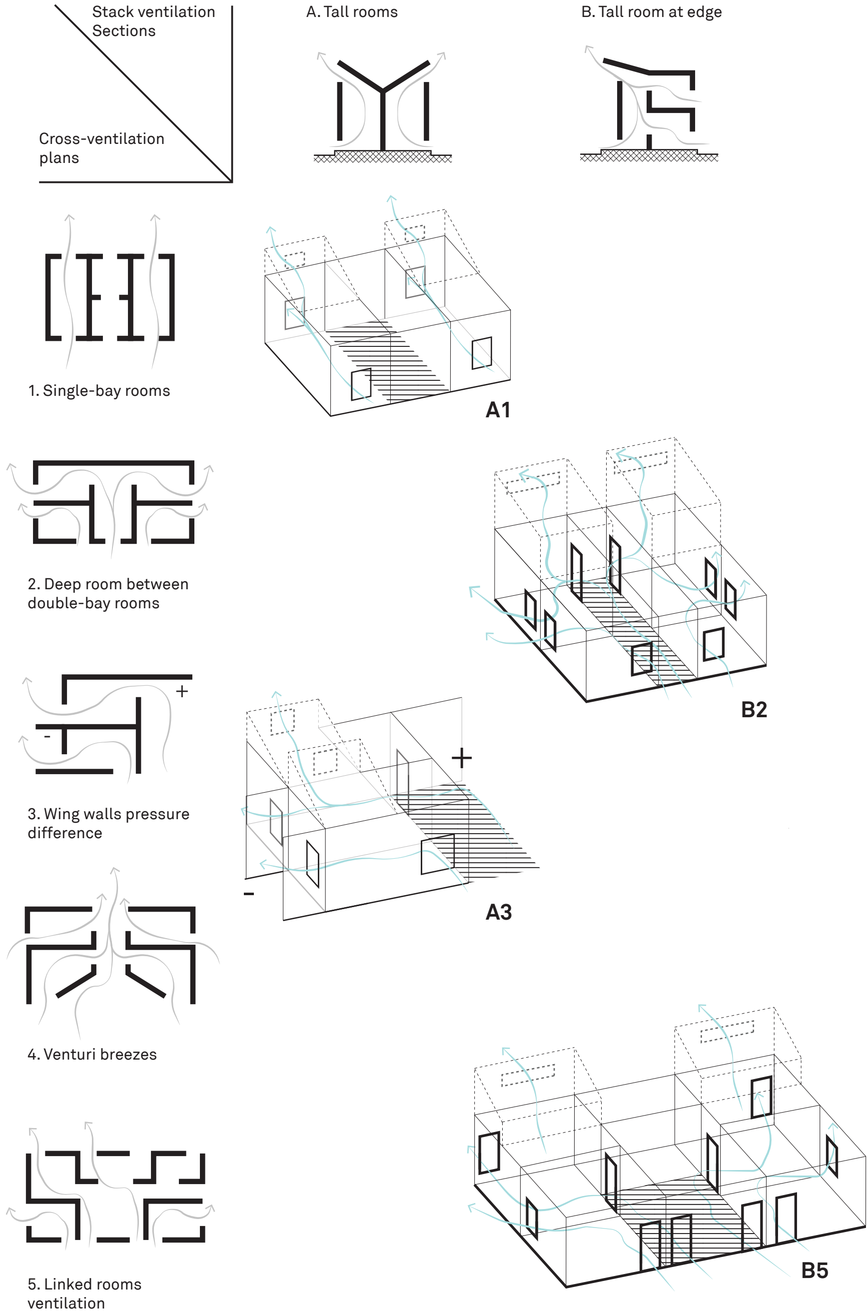


*Diagram of a combination of cross- and stack-ventilation*

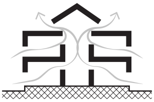
Cross-ventilation is a particularly valuable means of cooling during warm periods because it not only removes heat from the space but also increases the sensation of cooling by increasing people's rate of evaporation. However, in hot climates and in temperate climates at night, air movement is frequently slow, in which case stack-ventilation becomes an important supplementary strategy. Combined strategies may also be used for different rooms in the same building. For example, cross- ventilation might be used in windward side and upper level rooms, while stack-ventilation might be used in lee side and lower rooms that have little access to wind.

Both cross-ventilation and stack- ventilation work better in certain configurations, yet can be facilitated with a variety of different room organizations. When designing a scheme for both types of ventilation, parts of both the plan and the section must be kept open to air movement.

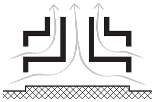
The ideal cross-ventilated building is one room thick, thin in plan and elongated to maximize exposure to prevailing winds. In practice, this is rarely possible in all but small buildings with few site constraints. In buildings more than one room thick and in all buildings with circulation corridors, the windward rooms can block the wind to leeward rooms. Stack-ventilation is dependent on the height between inlets and outlets and so is maximized by tall rooms and chimneys (DeKay, 2014). This chapter elaborates on the design for cross ventilation and stack ventilation inside buildings with the design methods: *wing walls, wind catcher* and *stack ventilation.*


Stack ventilation
Sections
Cross-ventilation
plans
A. Tall rooms
B. Tall room at edge
1. Single-bay rooms
A1
2. Deep room between
double-bay rooms
B2
3. Wing walls pressure
difference
+
-
A3
4. Venturi breezes
5. Linked rooms
ventilation
B5

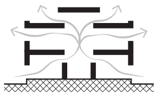
C. Tall room within

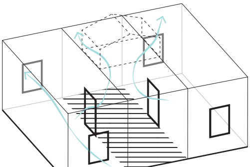


D. Stack vent every space

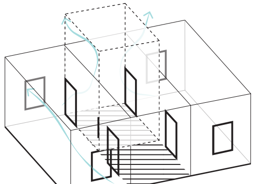


E. Use stair case as stack

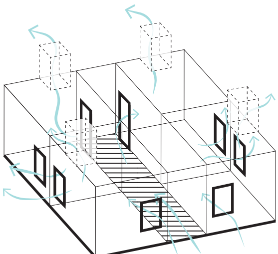




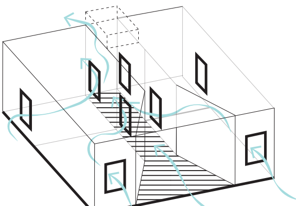
C1



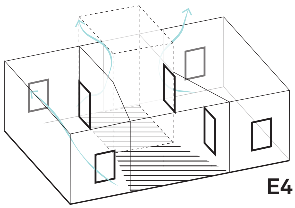
E1



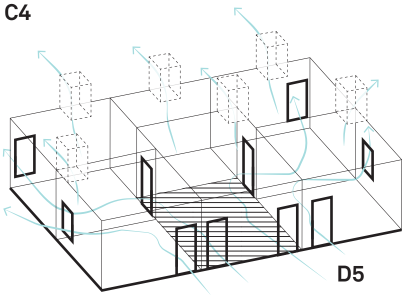
D2



C4



E4

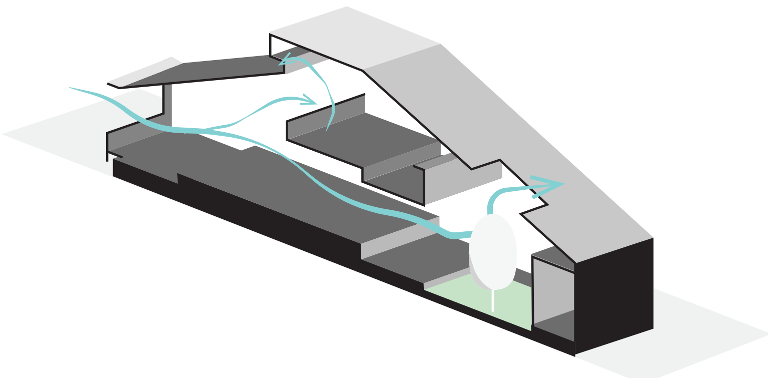


D5

# Reference Project

Charles Correa - Tube Housing
Ahmedabad, India

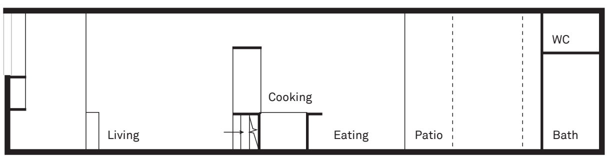
*Exterior of the Tube House on the windward side looking at the openings on the ground floor.*



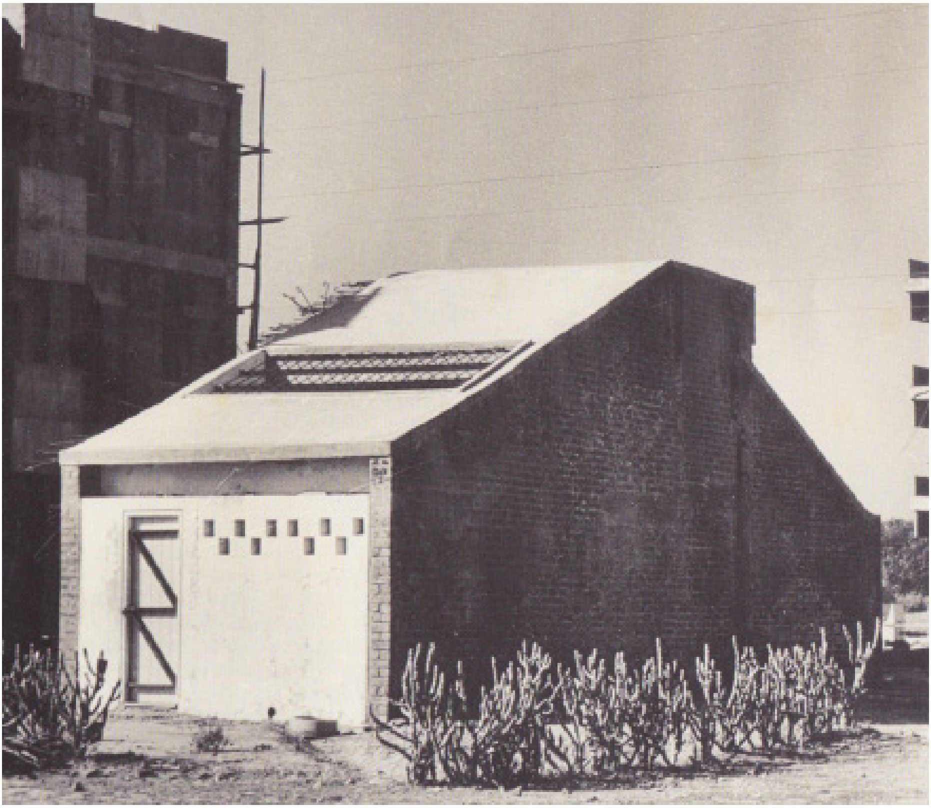
*Cross-ventilation diagram of the Tube House.*

**General information**
This building was designed in 1961 which was a period in which Charles Correa was interested in the design of affordable housing and planning that is designed according to the Indian climate and traditional way of living. With the tube house he won a design competition which was organised by the Gujarat Housing Board, to optain ideas for low-income housing.
The Tube house is an early example of Correa's 'Form follows Climate' philosophy. He managed to optain the required density by making deep narrow buildings. Research on possibilities to cross-ventilate and the limited materials at hand resulted in a closed building on the outside but opened up to the sky on the inside. The section is shaped in such a way so that hot air rises and exits in the top. This creates a convection flow in the form of stack-ventilation. The theme that returns





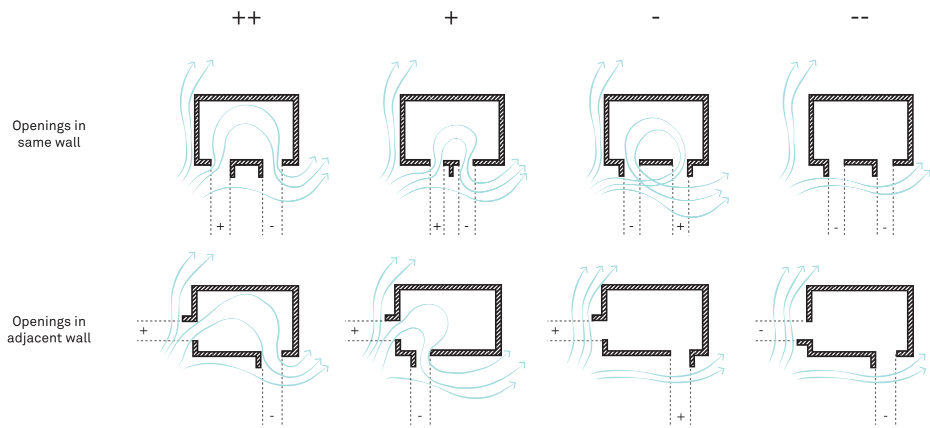

*Plan drawing showing the middle stairs, opening above the patio and connection of ground floor spaces.*



*Exterior of the Tube House where the opening above the courtyard is visible.*

*Interior picture of the Tube House.*

# 2.1.1 Cross-ventilation: wing walls

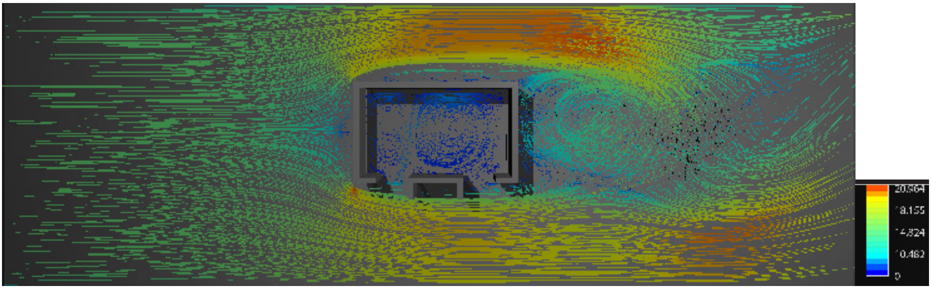


A method of improving the cross-ventilation inside a building is by using *wing walls* at facade openings. The windward side of buildings endure a positive wind pressure and the leeward side a negative pressure. If vertical elements are placed along the facade of the windward side of the building, a surface is created which is subjected to a positive wind pressure and a negative pressure on the leeward side of the vertical element.

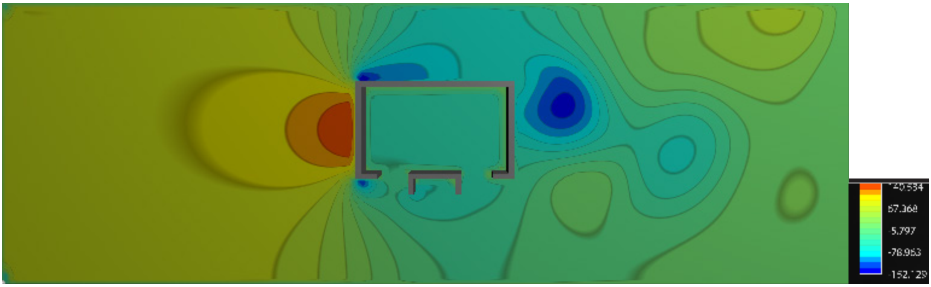
Where the *wing walls* need to be placed is dependant on the wind direction and the orientation of the building. The image on opposing page shows several strategies how to allow cross-ventilation into different rooms when the wind direction comes from a certain direction (South-West in this instance). This strategy is a very good alternative when there is no possibility to let the wind enter on the leeward side of the building.

The image shows that the best options are the ones where one *wing wall* is positioned so that it creates a positive pressure, forcing the wind to enter a room. Another wall is positioned next to another window in order to create a negative pressure which sucks the air out of the room, creating a cross ventilation effect.

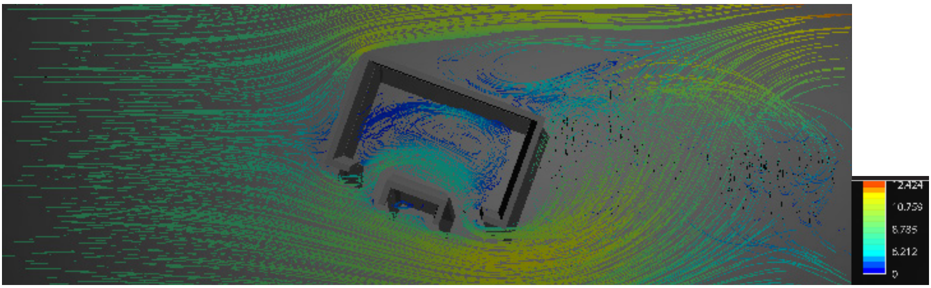
There are many options to choose from but some work better than others. The least effective options under the "-" and the "--" are the effect of misplaced wing walls. If the walls both create the same pressure, negative or possitive, this strategy will not work well (depending on wind gusts).



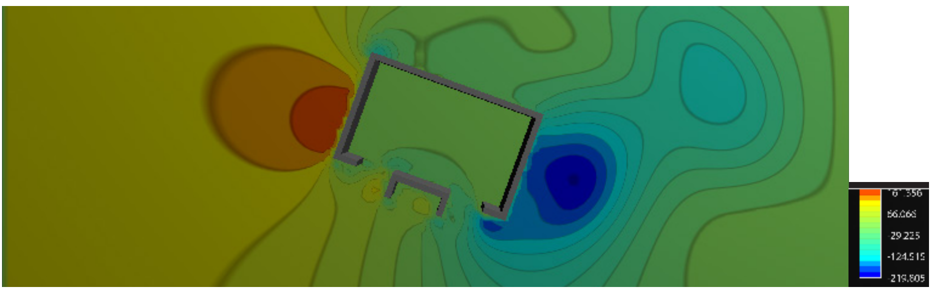
*Interior wind flow due to placement of wing walls parallel to the wind direction.*



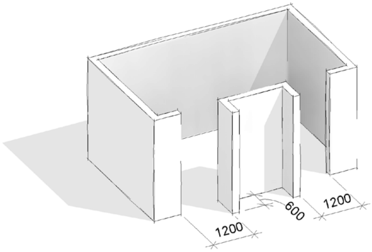
*Wind pressure on the building showing that the wing walls are barely put under pressure.*



*Interior wind flow due to placement of wing walls rotated 20° towards wind direction.*



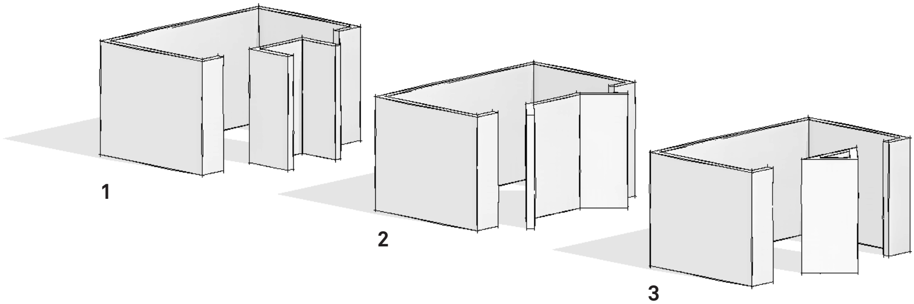
*Wind pressure showing that the wing walls are put under a positive pressure.*

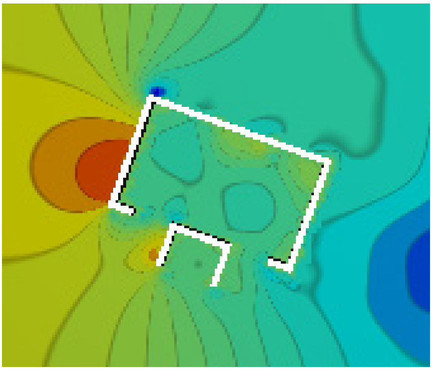



Above, a certain *wing wall* composition is shown, similar to the first composition on the previous pages (top left). The rule of thumb explains that the recommended *wing wall* length should be half or the full size of the window opening width (DeKay and Brown, 2014). The example below has half the size of the window openings.  This composition is put in a wind flow simulation software, Autodesk Flow Design. The images on the opposite page show the results of two differing angels. The first images show the window openings parallel to the wind direction and in the last two images the building is rotated 20° towards the wind direction.

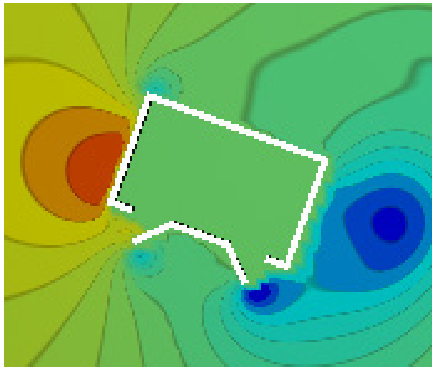
**Wind speed & pressure**
Both the wind speed diagrams illustrate that there is a difference in the interior wind speed when the wind direction approaches the building at an angle. When the wind direction is parallel to the facade openings, the use of wing walls is less effective. The wind pressure diagram elaborates this more clearly. The pressure difference between the two wing walls is minimal. That pressure difference is essential for this method to work. The wing walls in the second example clearly show a pressure difference, hance the effectiveness. This clearly shows that carefull attention is required in a early stage of the design process to ensure the effectiveness of this cross ventilation method.

**Hurricane resilience**
Altough wind pressure is necessary for this method to provide cross ventilation it is possible to adapt them to different situations. When there are larger wind speeds and the interior wind flow becomes uncomfortable, the wing walls can close or put in a different position to provide less, more or no interior wind flow. The next two pages display how the position of wing walls can influence wind pressures.

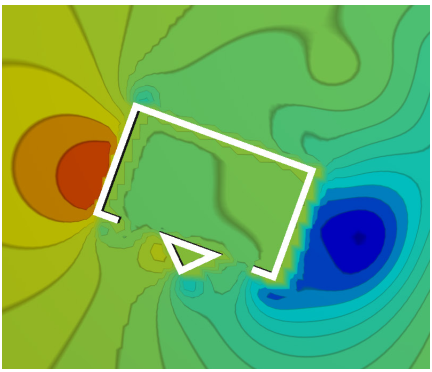


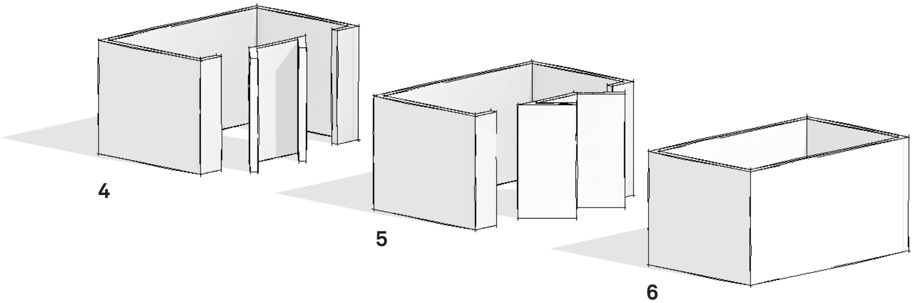
1 Wing walls perpendicular to openings.
Drag coefficient: 0.75

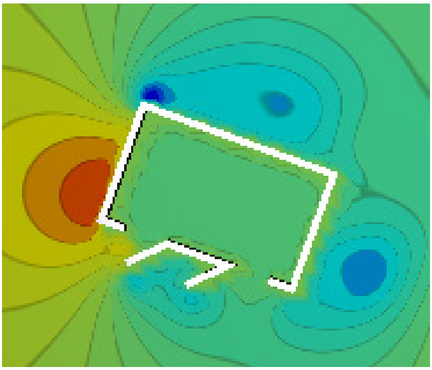


2 Wing walls half-way closed (45°).
Drag coefficient: 0.68

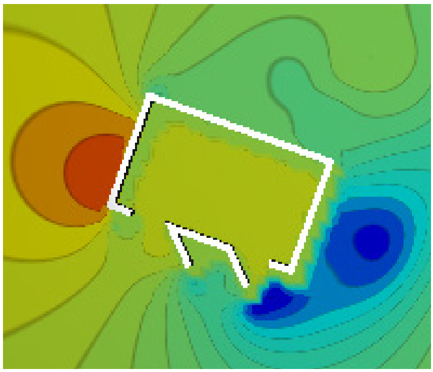


3 Wing walls half-way open (45°).
Drag coefficient: 0.86



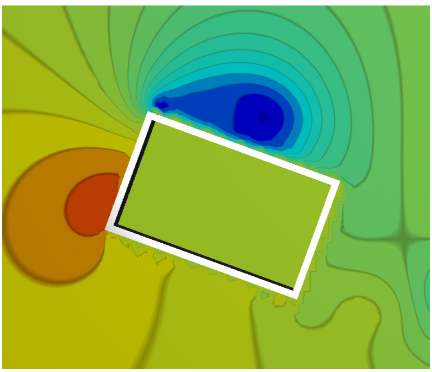



**4** Wing walls half-way open and closed towards wind direction (45°).
Drag coefficient: 0.76



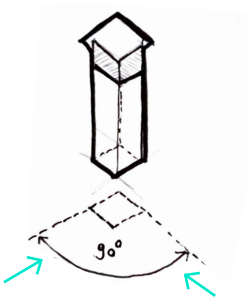
**5** Wing walls half-way open and closed away from wind direction (45°).
Drag coefficient: 0.87



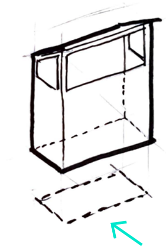


**6** Wing walls closed.
Drag coefficient: 0.77

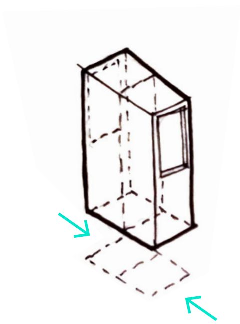
## 2.1.2 Cross ventilation: wind catcher



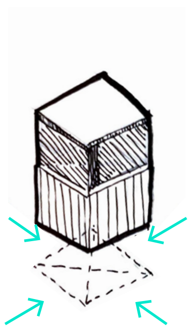

*A wind catcher mostly applied in Pakistan because the main wind direction is mostly within a 90° section of the compass.*



*The Egyptian wind catcher applied when wind blows consistently from 1 direction.*



*When wind directions fluctuate between two directions, the Iranian 2-sided wind catcher proves to be effective.*



*A Iranian wind catcher that is designed to catch winds from all directions.*

The wind catcher, which was an inspiration for the design of the previously mentioned Tube House, was applied for the stack effect by Correa. Wind catchers or chimneys are chimney-like elements that tower above roof level and are able to catch the more undisturbed wind flows. Wind catchers can be employed to allow fresh air in directly, using the principle of cross ventilation, when the opening in the chimney is pointed towards the direction of the wind. When the opening of the chimney is at the leeward side of the wind an under pressure arises near the opening causing the air to be drawn out from the building. Because the wind speed is increased with height above ground, the opening of the chimney can have a smaller surface than the windows on ground level.

# Reference Project
"Bad-gir" windscoops
Sindh district, West-Pakistan

*Multistory building with many windscoops leading down to the rooms. Picture by Rudofsky, 1964.*

In the Sindh district in West-Pakistan the roofscapes are dominated by a very prominent feature, the "bad-gir" or windscoops which have been used for at least 500 years. During the summer months temperatures range up to 50 °C, which with a light breeze can go down to around 35 °C. To direct the breezes into the building, windscoops are installed on the roofs, one for each room.
Since the wind is always blowing and from the same direction, the windscoops are fixed towards the same direction, creating this characteristic landscape. Multistoried houses use shafts that reach al the way down and are also used as a internal telephone (Rudofsky, 1964).



*Roofscape picture of Sindh, West-Pakistan. Picture by Rudofsky, 1964.*

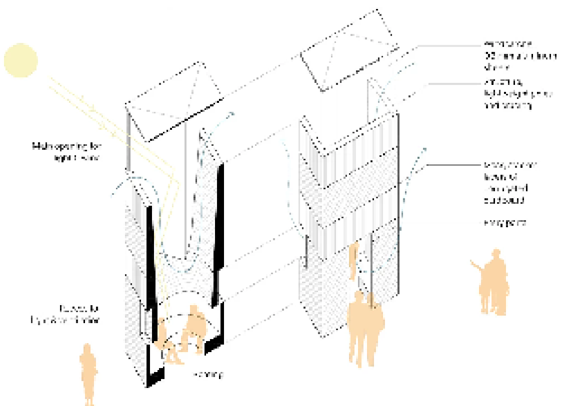
<u>Reference Project</u>
MAD Architects - Barjeel
Dubai, UAE

*"Barjeels have been used for passive ventilation over centuries, nowadays they're being used less and less because, today, the typical answer to acclimatisation is high technology and mechanical systems." - Kerim Miskavi, MAD Architects*

***Climate Design***

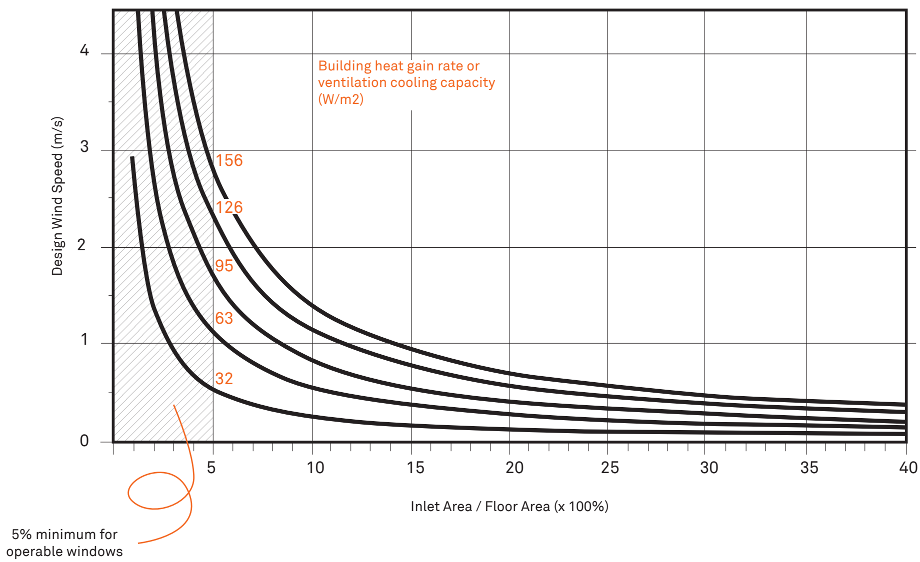
'Barjeel' is a contemporary architectural installation inspired by the iconic wind towers of the Gulf region, which have been used for centuries as passive cooling devices. Through geometric abstraction and the use of readily available recycled cardboard and aluminum, the installation re-interprets the traditional wind tower while creating a cool place of rest and contemplation for visitors.

Cooling breezes are funneled down to the seating area below via the windcatcher, and natural light filters through the top and side recesses to create a passively cooled, shaded space with lighting qualities that change throughout the day. At night, the structure is illuminated through an array of LED strips embedded in the layers of cardboard, producing the effect of a solid structure that seemingly emanates light from within.



# Application on St. Maarten

A5 A6 B3

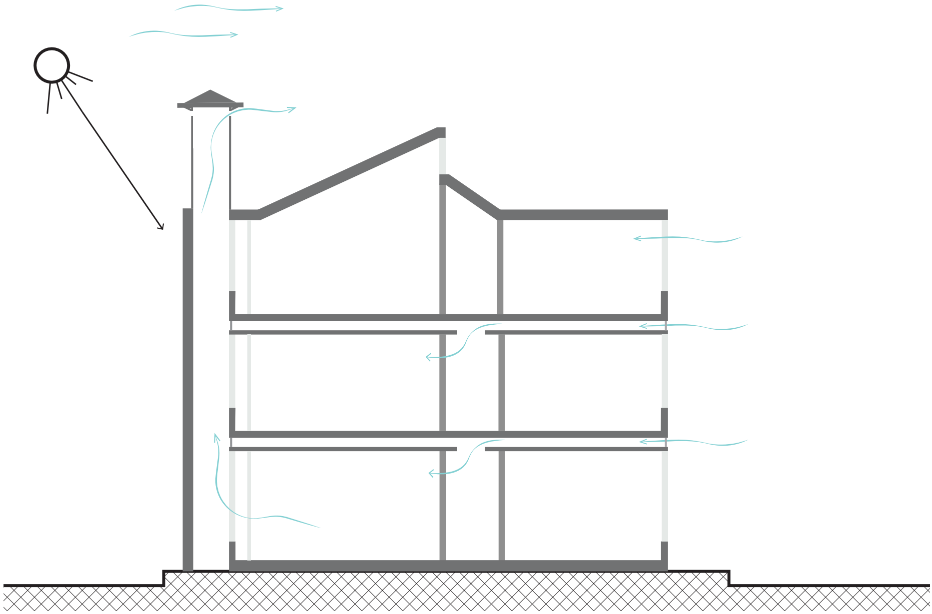


**Orientation & Inlet area**
The analysis diagram A5 shows the wind direction on St. Maarten. A wind catcher can be oriented independently from the building because the building also accounts for the sun shading and has to adhere to the urban plan. The predominant wind direction in St. Maarten is from the East but can fluctuate between South-Southeast and East-Northeast. Throught the year predominant wind directions fluctuate within a 90° angle and therefore the most efficient direction for a wind catcher would be the East-Southeast direction on St. Maarten.

The graph on opposite page explains the advised minimum inlet area necessary for a certain ventilation cooling capacity. On St. Martin the average wind speed is 4 m/s which means that the inlet area of the wind catcher should be 5% of the floor area of the room that is being ventilated by it (DeKay and Brown, 2014).

**Hurricane resilience**
The disadvantage of applying a wind catcher in a building is that it has to extend a minimum of 2,4 meters above roof level to catch undisturbed wind flows. This extension catches wind and becomes hazardous during high wind speeds. Chapter B3 explained different drag coefficients of certain shapes. Applying a shape with a low drag coefficient minimizes the total wind load and minimizes the risk of collapse. Naturally the structure of the chimney needs to be strong, secure and tied together from the foundation up. Additionally to minimze wind loads, the shape of the chimney should be accounted for.

## 2.1.3 Stack-ventilation

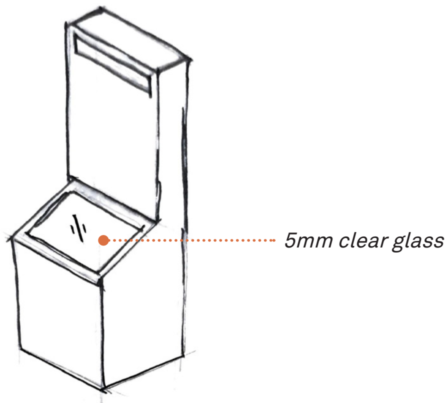


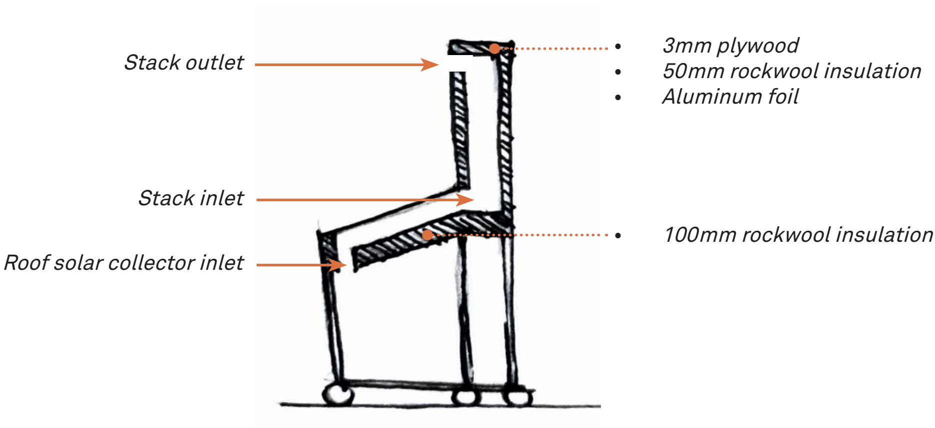
*Section diagram of a building showing the natural stack-ventilation effect enhanced by solar radiation and natural wind flow. Image by author.*

Previous natural ventilation methods were focused on cross-ventilation principles. This chapter describes the second method to naturally ventilate interior spaces, by stack-ventilation. Stack ventilation can prove to be a good alternative when there is a low average wind speed because it does not require wind to move the air through the building. Not being dependent on external air flow means that this method is also orientation independent.

A room cooled by stack-ventilation functions when hot air rises and can exit through openings at the top of the building. When air leaves the room it has to be replaced by fresh air, creating wind flow in the room. When there is a significant difference in air temperature between inside and outside this method is more efficient than when there is little difference in air temperature (DeKay and Brown, 2014).

The stack effect can be enhanced by using a stack chimney at the top of the building. The way that this chimney is designed within the building determines its effectiveness. The image on opposite page shows how solar radiation can be used to heat up the air inside the chimney and how the natural wind flows can be used to create a negative pressure or suction zone on the leeward side of the chimney. Both these aspects enhance the stack effect.




*Protoype device A of the study by Yusoff et al. (2010). Section view showing the materials, wind speed measuring points at the inlets and outlet.*

In hot humid climates, stack-ventilation is inefficient due to the small temperature differences between inside and outside. A study by Yusoff et al. (2010) elaborates on the effectiveness of a proposed strategy in enhancing the stack-ventilation in the hot humid climate of Malaysia. They propose a solar induced ventilation method which uses a combination of a roof solar collector and vertical stack. The vertical stack is important in providing significant height for sufficient stack pressure.

The findings of the study show that solar induced ventilation enhances the stack-ventilation in hot humid climates. It is able to create air temperature difference of more than the usual air temperature difference reached by naturally ventilated buildings. The highest air temperature difference achieved between the air inside the stack and the ambient air was 9.9°C. This was achieved with semi-clear sky conditions with a solar radiation of 877 W/m$^2$. With overcast sky conditions, providing a solar radiation amount of 552 W/m$^2$, a temperature difference of 6.2°C was achieved. This temperature difference is important because a greater difference will enhance air movement inside the chimney and inside the building.

Climatic diagram A3 shows the average hourly solar radiation through the day over a year on St. Maarten. The highest average solar radiation was 782 W/m$^2$ in March at 14.00. Through the year the solar radiation at midday fluctuates between 780 and 550 W/m$^2$. Similar to this study, St. Maarten also has a high average yearly RH (77%) making it a relevant study for the context of St. Maarten. The study by Yusoff et al. shows a more elaborate explanation on how to apply this method.

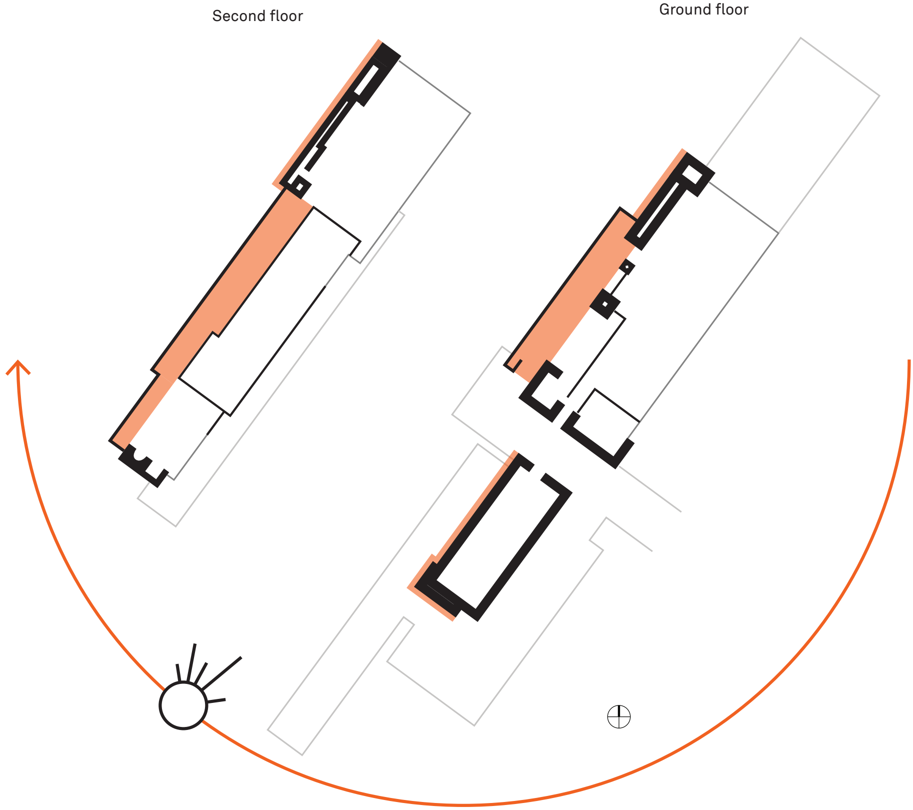
Regarding hurricane resilience, the previous chapter about wind catchers explained how chimneys can be designed to minimize the chance of collapsing.

## 2.2 Zoning for cooling

This chapter elaborates on how to cool buildings by using smart design to create comfortable (cooler) zones within and around buildings. The methods that will be discussed are the following:

- Use **Buffer zones** inside or outside buildings to prevent living spaces from absorbing conducted and radiated heat.
- **Transformation** of the building such that its spatial boundaries are expanded or contracted. In this way, the building can either open itself more to the climate forces on site or withdraw to create a thermal enclave.

## 2.2.1 Zoning: buffer zones



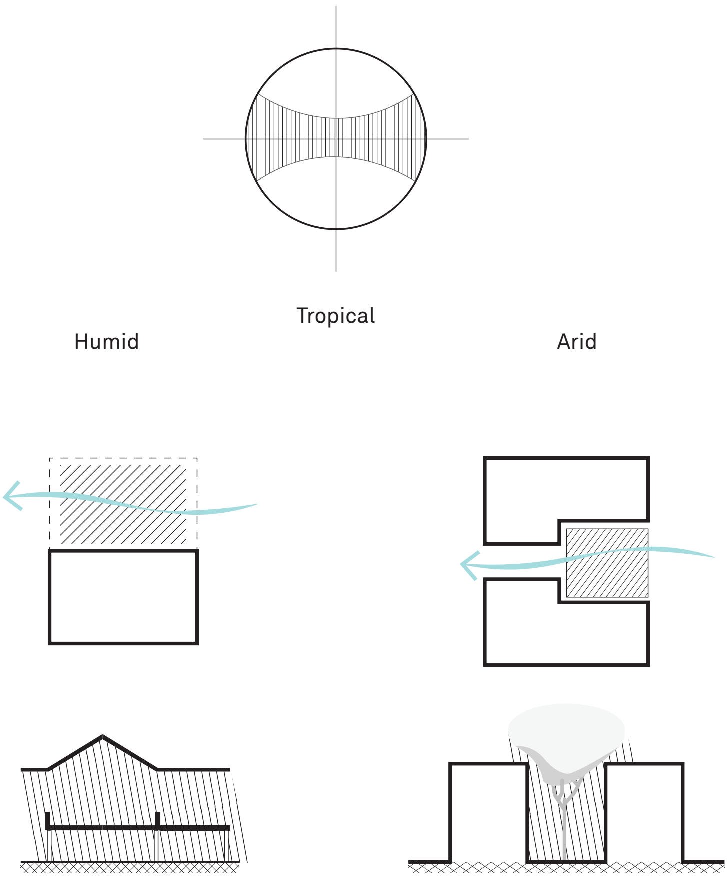

*Plan diagram with buffer areas highlighted in orange. The interior spaces are hallways and storage spaces. The exterior buffer walls are build out of thick natural stone.*

*West facade*

**Interior spaces**
In hot climates it is a challenges to create comfortable interior spaces with natural methods.Solar radiation is the main cause of internal heat gain in the tropics. It heats the outside of building surfaces and enters them through facade openings. Hereby, the building gains heat through conduction and radiation. Using buffer zones within or attached to the building can moderate the heat gain inside the building during the day.

Some spaces in a building's program have less rigid temperature requirements because of the nature of their use, like storage, or the duration of their use, like circulation. Some spaces, like bedrooms, have temperature requirements only at certain times of the day. These spaces can frequently be used as thermal buffer zones between the exterior environment and spaces that need careful temperature control. The first reference project, displayed on opposite page, which is a residential building in the desert of Phoenix, Arizona, designed by Frank Lloyd Wright uses this method to create comfortable interior spaces.

The buffer zones mentioned before focus on the heat gains through exterior walls, but the roof is also of importance to minimize internal heat gains. The roof of single to two storey buildings in the tropics has a heat transmission of 50-70% of the total heat entry for the rooms below the exposed roof (Vijaykumar et al., 2007). There are multiple solutions to reduce that amount such as the application of reflective coating and/or insulating the roof.




*Plan and section view of the ideal location of outdoor living spaces in a tropical humid and arid climate.*

**Exterior spaces**

Because buildings can block sun and wind, they createmdifferent microclimates around them. Combinations of wind and sun directions have implications for where to locate outdoor rooms. When locating outdoor rooms based on microclimate in tropical arid/humid climates, when wind and sun directions are oblique to each other, the outdoor room can be located to the north side (south in Southern Hemisphere) of the building where there is more shade and the wind will blow through the space.

In tropical climates it is a necessity to create shaded outdoor spaces. First of all, these spaces become outdoor buffer zones which prevents solar radiation from heating up the facades and entering the building through windows. Secondly, shaded spaces create a cool microclimate around the building. This space requires access to natural ventilation to become comfortable. Such a space is displayed in plan and section on opposing page.

## Reference Project
ISSHO Architects - Shinmanka house
Okinawa island, Japan

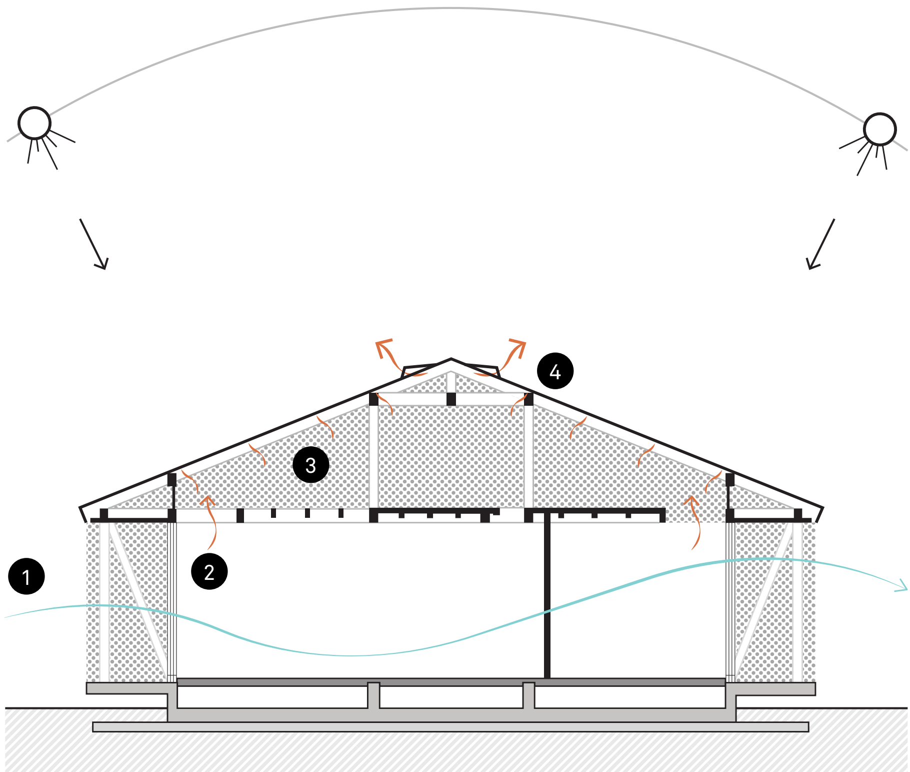
*Exterior view of the Shinmanka house.*

*A traditional house on the island of Okinawa. The similarities with the Shinmanka house are clearly visible.*

The Shinmanka house, designed by the Japan based architectural ofiice ISSHO Architects, is a modern reinterpretation of a traditional house in the area. On the opposite page the two photos show the Shinmanka house and the traditional Okinawa house. The contemporary elements are seen in the materials and building elements, such as the sliding doors which are also a modern interpretation of the traditional Japanese Amado storm door. The structure is braced at the outer edges of the building ensuring a flexible open floor plan and natural ventilation through the house.

How this house uses buffer spaces is essentially by a well designed roof. The roofs eaves are extended to protect the interior spaces against solar heat gains and create outdoor patios around the house. This creates a cooler microclimate because shaded spaces have a cooler air temperature. Allowing natural ventilation through the house takes this cooler air through its spaces.

The other part of the roof that provides a thermal buffer are the high ceilings. Through the stack effect, hot air rises to the top of the roof and exits through the openings in the top. As mentioned before, the roof in tropical climates has a heat transmission of 50-70% of the total heat entry for the rooms below the exposed roof (Vijaykumar et al., 2007). By allowing the hot air to exit the house it is preventing the spaces from heating up. This natural cooling method is displayed in the sectional drawing on the next page.




*1. The open floor plan allows natural wind flow through the space.*

*2. Hot air rises due to the stack effect above the cailing.*

*3. The buffer space is allowed to heat up.*

*4. Hot air exits through the vents in the roof.*

*Interior view of the Shinmanka house. Large eaves minimize the sun from entering the living spaces.*

## Application on St. Maarten

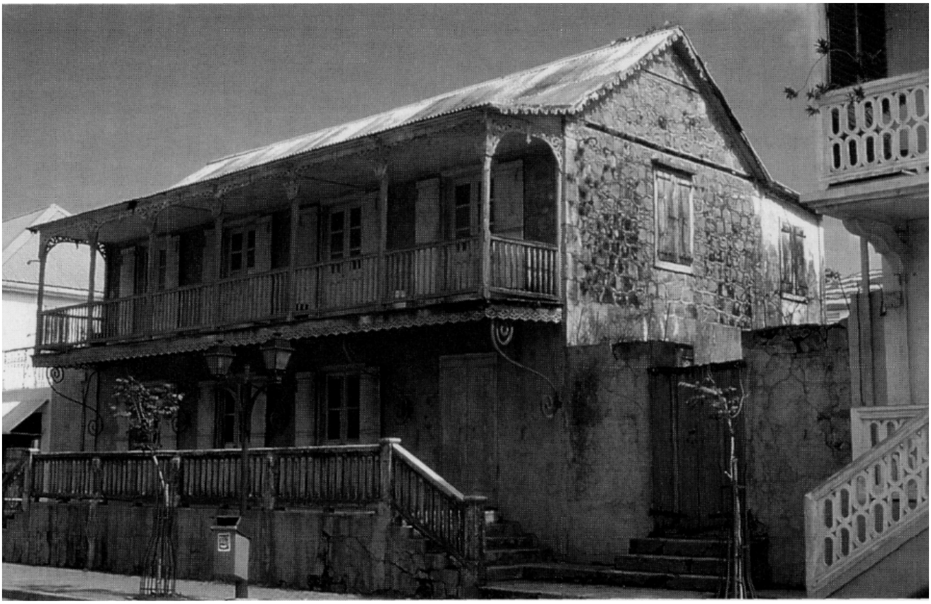
*Front street in St. Maarten in the year 1906. The buildings on both sides of the street are designed with some sort of front porch or shaded area.*
*Source: Van Andel, 1985 .*

**Terrace as buffer**
On St. Maarten the single storey terrace house has been a standard typology occuring all around the island. These spaces provide a comfortable recreational space during the day when it becomes too hot inside the house. This 'buffer space' then also prevents sun from heating up the facade and therefore the interior spaces of the house.

Traditional houses on St. Maarten, influenced by western building methods, were build using a 'balloon frame'. A balloon frame is essentially a frame out of dimensional lumber fastened with nails instead of joinery, making it a one of the cheapest construction methods of the time. All of the one storey buidlings were constructed using that method. The two storey buildings, as displayed in the image on opposite page, had a ground floor build from stone and a upper floor again build with the balloon frame.

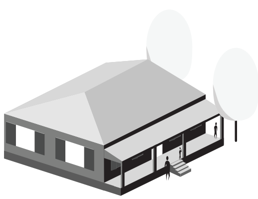
Nowadays you see many variations of this traditional domestic typology and the material used most is cast-in-place concrete or concrete blocking. The material change is largely due to the reoccurance of hurricanes on the island.

## Traditional caribbean homes



*A traditional two storey house on St. Maarten. These were originally merchants houses were the first floor, used as a warehouse, was constructed from natural stone and the second residential floor out of wood.*

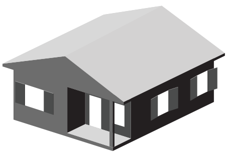
***Traditional domestic “lil house”.***



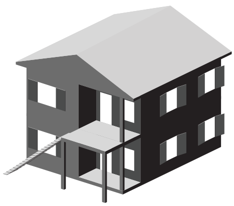
***Traditional house with terrace.***

***Traditional two storey house with terrace.***

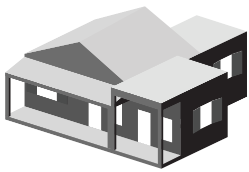
*A modern home with traditional elements in the neighborhood of Defiance. Homes that were build in more recent years are mostly constructed out of concrete and concrete blocks. Image made by author.*



***Single storey Terrace house***

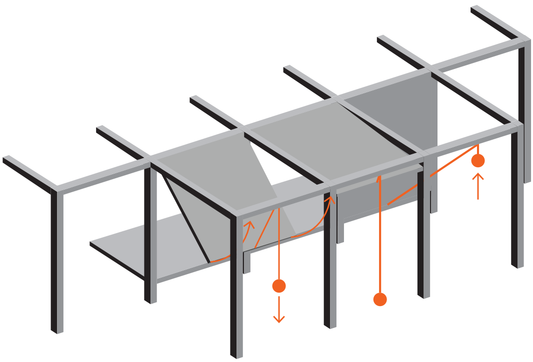


***Two storey Terrace house***



***Single storey house Expanded***

## 2.2.2 Zoning: transformations



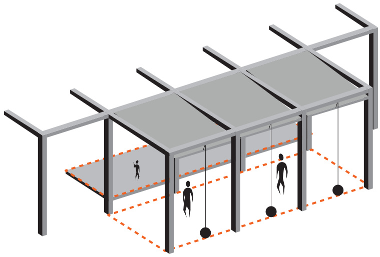
Designing a house in such a way that it can transform and adapt to the occupants' need can be a very effective way to create comfortable living spaces. In the context of St. Maarten this method can prove to be a effective way of providing natural ventilation and protecting against high wind speeds. In addition, this method could integrate the option to allow wind into the home during hurricanes.

**Paul Rudolph - Walker guest house**
**Sarasota, Florida**

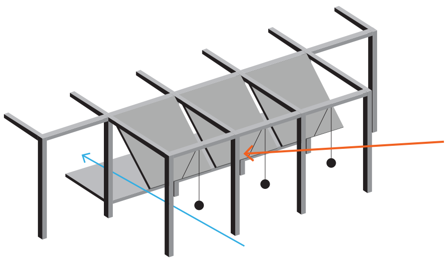
This vacation home is stricly based upon a 8' x 8' (2.4 x 2.4 meters) cubic module, Rudolph created a one-unit high, three-unit wide by three-unit deep 7.2 meter square pavilion.

These frames support a pulley system connecting a weighted ball and plywood panel. The raised ball shuts the flap to secure the screened bay, when lowered, it yields a canopy of shaded exterior space while affording natural ventilation within and through, earning the guest house the moniker of "the cannonball house" in the process. Occurring on two consecutive of every three bays per side, these panels form a pinwheel that is accented by one solid glass bay or door per side. The home is designed with certain methods to ensure comfortability in and around the home, as shown on the next two pages.

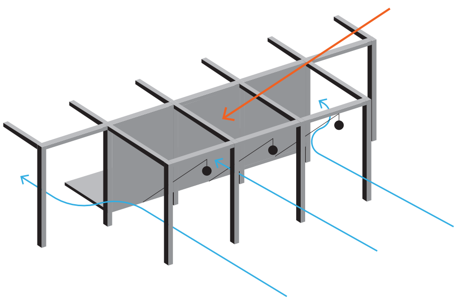
*Exterior view of the pulley system in opened position, creating outdoor living space.*



*Open: create a living zone around the house, providing a range of spaces for migration.*

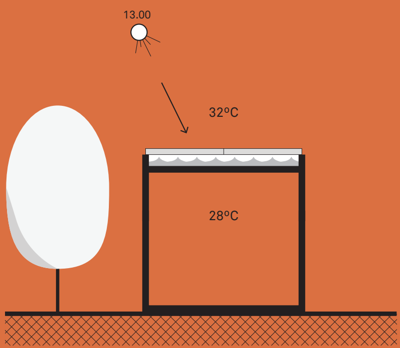


*Half closed: open to the breezes and can shade low sun, control views and moderate light.*

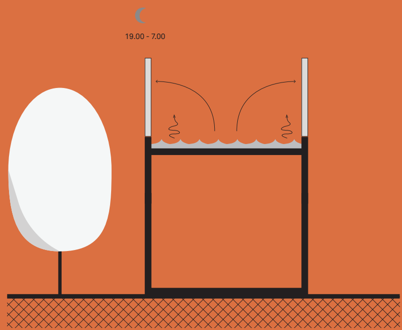


*Closed: block intense sun and light and provide security when the house is empty or in the case of a hurricane.*

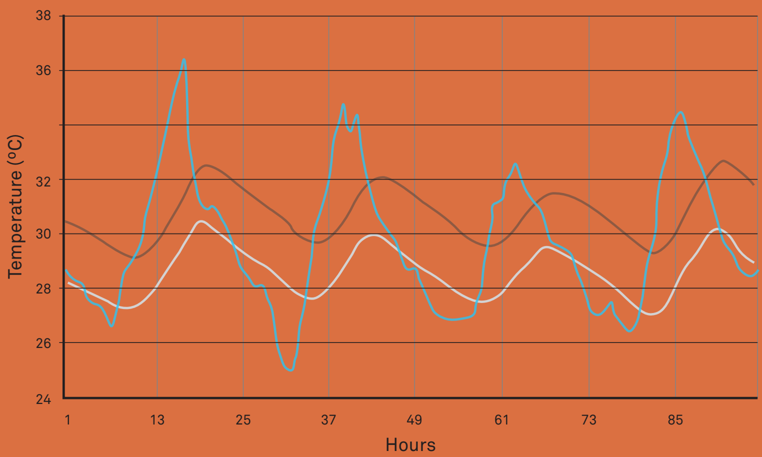
# 2.3. Cooling mass: roof pond




*Day*




*Night*




*Roof pond cell temperature*

*Reference cell temperature*

*Outside temperature*

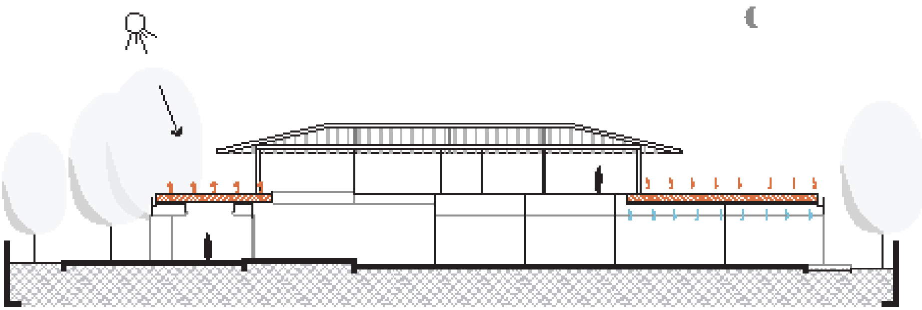
The strategy of using a roof pond to passively provide cooling does so through indirect evaporative and radiant cooling. The roof functions as a heat exchanging element which is cooled by evaporation on its surface and/or by longwave radiation to the sky.

A study on the effectiveness of passive cooling by roof ponds was executed by González and Givoni (2004) in the hot-humid climate of Maracaibo, Venezuela. Their study suggests that even in the climate of Maracaibo, there is a potential for passive cooling. The experiment was executed using two test buildings. One with roof pond and one without. The roof pond had two openable foldable panels that were open during the night (19.00 - 7.00) and closed during the day. Their results show that their is a difference in interior temperature between the two test cells. Firstly, it is noticable that the temperature of the roof pond cell is around 2 C less than than the temperature of the reference cell. Therefore, there is a longer period of time during the day where there is a lower temperature than the outside temperature. This is less than the reference cell. Lastly it is also noticable that the temperature inside the roof pond cell is more stable than the experimental cell.

The roof pond strategy is potentially a effective way to cool buildings during the such as shown by Gonzalez and Givoni (2004). Applying roof ponds requires a thurough understanding of its workings in different climates. For alternative studies on the application of roof ponds, see references Sharifi and Yamagata (Review article) and Spanaki et al. (2011).

# Reference Project

Wallflower Architects - Water-cooled house
Singapore



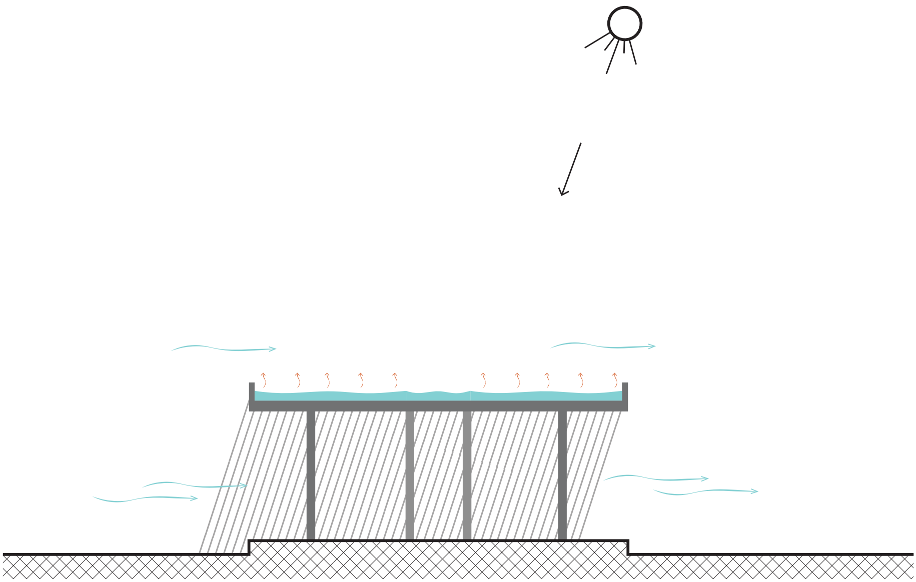
This villa designed by Wallflower architects implements a roof pond on the second floor of the building surrounding the living spaces. Besides that the pond assists in refining the experience of serene isolation and privacy, it functions as thermal insulation against solar radiation. As mentioned before, the water body also helps to regulate temperature swings during the day.

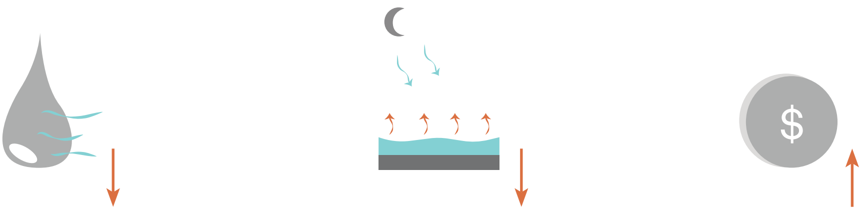
The so-called “open roof pond” which is applied here is the simplest and most applied roof pond configuration. The minimum recommended depth for this pond is 30 cm (Sharifi and Yamagata, Review article).

During the day the heat that is absorbed by solar radiation is stored in the water before it gets into the room, delaying the indoor peak temperature to later in the afternoon. At that time the ambient air temperature is already cooler, making it easier to acquire thermal comfort by means of natural ventilation for example. When the water gains heat during the day, the water temperature will increase and a certain amount of it will evaporate causing a cooling effect. During the night, heat flux moves outdoors because the ambient temperature is cooler. The pond is then cooled by convection and through nighttime radiant cooling. A way to enhance the heat absorption and evaporative cooling effect of the roof pond is by spraying water over the roof.

Although Sharifi and Yamagata found in their study that high levels of air humidity reduce the potential for evaporative cooling and radiative cooling, the study by Gonzalez and Givoni (2004) clearly shows a difference in interior temperature.

## Application on St. Maarten





*Due to the high humidity of St.Maartens climate, evaporative and radiative cooling are less effective. Roof ponds also need carefull design considerations and have a high initial cost.*

There are no known projectst that use a roof pond as a passive cooling means. The disadvantage of applying a roof pond or cooling pond in the context of St Maarten is that the climate, and specifically the relative humidity, reduce the potential of the cooling effects of a roof pond. The main advantages of a roof pond are its evaporative cooling and radiative cooling aspects which makes it a strategy which is more suitable for hot-arid and warm-temperate climates.

The initial cost and knowledge that is necessary to construct a roof pond properly is very high for the context of St. Maarten. This does not weigh out against the potential benefits it offers as compared to natural ventilation, which provides more cooling. The project by Wallflower architects shows that such a roof pond is largely used as a luxury feature with the additional benefit of its passive cooling potential. The climate of Singapore has, similar to St. Maarten, a very high relative humidity with a maximum of 96% and a minimum of 64%. This results in a reduced evaporative- and radiative cooling effect.

The roof ponds have a great potential to provide passive cooling in hot-arid and warm-temperate climates (Sharifi and Yamagata, Review article), but its cooling effects are reduced when relative humidity is high. When designed correctly, even in humid climates a roof pond can provide cooling (Gonzalez and Givoni, 2004). Nevertheless, the application of a roof pond needs carefull design, maintenance and a high initial cost of construction. Coming to the conclusion that the a roof pond is not the most effective way to passively cool buildings and that the (few) benefits do not weigh out against the disadvantages.

# Recommendations
# Building scale

The core aspect of providing a comfortable indoor climate is the access to natural ventilation. Hence the elaborate size of the first chapter *permeability* where several methods explain how to improve cross- and stack ventilation. Starting with the plan and section of the building; the plan influencing the **cross ventilation** and the section influencing the **stack ventilation**. Depending on the design of the building, these configurations can be applied to make use of passive cooling.

The application of the first method within the permeability chapter is dependent upon the **orientation of the building** towards the prevailing wind direction.If the orientation is unfavorable, several configurations of *wing walls* can be applied in the design. Wing walls create a possitive and negative pressure near facade openings which pushes and pulls wind through the building, whereas without wing walls there would be no cross ventilation.

A *wind catcher* is a architectural element mostly applied in dense cities in the middle eastern desert climates. Due to their density, the buildings have a limited access to natural ventilation except by the use of wind catchers to **catch more undisturbed winds** above roof level (see the Bad-gir example in Pakistan). Designing a additional element on a building is more costly and therefore not a aspect which is favorable to account for from the start. In the first place should natural ventilation be provided by cross- and stack ventilation. If that is not a option, then a wind catcher will do the trick.

As mentioned, *stack ventilation* **ensures air movement within the building without natural wind flow**. Hot air rises through the chimney and exits above roof level. Cooler air enters the building below to cool the insed. Stack-ventilation can be applied if a interior space is multiple levels high and has a air outlet at the top. Connecting rooms to this space enhances the stack effect.

The smart design of rooms inside a building is a way to either **adapt to the climatic conditions** by *transformation* or **sacrifice spaces** as a *thermal buffer* to make others more comfortable. The reference project study shows how a more comfortable indoor climate can be realised with these strategies. Perhaps for St. Maarten a combination of the Shinmanka House and the Walker Guest House would be appropriate. Using smart buffer spaces and having the abbility to adapt to climatic conditions.

Lastly, the method of cooling mass is discussed with the strategy of applying a *Roof pond*. Here the idea is to use the properties of water to create lower and more stable temperatures within the house. This method can provide interior cooling in St. Maarten's climate but it will not be very efficient. Additionally, a roof pond needs carefull design, maintenance and a high initial cost of construction and the (few) benefits do not weigh out against the disadvantages for application on St. Maarten.

**Hurricane design**

The building scale has significant implications regarding hurricane design. In the design phase, the hurricane design aspects of chapter B should be accounted for. A certain strategy regarding the *projected area* should be chosen. Either allow air to enter the building and **minimize surface area** or resist against the wind forces with a **strong structure**.

Then, investigate the possibility to apply windbreaks around the building such as applied in Villa 921 in Japan. This minimizes wind pressure and protects the interior of the building when air is allowed to enter the building.

Lastly, the shape of the building should be designed to have a low drag coefficient. This is mostly important when applying stack and/or wind chimneys but also with regards to the roof shape as is shown in chapter B3.

The reference projects: Shinmanka House (chapter 2.2.1), Villa 921 (chapter B4) and Walker Guest House (chapter 2.2.2) show diferent strategies towards hurricane resilience. The Shinmanka house is designed to be hurricane resistant. Noticable by its heavily braced outside ring of columns and strong sliding doors. Villa 921 allows wind to enter the building and therefore provides a windbreak net to protect the inside of the house against airborn projectiles. The Walker Guest House is also designed to be hurricane resistant but in a adaptable way. It provides a additional layer of protection with the foldable panels that cover the glazed facade.

Regarding hurricane resilience, it is up to the designer to choose a strategy. Resistant, resilient, adaptable or a combination all three.

# Reflection

This catalogue is meant to provide a set of design strategies that can be applied in the Tropical Savannah Climate of St. Maarten. The design strategies provide a description of how they work and should be implemented. After writing this catalogue it has become clear that hurricane design is essentially also a set of recommendations that function as a supplement to the design strategies. There is no one perfect combination between hurricane design principles and design strategies because of the diverse circumstances of every project. The construction principle, materials used, etc. The design strategies that are included on each of the two scales, urban or building, all explain how they can be applied and what the hurricane strategy should entail (when applicable).

The expectations of this research were to use the design strategies in my design project and in that I succeeded. Not every aspect will be applied, because some are only necessary in certain conditions. An example of this is the wind catcher. The wind catcher is only necessary when building on ground level have no access to natural wind flow due to the urban pattern for example.

The discovery that the constant humidity of St. Maarten, which is due to the sea climate, results in the decreased effectiveness of many strategies. Additionally it gives a constant temperature through the year. Humidity decreases the evaporative- and radiative cooling effect, as shown by Sharifi and Yamagata[17]. Yet, when designed properly it still is able to provide cooling. Largely due to the delayed heat absorption of water (Gonzalez and Givoni, 2004.). The strategies that therefore become less effective are the roof pond and the microclimate strategies. Altough less effective, it still provides more cooling than hard, heavy surfaces such as concrete.

This catalogue is meant to be a working document, meaning that over the course of my graduation project (and perhaps thereafter) I will be adding strategies to the collection as I will be discovering more of them. It also means that the strategies now have a certain amount of depth to them, this is due to time management and the phase of my graduation project I am in now. There are many aspects of the design strategies that I have not touched upon (yet) but with time it will become more complete.

For future research, another design strategy scale could be added which provides another layer of detail. For example, looking further into material properties and how they influence heat load and/or cooling need. Even options on how building elements can be used to adjust to climatic conditions would be incredibly valuable.

## References

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel. (2006). *World Map of KöppenGeiger Climate Classification updated*. Meteorol. Z., 15, 259-263.

Yokoyama, M, May. (2019). *Stories of St. Martin: Beyond a Drought.* The Caribbean Herald N.V. dba The Daily Herald, 2019. Retrieved from: https://www.thedailyherald.sx/supplements/weekender/87399-stories-of-st-martin-beyond-a-drought

[3] DeKay, M and Brown, G.Z. (2014). Sun, wind & light: Architectural design strategies (3rd edition). John Wiley & Sons, Inc., Hoboken, New Jersey.

[3] Shan, J. (2019). *The Meaning of Yin and Yang*. ThoughtCo. Retrieved from: https://www.thoughtco.com/yin-and-yang-629214.

[4] Hurricane City. (2019). *Saint Martin / Maarten's history with tropical systems*. Retrieved from: http://www.hurricanecity.com/city/saintmartin.htm.

[5] The Netherlands Red Cross, (2019). *Making Sint Maarten strong again*. Retrieved from the Red Cross in Sint Maarten.

[6] Perez C.I. (2018). *Hurricane resilient wooden houses: safer buildings and retrofitting guidelines*. Habitat for humanity, 2nd edition. Retrieved from: https://www.habitat.org/

[7] Tomaniga, Y et al. (2014). *Air flow around isolated gable-roof buildings with different roof pitches: Wind tunnel experiments and CFD simulations*. Building and environment 84, 204-213. Elsevier, 2015.

[8] Maraveas, C. (2019). *Design of Tall Cable-Supported Windbreak Panels*. Open Journal of Civil Engineering, 9, 106-122.

[9] Bitog J.P., et al. (2011). *A wind tunnel study on aerodynamic porosity and windbreak drag*. Forest Science and Technology, Vol. 7, No. 1, 8-16.

[10] Van Andel J.D. (1985). *Caribbean traditional*

*architecture: the traditional architecture of Philipsburg, St. Martin (N.A.)*. Department of Caribbean Studies, Royal Institue of Linguistics and Anthropology, Leiden, The Netherlands.

[11] Shishegar, N. (2014). *The impacts of green areas on mitigating Urban Heat Island Effect: A Review*. The International Journal of Environmental Sustainability, Vol. 9, Issue 1, 119-130.

[12] Wu, Z and Zhang, X. (2019). *Water bodies' cooling effect on urban land daytime surface temperature: ecosystam service reducing heat island effect*. Sustainability 2019, 11, 787.

[13] Akbar, H et al. (1992). *Cooling our communities: A guidebook on tree planting and light-colored surfacing*. Lawrence Berkeley Laboratory, Berkeley CA.

[14] Aram, F et al. (2019). *The cooling effect of large-scale urban parks on surrounding area thermal comfort*. Energies 2019, 12, 3904.

[15] Yusoff, W.F.M. et al. (2010). *Enhancement of stack ventilation in hot and humid climate using a combination of roof solar ollector and vertical stack.* Elsevier Ltd., Building and Environment, October 2010.

[16] Vijaykumar, K.C.K. et al. (2007). *A performance of hollow clay tile (HCT) laid reinforced cement concrete (RCC) roof for tropical summer climates.* Elsevier Ltd., Energy and Buildings, 2007.

[17] Sharifi, A and Yamagata, Y (Review article). *Roof ponds as passive heating and cooling systems: a systematic review*. Elsevier Editorial Systems for Applied Manuscript Draft.

[18] Spanaki, A et al. (2011). *On the selection and design of the proper roof pond variant for passive cooling purposes*. Elsevier, Renewable and Sustainable Energy Reviews 15 (2011).

[19] Gonzalez, E and Givoni, B. (2004). *Radiative and Radiative/ evaporative passive cooling systems for a hot humid climate - Maracaibo*. Plea2004 - The 21th conference on passive and low energy architecture. Eindhoven, The Netherlands, 19-22 September 2004.

[20] Priya, G and Kaja, N. (2016). *Significance of air movement for thermal comfort in educational buildings, case study of a classroom*. International Advanced Research Journal in Science, Engineering and Technology, Vol. 3 Iss. 3, March 2016.

[21] Rudofsky, B. (1964). *Architecturee without architects*. Doubleday & Company, Inc., Garden City, New York. Pg. 48.

[22] Looman, R.H.J. (2017). *Climate-responsive design: A framework for an energy concept design-decision support tool for architects using principles of climate-responsive design* (doctoral thesis). A+BE | Architecture and the Built Environment No 1 (2017). Retreived from repository TU Delft.