City of Wind

Exposing the Invisible

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

ABSTRACT

Strong winds have breached the city walls. A set of iron chairs launch toward a couple passing an outdoor patio. Bags of groceries fling from unsuspecting hands and scatter across the sidewalk. A group of cyclists swerve onto a busy road as they pass a newly constructed tower.

Pedestrians are experiencing these disruptive wind-related events as a result of the increase in tall building construction and its unavoidable interactions with wind. Enclosures that provide controlled environments are unintentionally encouraging winds that challenge pedestrian safety and comfort at grade. With few visual guidelines and tools accessible to them, designers are not only limited in their ability to understand architectural aerodynamics but also lack the knowledge to properly make use of available modes of software and testing. While other elements of design such as daylighting, can be verified through sight, the invisibility of wind makes deciphering its effects a difficult and perpetual task.

This thesis offers insight on how and where to look for wind — not to "see" in the traditional sense, but t*o look beneath the surface of things.* An exploration of architectural aerodynamics is visually represented and organized in three interrelated parts: *Drawing the Wind, Laws of Motion,* and P*arameters of Prediction.* The first is a historical overview of humanity's relationship with wind, the second a documentation of architectural aerodynamic principles, effects and methods of simulation, while the final is a visual exploration of the link between buildings and wind sited in Toronto, Ontario. Each part is a visual exploration in, and reflection of, environmental awareness.

By using visualization methods to improve the communication between designers and wind specialists, this document promotes a design practice that enables a productive consideration of wind in the city. Ultimately, designers must be aware of basic aerodynamic principles and the corresponding effects to not only provide optimal interior environments within buildings, but also in between them.

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"Virtually every part of the world has named winds - regular winds that the locals have personified over the centuries. Although no one knew where they came from or what caused them, winds were given names because, invisible and mysterious though they were, they were as real a presence as any mountain, river, or sea."

- De Villiers, *Windswept,* 15.

WHY WIND?

FIGURE 1.1.

SENSING SURROUNDINGS

During the Renaissance wind and weather were believed to be the "fundamental link in establishing harmony between the human body, building and the cosmos."[1] The relationship between people and weather has always been inherently complex, not only because the elements of weather affect the body and mind, but also because their origins are ambiguous, mysterious and difficult to comprehend. Throughout the course of history, many have attempted to simplify and categorize the complexity of wind, such as roman architect Virtruvius, in the first century B.C. He believed that a strict orientation of city streets in relation to the prevailing winds would ensure a healthy city. Since then, the concept of wind in design has been continually revisited, with each new investigation involving a different approach to thinking about wind. Unlike other intangible elements used in design, such as the sun, the cause and effects of wind cannot be confirmed through the sense of sight. Although technological advancements have provided ways of examining wind, it is typically perceived as an unpredictable force that must simply be withstood in standard practice. As Marq De Villier's writes in his book Windswept, "birds-and insects… have learned over the long millennia of evolution to live in the wind in a way that humans cannot, to live in it, understand it, and use it, as transportation, a source for food, as locus for sexual adventure, and even for foretelling, since many birds seem able to predict the weather from the winds."[2] Although humanity has evolved to use wind in many of these ways, truly accepting wind and its potentials to affect people through design is far from being commonplace in practice.

1. Kenda, *Aeolian Winds,* i.
2. De Villiers, *Windswept,* 237.

FIGURE 1.2. Collage, Visualizing the Experience of Wind

Sensing

Of the four classical elements — earth, water, air and fire — air is the only element that cannot be physically seen, requiring the individual to "see" their surroundings through other senses. A benefit of this is that while "vision separates [people] from the world… the other senses unite [them] with it."[3] The experience of wind is therefore extremely personal, uniquely filtered through an individual's senses. The sound of the rustling of leaves, the smell and taste of the air, the feeling of a rush of wind brushing upon one's skin on a hot summer's day: these are all ways wind renders itself visible, and can be welcomed or rejected depending on the individual. "The mystery of winds all-powerful presence, is deep seated in the human psyche,"[4] as human perception of wind is informed by the combination of varying physical, psychological, spatial, cultural and climatic factors.

For reasons unknown, the chaos of weather has always instilled fear and reverence for the unknown within human culture, as it seems to link the external environment to an individual's internal, personal fears and experiences. In art and literature, wind and weather are often reflections of human emotions. For instance, Shakespeare would often personify wind as an exterior condition that gave expression to the inner emotions of his characters. These feelings of connectedness appear to intensify when individuals are close to water or in similar "natural" landscapes. In urban settings, commonly mild winds act simply as a backdrop to everyday life. Most of the time, these winds are simply written off as minor annoyances or symptoms of the "last form of 'uncontrollable nature' that persists within the city"[5]. It is only when these forces interfere with human limits of control, by blowing hats off, dishevelling clothing, or whirling newspapers around the street, that they are noticed. However, on rare occasions when human and atmospheric parameters align, the wind can be a good friend. As Mark De Villiers writes "If [an individual is] a sailor or a wind farmer - or a child with a kite- then doubtless psychology will trump physiology and [they] will find positives where others find only irritation."[6]

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3. Pallasmaa, *The Eyes of the Skin,* 25.
4. De Villiers, *Windswept*, 24.
5. Mayer, *-Arium,* 24.
6. De Villiers, *Windswept*, 20.

"I think I was always misunderstood. People just didn't seem to like me. I think I annoyed them, I got on their nerves. I don't know why. That's just the way it was. Maybe I was too intense. Maybe I came on too strong. I don't know, I really can't say. Yeah, it was lonely, really lonely, but you – you get used to it after a while. And then one day, everything changed – somebody finally accepted me for – for what I am. Since I've got this job, life is completely different. I finally feel useful – good at something. The Wind. His potential is ours." - Epuron Commercial for Wind Energy

FIGURE 1.3. Mr. Wind - Man Acts out Effects of Wind

Comfort and Health

"Human bodies are [believed to be] hardwired to weather,"[7] primarily sensitive to subtle shifts in "long-term climate and seasonal variations,"[8] but also sensitive to daily pressure changes. Common examples of this include reports of migraines or flare ups of arthritis during rainy days.

According to the American Society of Civil Engineers, human health and comfort are governed by a combination of seven components of the atmosphere: wind speed, air temperature, humidity, solar radiation, precipitation, air quality and noise level.[9] These components make up the overall temperature and humidity levels that cause varying health issues in individuals. Considering built form inherently augments wind speeds and wind speeds can significantly alter the perceived temperature and humidity (in combination with other atmospheric components), it is evident that buildings play a significant role in establishing human comfort and health within the urban realm.

Wind speeds are capable of: intensifying the perceived temperature of the air, described as the wind chill factor or heat index, accelerate and re-divert the rain, disperse pollutant air particles, as well as create sounds by interacting with objects, such as the prolonged humming sounds created by a vibrating facade component of the Beetham tower in Manchester, England[10]. In combination with other atmospheric components, an individual's ability to adapt to the changing environmental conditions is a factor in determining comfort. This ability to adapt depends on the individual's "age, sex, state of health, and mood."[11] When an individual is unable to adapt, they can become uncomfortable or unwell. Ultimately, it is a combination of wind and other climatic factors that dictate human health.

7. De Villiers, *Windswept*, 25.
8. Mayer, *-Arium,* 54.
9. Task Committee, *Outdoor Human Comfort and Its Assessment*, 1.
10. Slater, *The Beetham Tower Whistle*, manchestereveningnews.co.uk.
11. Mayer, *-Arium,* 54.

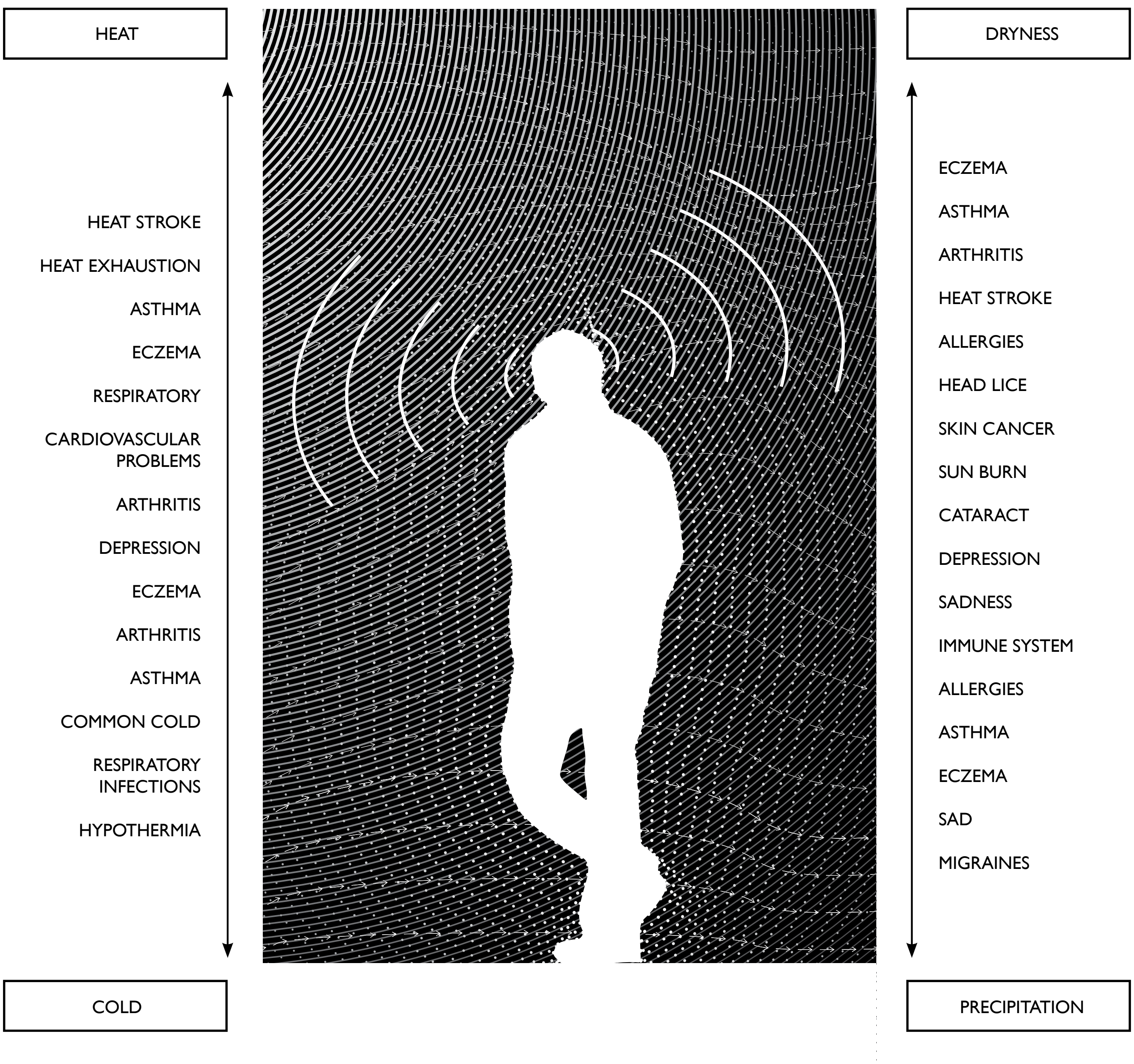


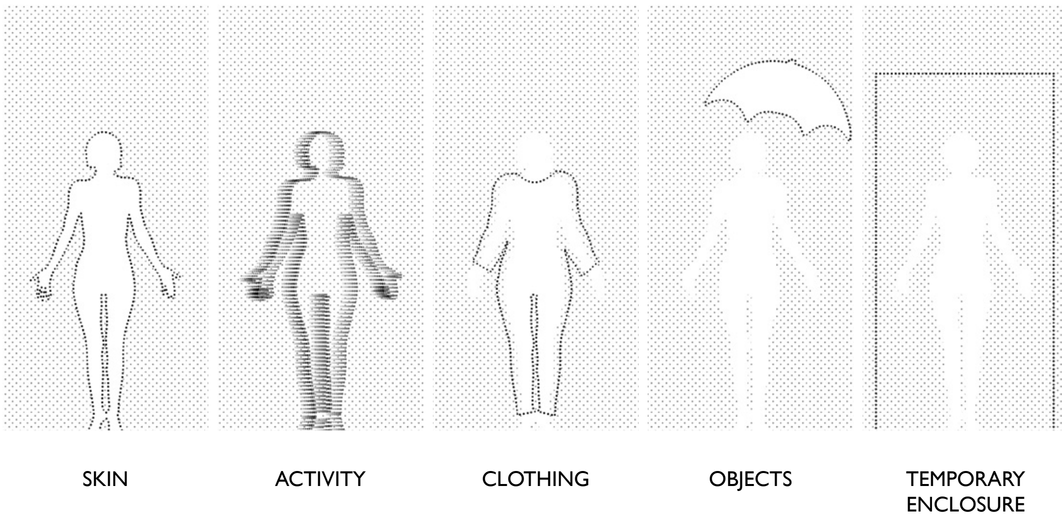
FIGURE 1.4. How Temperature and Humidity are Linked to Human Illnesses

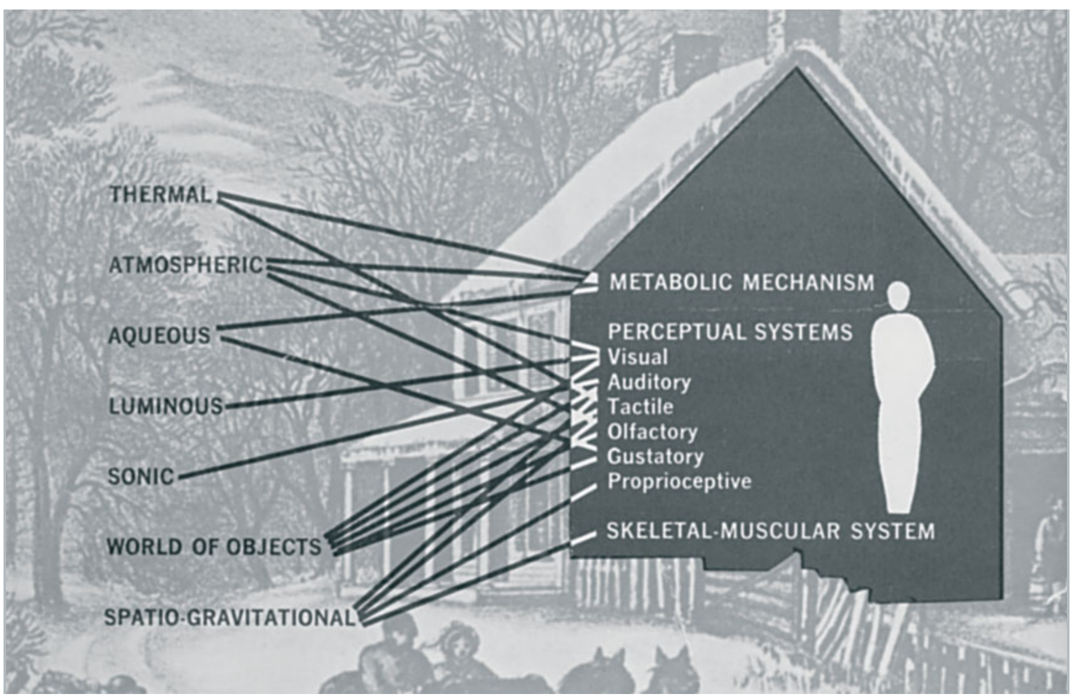
Architecture as a Mediator

To reduce the effects of wind and establish control over human comfort, humanity has historically modified the relationship between the body and nature through two types of interventions: temporary and permanent. Temporary interventions are direct in their application. An individual feeling cold can add clothing, generate heat through activity, and use objects such as umbrellas or tents to temporarily shield themselves from certain elements. Once these temporary extensions to the human body no longer provide comfort, permanent structures are constructed.

Over time, buildings have evolved in regards to their role as mediator between man and nature. In the 1970's it was believed that, "the ultimate task of architecture [was] to act in favour of man: to interpose itself between man and the natural environment;[12]" "to ameliorate the extreme conditions that were beyond the human body's ability for adaptation."[13] By the end of the 19th century, the invention of the HVAC system (heating, ventilation and air conditioning), released the building envelope from its obligation to mediate between the exterior and interior. After this, designers focused on controlling the interior. In *The Architecture of the Well-tempered Environment*, Reynar Banham describes how once architecture in the western world came to be seen as the "conscious art of creating massive and perdurable structures[14]," architects could not remember how to deal with the environment in any other way. Banham goes on to point out that the issue with massive structures is that the require power to function because while "a suitable structure may keep a man cool in summer, no structure will make him warmer in sub-zero temperatures[14]." In this lies the untapped potential of the sun and wind that inherently provide necessities for comfort. While the 21st century saw buildings such as *The Blur Building* by Diller Scofidio and Renfro push the boundary of the relationship between interior and exterior, the majority of practicing architects continue to focus on interiors and avoid the exterior consequences of doing so.

12. Fitch, *American Building 2,* 1.
13. Addington, *Contingent Behaviors*, 13.
14. Banham, *Architecture of the Well-Tempered Environment,* 21.





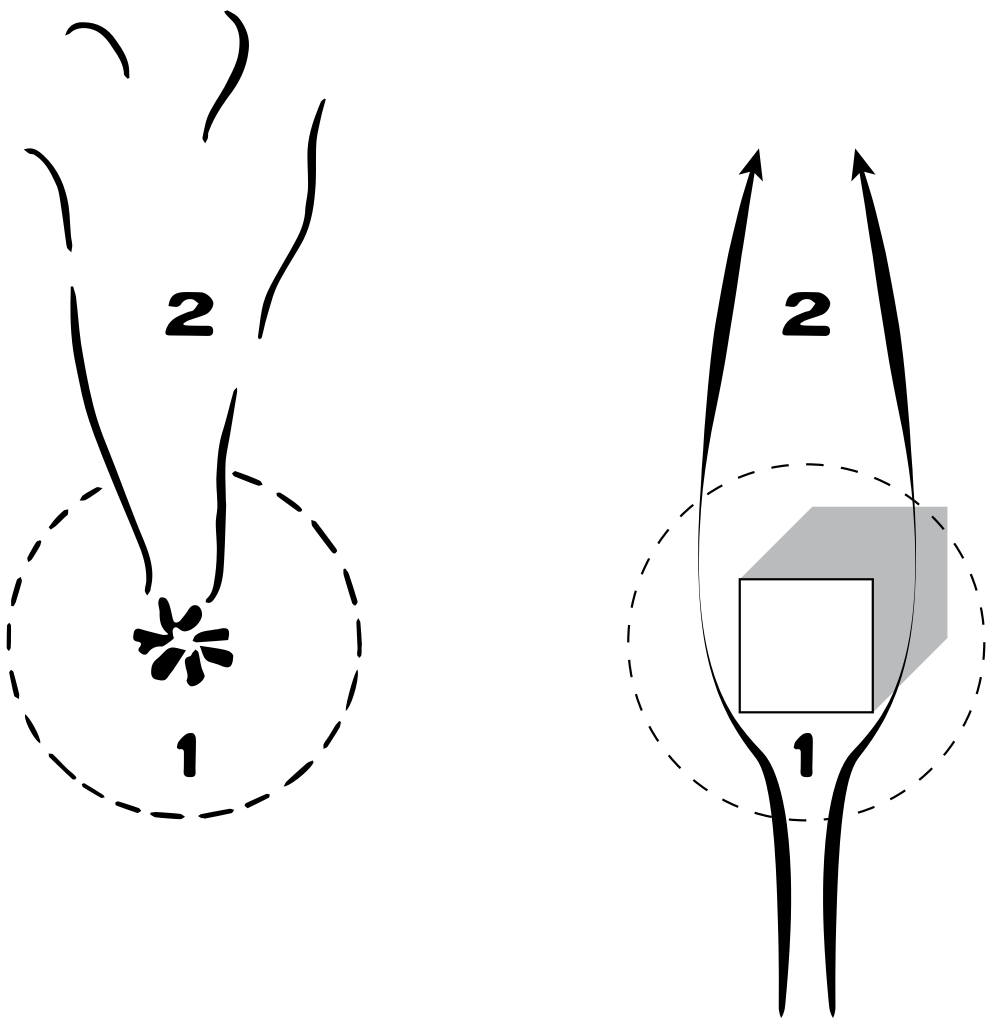
THE ENCLOSURE AS A MEDIATOR - BY JAMES MARSTON FITCH

FIGURE 1.5. Establishing Control

Retreating from Weather

In consequence to relying on the increasingly permanent nature of structures, society eventually lost its relationship to nature. Banham writes that due to the dependence on permanent structures "architects, critics, historians and everyone else concerned with environmental management in civilized countries, lack a range of spatial experience and cultural responses that nomad people have always enjoyed."[15] By building completely controlled interiors, society could not remember how to live without walls, whereas nomads could use and adapt to changing thresholds such as the fluctuating temperatures and flowing smoke around a campfire. However, similarities between the campfire archetype and the modern building can be found in the surroundings. Just as conditions vary around a campfire, the wind, sunlight, and quality of air vary around a structure, forcing people to adapt and change position to achieve comfort. Similar to the campfire, the building size, form and placement alter the conditions of the surrounding environment, just at a different scale. While many buildings require the individual to adapt to the changing exterior conditions, there are examples of buildings that have been designed to adapt themselves such as Renzo Piano's *Tjibaou Cultural Centre* in New Caledonia, which uses movable screens with multiple configurations to adapt to the changing conditions that vary from light to hurricane force winds. However, it is more common that the environment be thought of as a force to retreat from, rather than a force with which society actively participates. Therefore, perceptions of wind and weather are purely driven by an ancestral instinct to retreat, to stay safe, and to control while avoiding how the exterior conditions surrounding a shelter are altered by the very form created to shelter from those conditions.

15. Banham, *Architecture of the Well-Tempered Environment* 19.



CHANGING ENVIRONMENTAL
CONDITIONS AROUND A CAMPFIRE

1. Zone of Radiant Heat and Light
2. Downwind trail of warmed air and smoke

CHANGING ENVIRONMENTAL CONDITIONS
AROUND A BUILDING

1. Zone of Radiant Heat and Light and Shade
2. Downwind trail of disturbed winds carrying exhaust

FIGURE 1.6. Banham's Illustration of the Changing Conditions Around A Fire Compared to the Changing Conditions around a Building

THE NEW ERA

In 2015, a record amount of tall (over 200 meters) and super tall (over 300 meters) buildings were completed. This was the first time the top 100 buildings in the world all reached super tall status, with the residential tower 432 Park Avenue capping the list. The total number of supertalls has doubled from 50 to 100 in just 5 years. Over 76% of the buildings built in 2015 were in Asia, 9% in the Middle east, 8% in Europe, 4% in central America, 3% in north America and 1% in Australia[16]. What does this mean for the wind?

Every form introduced into the atmosphere affects and is affected by wind. As cities grow in height and density, buildings come into contact with forces of wind not experienced previously. Winds that once passed over the city streets are now being intercepted by buildings and washed down into the pedestrian level. At approximately two-thirds of the height of a building, winds split and either flow over, around, or are directed down to street level.

An increase in the number of tall buildings constructed affects three major aspects of wind in the urban realm: the quality of air, safety of pedestrians in regards to secure structures and the comfort of people at pedestrian level. Effects that might have remained unnoticed, such as winds flowing down into the pedestrian level, are now amplified at the tall building scale causing comfort and safety issues for people. Due to its invisibility, the majority of wind issues discovered are through failure. As Bruce Mau describes "When systems fail [humanity] become[s] temporarily conscious of the extraordinary force and power of design, and the effects that it generates."[17] Each error allows the designer to uncover another layer of understanding that was previously unseen. Over time, issues of ventilation and structural integrity in relation to the forces of wind were brought to light through failure. Some examples include the poorly ventilated, densely packed, and air-polluted cities in China, the flutter induced collapse of the Tacoma Narrows Bridge, and the death of an individual from the toppling of a car close to a building that occurred in Leeds, England in 2015[18]. As people experience the effects of tall building construction, it becomes apparent how building form, orientation, and spacing influence life in the city.

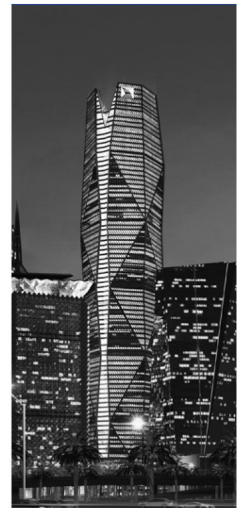
16. Gabel, *The "Year of 100 Supertalls*, 10.
17. Mau, *Massive Change*, iv.
18. BBC, *Wind Death in Leeds*, bbc.com/news/uk-england-leeds-12717762.

SHANGHAI TOWER
Shanghai, China
632 meters
3rd Tallest

WUHAN CENTER
Wuhan, China
438 meters
19th Tallest

MARINA 101
Dubai, UAE
426 meters
21st Tallest

432 PARK AVENUE
Manhattan, NYC
426 meters
22nd Tallest

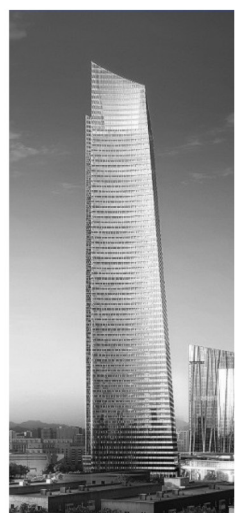


CMA TOWER
Riyadh, Saudi Arabia
385 meters
34th Tallest

ETON PLACE DALIAN
Liaoning, China
383 meters
37th Tallest

VOSTOK TOWER
Moscow, Russia
373 meters
43rd Tallest

OCO TOWER
London, UK
352 meters
5th Tallest



FORUMN 66 TOWER II
Shenyang, China
351 meters
56th Tallest

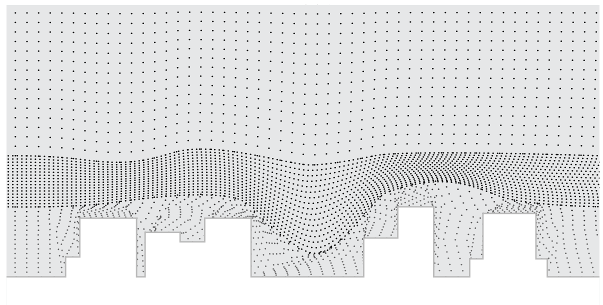
ADNOC HQ.
Abu Dhabi, UAE
342 meters
62nd Tallest

FIGURE 1.7. The Ten Tallest New Buildings in 2015

High-Rise Developments

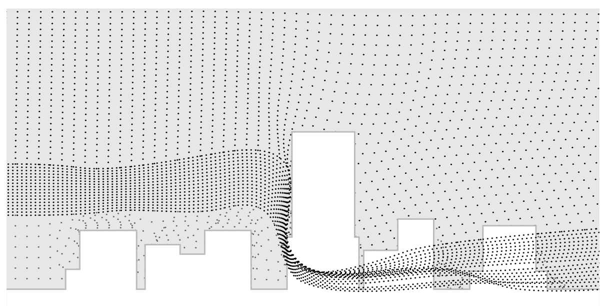
Currently, the building codes of Boston, San Francisco, Toronto, Mississauga, London, Hong Kong, Montreal, and Ottawa require pedestrian level wind tunnel testing prior to construction. Wind engineers would suggest involving experts early on within the design process, but more specifically when: areas have well-known issues with high speed winds, if the height of the new building is significantly taller than its surroundings and also if the proposed building is of a certain size and shape that may cause wind issues.While accelerated winds at street level are generally unwanted in relation to comfort (especially in colder climates), there are benefits to these winds. When a building that is considerably taller than its surroundings is first constructed, it can be common to experience accelerated winds at street level. However, as the city continues to densify, winds may be blocked from entering the streets and diverted around the city. This can result in an accumulation of air pollutants that winds would have carried out of the city. In dense urban areas, large open areas such as Central Park in New York City, New York, can be utilized to allow winds to enter narrow city streets and carry away pollutants expelled from building exhaust systems. To solve these transforming wind issues of that develops with the growth of a city requires foresight.

Designers must be aware of architectural aerodynamics earlier on within the design process to utilize the benefits and avoid the negative aspects of wind in the city. It is not sufficient to focus on one individual building but important to understand the impact of each individual building in time and as it fits within and relates to its growing context.



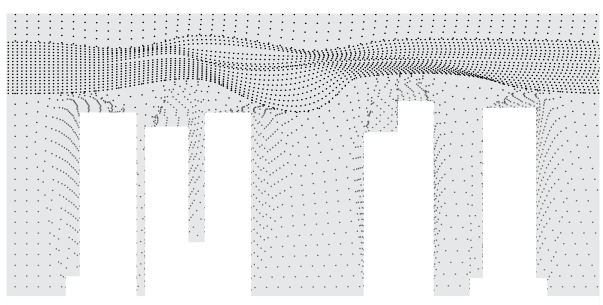
MID - RISE BUILDINGS

3-4 Storey Buildings
Wind can enter open spaces to ventilate streets.



FIRST TALL BUILDING

Tall Building in Relation to Context
Potential for high speed winds to be directed down toward pedestrian level.



TALL, DENSE BUILDINGS

Context Grows
Larger spaces needed between buildings in order to ventilate streets.

FIGURE 1.8. Developing Cities and their Respective Wind Effects

AWARENESS

In light of the increase in construction and density, the ability for the designer to become more attuned to the environment and aware of the interaction between wind and building is of great significance. However, the invisibility of wind provides a significant obstacle. In the book *Windswept*, Marq De Villiers recounts a story of a young boy contemplating the presence of air. The boy asks "if crayfish can't see the water… do they think fish are flying?[19]" In this sense, humanity exists at the bottom of a vast ocean, where birds and planes ride on gusts or jet streams, similar to the ones found in ocean currents. Although the physical properties of these elements are different, these mediums are governed by comparable principles of fluid dynamics. Understanding wind through water is one method of visualizing and understanding a flow that is typically invisible. Although it is possible to see the effects of wind as it registers as force and sound on and in between objects in the city, the fact that wind cannot be seen plays a major role in the designer's hesitation to incorporate it.

Many studies documenting the interaction between wind and buildings have been made by wind engineers, but few are written by or for designers. Although aerodynamic effects have been investigated, there are no studies that take into account the available tools or clearly outline parameters that would be significant for architects to comprehend. Effects are often expressed through formulas or jargon and use context-less projects that cannot be applied to other projects. This leaves designers not only limited by the inaccessibility of visualization tools, such as wind tunnels, but also by a lack of experience and knowledge of the principles of architectural aerodynamics in relation to those tools. Deciphering the wind is difficult because ther are endless ways to depict the wind and infinite ways to interpret those depictions. If designers continue to unintentionally allow architecture to alter the element of wind and only address issues after completion, projects will continue to require extensive redesigns or added mitigating elements proposed by wind engineers.

Instead, this thesis offers the designer insight on how and where to "see" wind, and what it can be used for. The act of "seeing" wind is the first and most significant part of considering it as a design tool.

19. De Villiers, *Windswept,* 28.

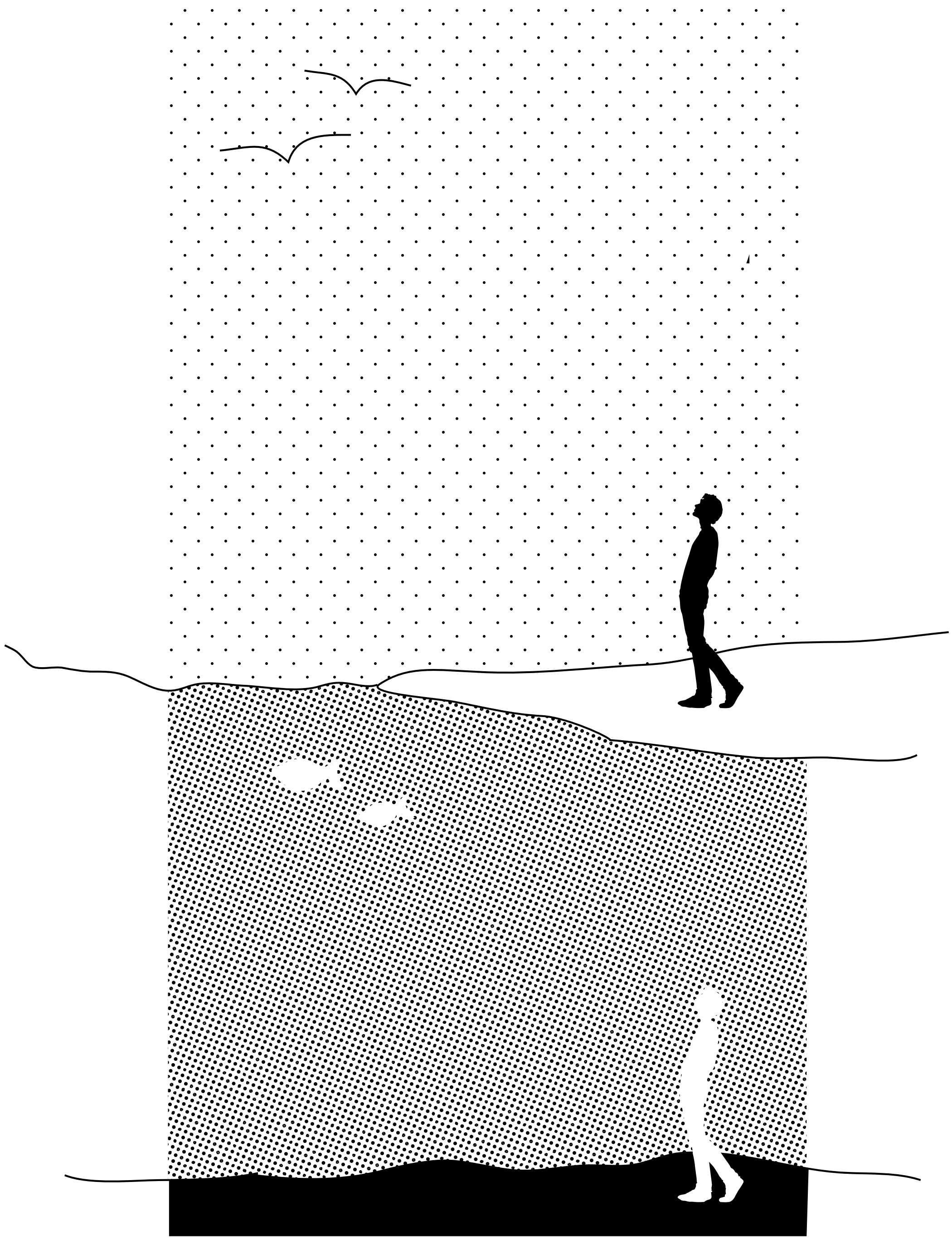


FIGURE 1.9. Seeing Wind by Examining Water

This document provides a visual introduction to wind research and is organized in three interrelated parts: *Drawing the Wind, Laws of Motion*, and *Parameters of Prediction*. *Drawing the Wind* explores the origins of wind and examines humanity's historical quest to comprehend and use wind. *Laws of Motion* utilizes methods of visualization and simulation to describe different wind effects that are the result of building form, orientation, and location. The simulations were performed in a water flume at RWDI to visually illustrate the different effects produced by different building forms. *Parameters of Prediction* then applies industry visualization methods to an intersection in the Financial District in Toronto, Ontario, to identify common wind effects and the associated urban developments that cause them. Using an industry-developed software, six stages of major tower development were tested to visualize the change in winds. A physical model of the intersection was constructed at a scale of 1:500. This model was tested within the water flume and wind tunnel to verify effects uncovered in the digital simulation. The visualization of the development of wind, in relation to the development of buildings, revealed that while some effects were unexpected and would require expert analysis, many effects could be anticipated by including and applying architectural aerodynamics to the initial designs. While the environment cannot be controlled, more importantly, it should not be. Instead, designers should be aware of these environmental conditions and humanity's interactions with them to work within the limits of those conditions.

This research seeks to use methods of visualization to improve the communication between designers and wind engineers. The industry tools were provided by the wind engineering company RWDI, located in Guelph, Ontario, Canada. This document frames a wind engineer's approach to wind and building in a visual way that is accessible to designers and engineers alike. Aspects of building function are purposefully excluded to isolate the interaction of a building shell and wind. Since the force of wind is only a single parameter of the list of elements that architecture is comprised of, designers must be aware ofthe effects in order to use it to its full potential.

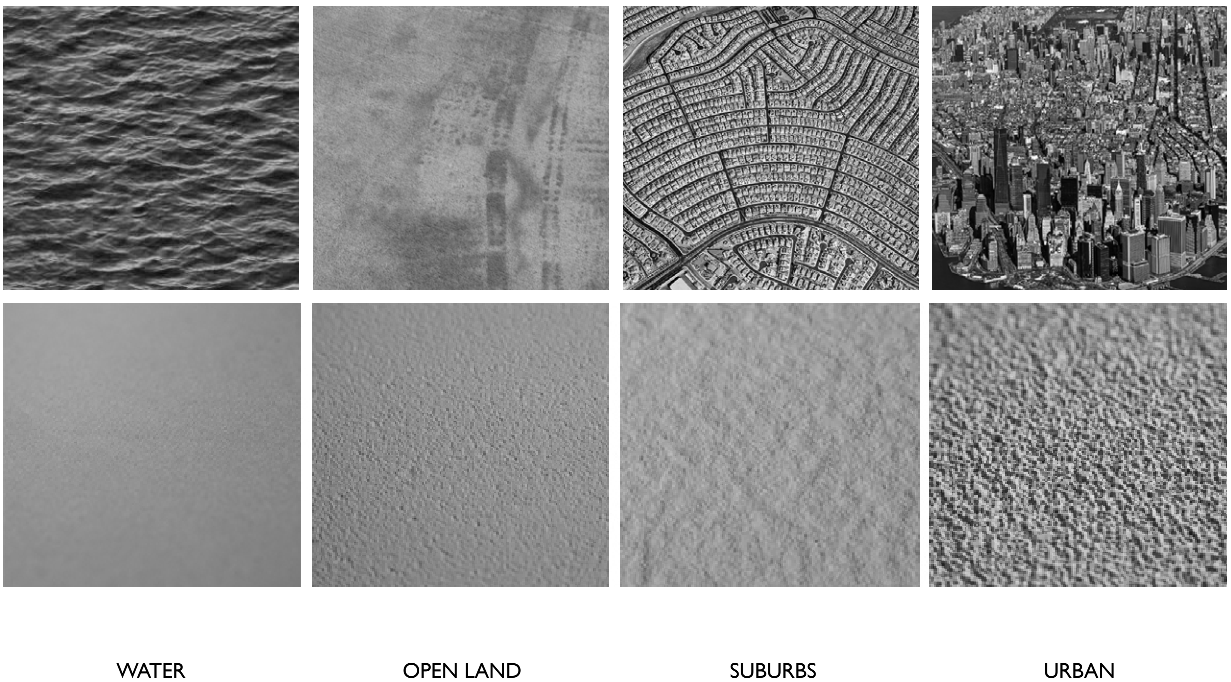
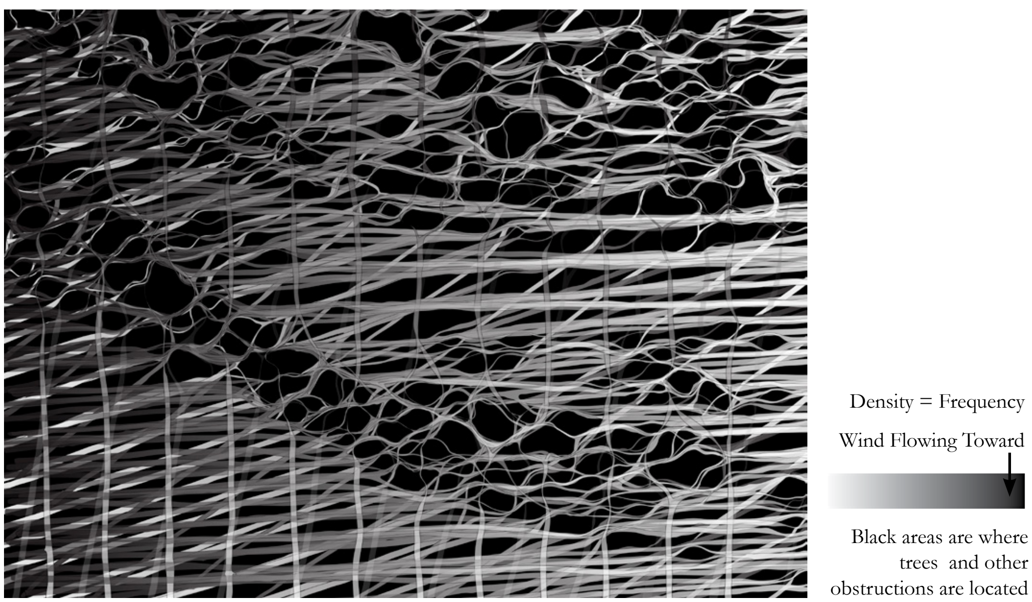


FIGURE 1.10. Surface Texture that Alters Wind Interaction

"Knowledge is very important
when you're dealing with the invisible.
People who don't know the invisible,
they won't see anything.
People who have knowledge,
when they are looking at the invisible,
they see something."

- Sonosopher Alex Caldiero:
"The Cover Up", Home of the Brave.



PLAN SHOWING ANNUAL WINDS OVER SOUTH PARKDALE, TORONTO

FIGURE 1.11. Visible vs. Invisible

"The relationship between what we see and what we know is never settled. Each evening we see the sun set. We know that the earth is turning away from it. Yet the knowledge, the explanation, never quite fits the sight. Perception and appreciation depends upon our own way of seeing"

- Berger, *Ways of Seeing*, 1.

DRAWING THE WIND

FIGURE 2.1.

ORIGINS

Air is not yet wind, but instead a part of the ongoing event of weather, with no beginning or end. In Deleuzian terms, the wind is both smooth and striated space; "smooth space [that] is constantly being translated, transferred into a striated space; striated space [that] is constantly being reversed, returned to a smooth space."[1] In *A Thousand Plateaus,* Deleuze describes how the sea was the first smooth space to be given strict striation through bearings and the map, and similar attempts at striating the sky can be seen today as skyscrapers begin to rise toward the clouds. Wind and water act as "bodies without organs;" all components of equal significance, without hierarchy. The smooth space that is wind is occupied by affects, haptic perception, and intensities that "cannot be divided without changing in nature each time."[2] Just as combining two separate rooms of fifteen degrees Celsius does not make the resulting room thirty degrees, the wind cannot be divided, making it difficult to measure.

This "body without organs" can gently carve beautiful landscapes in deserts while simultaneously destroying plains and homes in the form of tornadoes and hurricanes. This shift between destruction and creation, is the reason humanity is compelled to understand the complexity of wind and weather. As Jon Knechtel writes in the book Air, "Somewhere between a mote of dust and a Saharan storm [people] can intuit air's texture and grasp its vastness. Air suspends, escapes, pressurizes, equalizes.[3]" Through the course of history, humanity has slowly discovered various facets of wind that affect: transportation, warfare, enjoyment, safety, plant reproduction, energy, as well as many other parts of daily life. Advancements in technology and the capabilities of building materials are expanding the possible applications of wind. This chapter reviews how humanity has observed and measured wind through time.

1. Deleuze, *Smooth and Striated*, 474.
2. Deleuze, *Smooth and Striated*, 483.
3. Knechtel, *Air*, 20.

"THE WAVE" MARBLE CANYON, ARIZONA, USA

REMNANTS OF AN EF4 TORNADO, WASHINGTON, ILLINOIS, USA

FIGURE 2.2. The Sculpting and Destructive Forces of Wind

Uses for Wind

HUMAN COMFORT / SAFETY

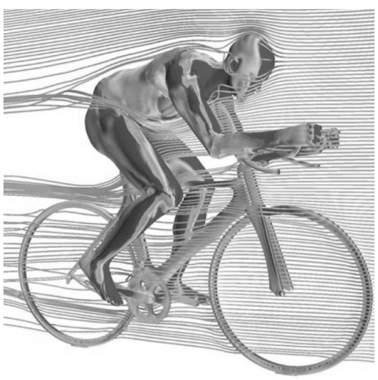
In combination with other atmospheric elements, wind augments an individual's perception of comfort and can threaten their safety depending on wind strength.

QUALITY OF AIR

A benefit of wind in the city is that it can sweep through and remove pollutants expelled by buildings. This is especially important in dense, urban environments.

SOUND / PSYCHOLOGY

Sound, created by vibrations in air, can psychologically affect individuals. The sound of wind can promote a sense of fear and destruction.



SPORTING RECORDS

The shape and aerodynamic quality of stadiums and sporting equipment can alter the results of competition. Cyclists benefit from the drag force by "drafting" (riding in a straight line)[4].

STABILITY OF BUILDINGS

The force of the wind tests the structural integrity of structures of all heights. Winds can also cause tall buildings to sway, causing discomfort. Typically dampers (pendulums) are installed to counteract this motion.

PLANT AND ANIMAL LIFE

Plants and animals have been using wind long before people such as orchids that use wind to propagate and tumble weeds that are entirely wind-dependent for travel[2].

4. Blocken, *Sport and Building Aerodynamics*, 2014.
5. De Villiers, *Windswept, 233.*
6. Krautheim et al, *City and Wind*, 39.
7. NASA, Saharan Desert Feeds Amazon Plants, nasa.gov/content/goddard.
8. Mayer, *-arium*,139.

SAILING / TRADING

The invention of sailing enabled travel and trading. The earliest globalization was built upon the reliability of the trade winds. Understanding these patterns have been beneficial at a global scale.

AIR TRANSIT

The application of aerodynamics in combination with advancements of technology established flight as a common mode of transportation.

ENERGY GENERATION

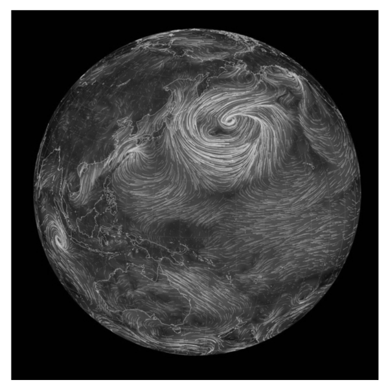
In 2012 the global capacity of wind turbines covered around 3% of the worldwide energy demand[6], with many wind energy markets continually growing.

SNOW ACCUMULATION

Wind blown snow can cause structural loading issues, block entrances to buildings and block roads. Wind fences were placed along highways to filter winds so they would drop the snow before it reached the road.

SAND ACCUMULATION

Similar to snow, sand can affect the strength of structures, block entrances, as well as affect the visibility and health of individuals. Winds also bring vital dust from the Sahara to the Amazon to feed the plant life[7].



WEATHER AND CLIMATE

While the "weather accounts for nearly 30% of the content in local news[8]," weather prediction is still fairly inaccurate anywhere outside of a 2-3 day window, but is slowly improving.

FIGURE 2.3. Uses for Wind

Where Does Wind Begin?

Wind is a product of solar radiation. Due to the earth's spherical shape, the sun heats the surface unevenly, resulting in three types of convection cells that transfer heat and energy from the equator to the poles. These convection cells, found in both the Northern and Southern hemisphere, are called the Hadley, Ferrel, and Polar cells. They mediate between areas of low pressure, that are dominated by unstable weather, and areas of high pressure that are characterized by stable weather and light winds. These cells circulate in a north-south direction, but due to the rotation of earth (Coriolis Effect), the winds are deflected and also begin to move in an east-west direction. The Hadley cells, being closest to the equator, form the strongest circulation that produce the most reliable winds.

9. Met Office, *Global Circulation Patterns*, metoffice.gov.uk.

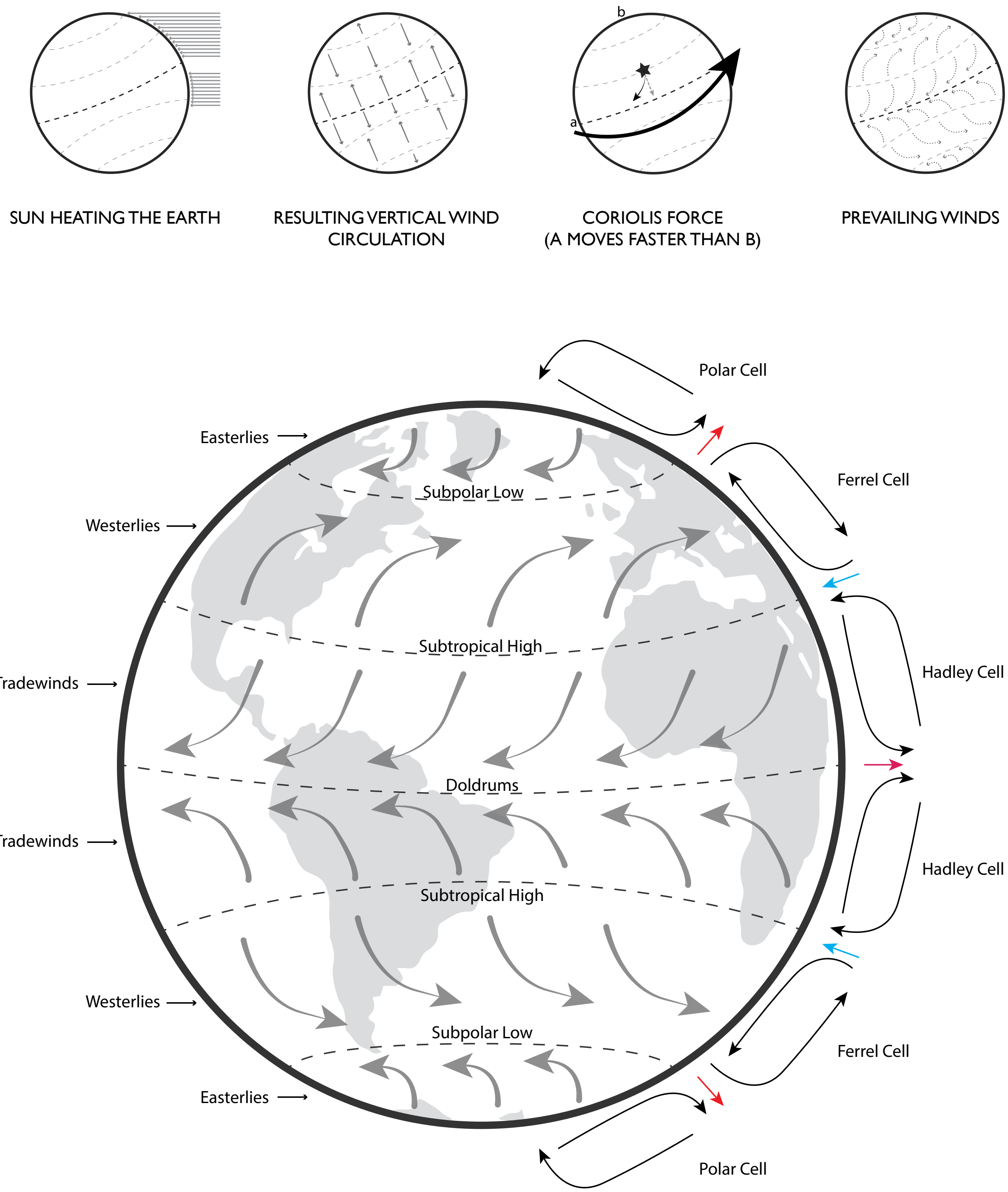


FIGURE 2.4. Development of the Prevailing Winds

Characteristics of Circulation

Beginning from the equator - where the most direct amount of sunlight is received - hot air rises, leaving an area of negative pressure behind. This area of negative pressure is known as the Intertropical Convergence Zone, or as sailors call it, the Doldrums. It is characterized by "a broken line of thunderstorms and almost no wind" that sailors will do anything to quickly get across or avoid.[9] The air that is pulled to fill the area left behind by the rising air creates the trade winds, which are the most reliable winds that enabled the establishment of trade routes across the Atlantic and Pacific oceans. These winds are also responsible for carrying sailors to discover much of the world; for steering the flow for tropical storms that form over the Atlantic, Pacific and Southern Indian oceans; and for the transport of African dust that travels westward across the Caribbean sea.[10]

As the hot rising at the equator travels north and south respectively, and sinks where it meets the Ferrel cells, areas of high pressure are created. These areas of high pressure cover the world's hottest deserts including the Sahara and North Africa. The Ferrel cells move in the opposite direction, carrying the surface air (the Westerlies) Poleward, and the upper level air back toward the Hadley cells. These lower "Westerlies" cover most of Europe, North America, China, and similar latitudes South of the equator, and are as constant and useful as Trade winds. Very complex weather is located in the mid latitudes, where warm equatorial air and the cooler polar air intersect in patternless turbulence. The most northerly and southerly cells, the Polar cells, have the weakest circulation because much of the energy has dissipated by the time it reaches this area. It is important to remember that although "winds are predictable in their larger patterns and behaviours, [they] are horribly intricate in their local behaviour."[11]

10. De Villiers, *Windswept,* 18.
11. De Villiers, *Windswept,* 70.

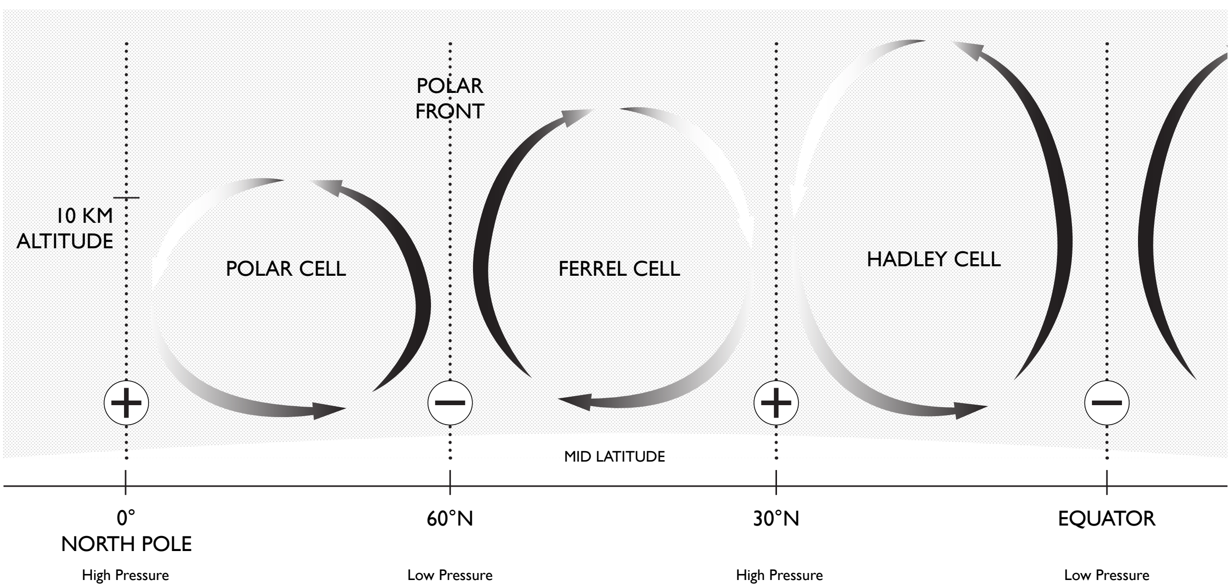


FIGURE 2.5. Section of Earth Showing the Rotation of the Prevailing Winds

Surface Winds

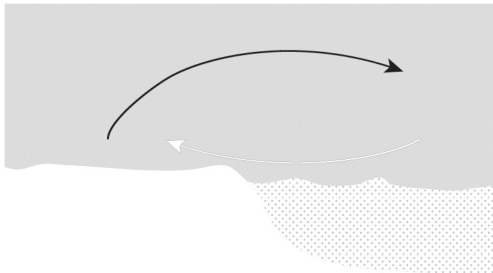
While wind patterns at larger scales seem straight forward, wind and weather are complicated by: long term cyclical fluctuations, the tendency of air to blend into whirling masses of air (vortices), and local or regional winds affected by microscopic topographic and geographic features that are not plottable on larger weather maps, but have significant consequences[12]. As winds approach the surface of the earth, they become altered by its texture and properties, creating micro-climates that differ from the overall expected patterns. For example, locations next to bodies of water, mountainous terrain, or highly elevated surfaces can alter the circulation of wind between day and night.

A land breeze and sea breeze cycle refers to the earth releasing heat during the day, pulling in cool air from the water, while at night the sea releases the heat it has absorbed during the day, reversing the wind direction. In a similar fashion, a mountainside heats up during the day, while at night the heat collected in the valley is released.

In an urban environment, the urban heat island effect describes dense urban areas that are hotter than their surrounding context. Due to the heat conductivity of the materials that make up a city, the unavailability of surface water to evaporate and cool the air, the modifications and at times blocking of wind fields, and the emissions of air pollutants, the hot air cannot escape. At night, the boundary layer typically cools and stabilizes and the city does not release much heat energy, while during the day turbulence is produced that helps ventilate the city streets. This can be a significant issue as many negative health issues can come from poorly ventilated areas that trap heat. As Otto Klemm emphasizes in *City and Wind*, a healthy city must "let air in, let air out![13]"

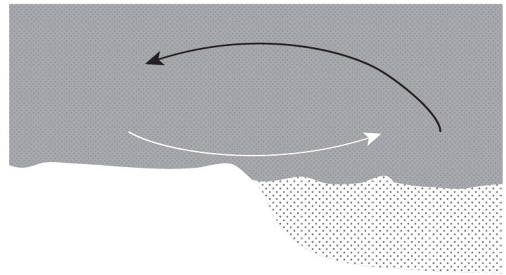
12.De Villiers, *Windswept,* 99.
13.Krautheim, *City and Wind,* 126.

DAY | **NIGHT**



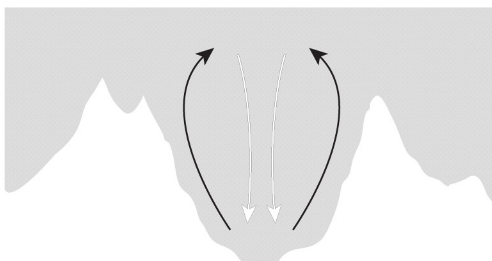
LAND BREEZE

During the day the ground heats up faster than the water. The hot air rises up and a cool sea breeze sucked inland.



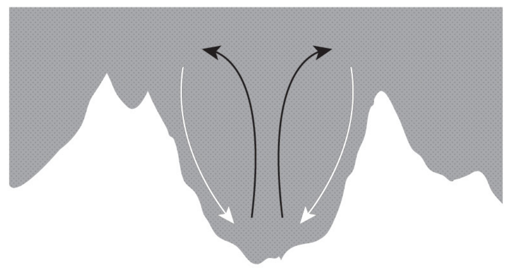
SEA BREEZE

During the night the sea releases the heat collected during the day and a cool land breeze is sucked out to sea.



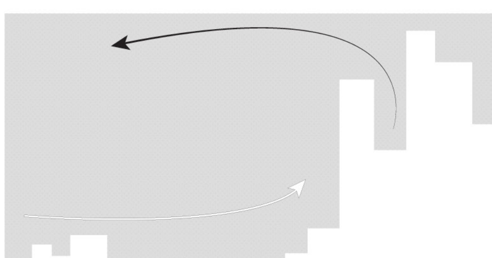
MOUNTAIN WIND

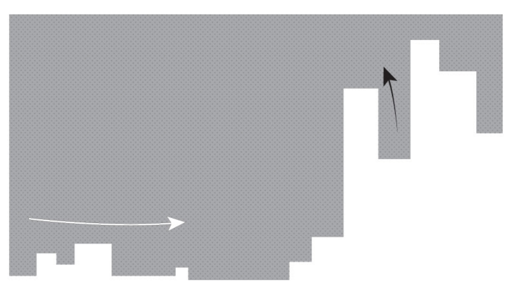
During the day the sides of the mountain are heated faster than the valley and cool wind is sucked down into the valley.



VALLEY WIND

During the night the valley releases the heat it has collected during the day and a cool mountain breeze is sucked down the sides of the mountain.





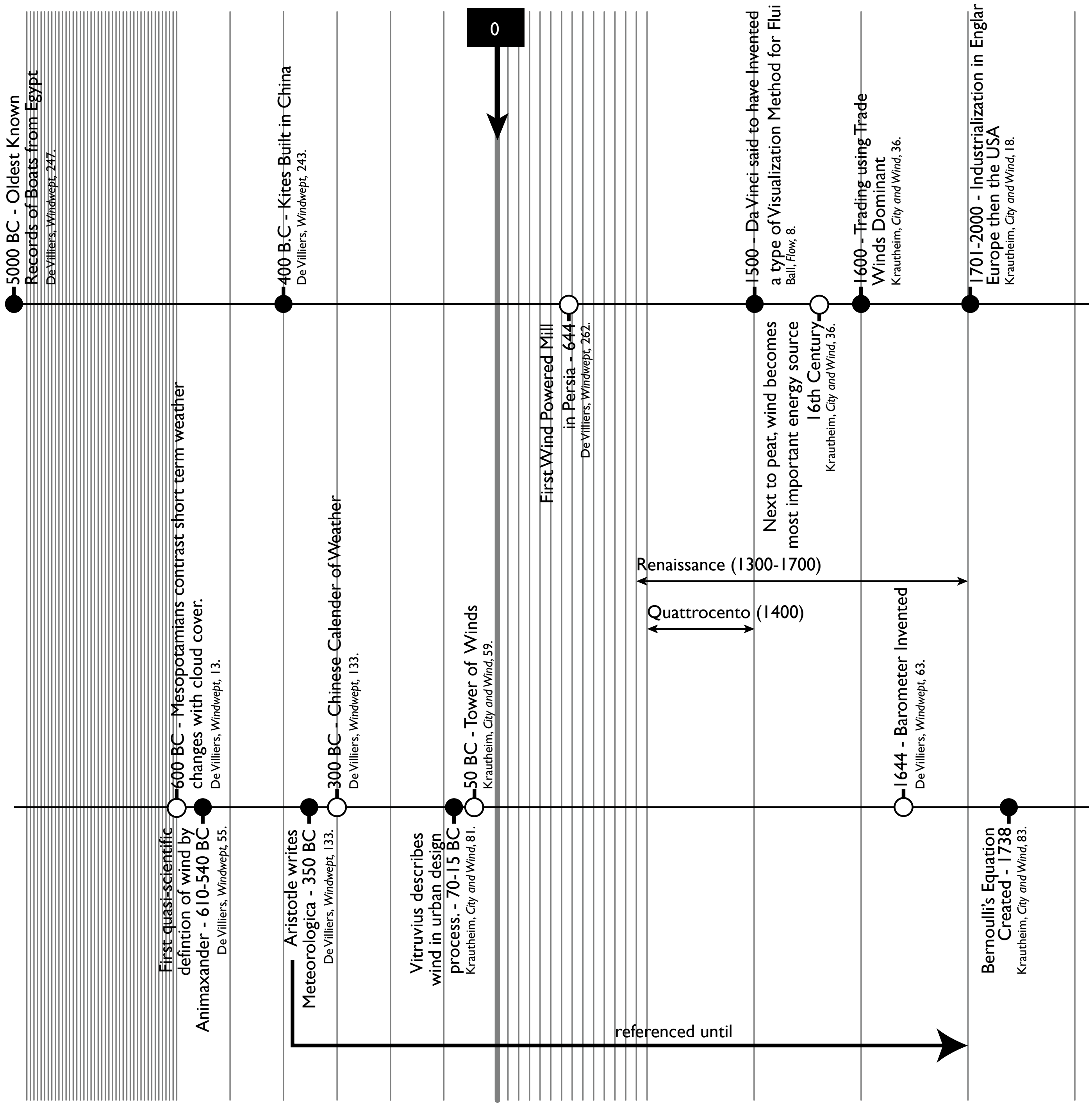
URBAN HEAT ISLAND EFFECT

During the day the city, made up of materials that collect the sun's heat, heats and sucks in air from the surrounding context, ventilating the streets and expelling pollutants.

At night, the atmospheric boundary layer typically cools and stabilizes. There is not much exchange in air masses between the urban environment and its rural surroundings.[13]

FIGURE 2.6. Exceptions to Prevailing Wind Motion Due to Surface Interaction

A HISTORY OF UNCOVERING



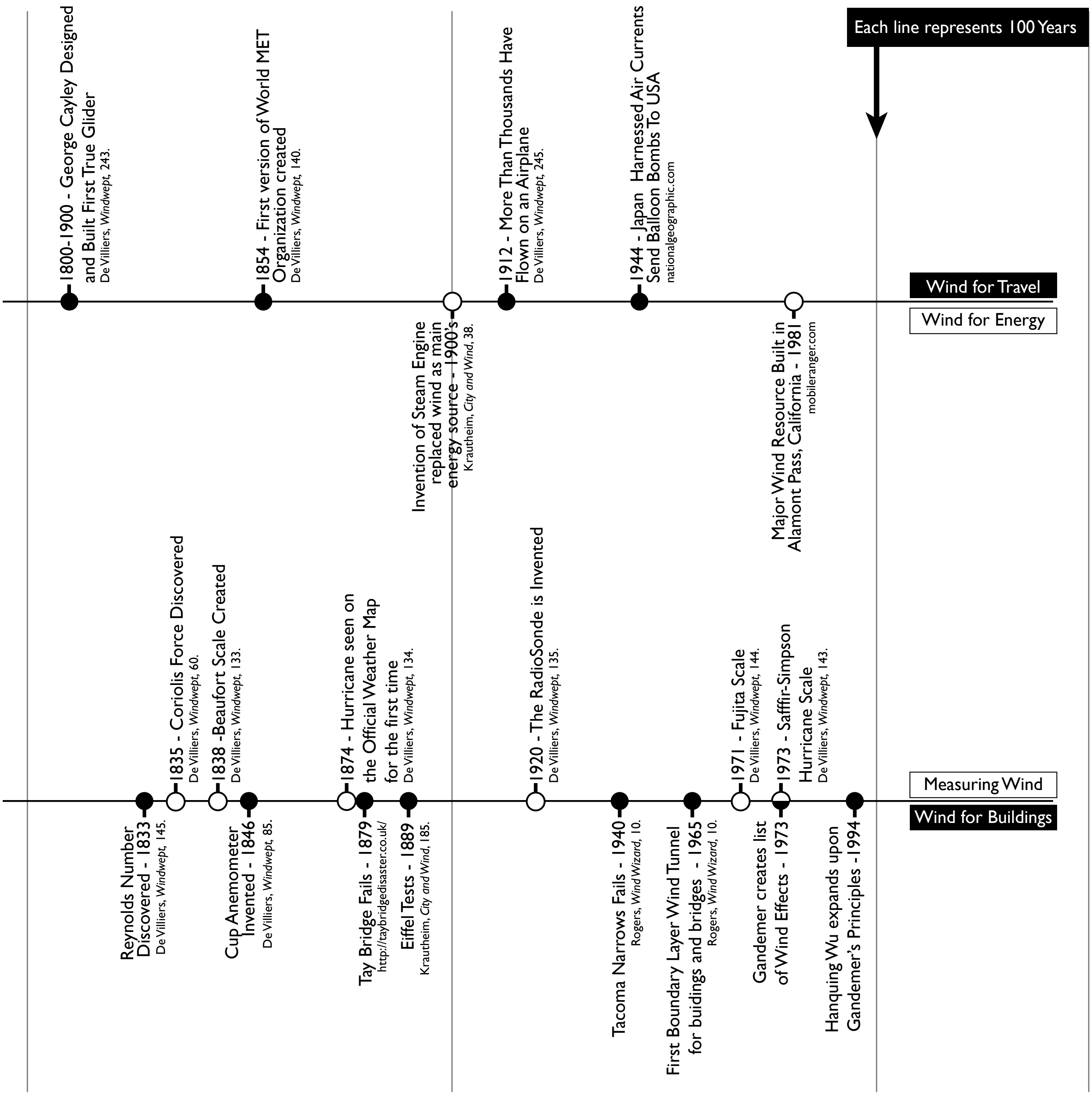


FIGURE 2.7. Timeline of Humanity's Expanding Relationship with Wind

Meteorlogica

350 B.C

Since the Egyptians sailed in 5000 BC, humanity has known that the winds play a significant role on earth. However, cultural fascinations with wind were always met with a yearning for scientific explanations. Philosophers including Animaxander and Aristotle were among the first people to search for wind's scientific meaning. In *Meteorlogica*, Aristotle questions methods of perceiving the origins, causes, and source of winds and "whether one ought to think of the wind as issuing from a sort of vessel and flowing until the vessel is empty, as if let out of a wineskin, or, as painters represent the winds, as drawing their source from themselves."[14] He used deductive reasoning and imagery in an attempt to simplify the complexity of wind. *Meteorologica* was the beginning of meteorology and the authority on weather theory for over two thousand years[15].

For years, without the tools necessary to document and measure winds, sailors used a type of informal folklore called Weather Lores, that were based on nature's signs, to predict and assess weather conditions. Weather lores including, "When the wind is out of the East, tis neither good for man nor beast" can be confirmed by meteorologists from the UK and Europe, as it implies that the harsh winter weather usually comes in from eastern Europe and Russia. Although scientific understanding has eliminating much of the mystery surrounding wind, remnants of pagan and fetish legends in areas such as Southeast Asia and Thailand have survived the twentieth century[16]. At times, when stories and myths could not suffice, symbolism was used to reproduce, in a sensorial way, the same feeling produced by the original source[17].

14. Hutchins, *The Works of Aristotle*, 455.
15. Mayer, *-Arium*, 46.
16. Melaragno, *Wind in Architectural and Environmental Design*, 13.
17 Melaragno, *Wind in Architectural and Environmental Design*, 13.

FIGURE 2.8. *The Rip Tide* - Beirut Music Video

The Aeolian Zone in the Pre-Scientific Era

100-50 B.C

Prior to the scientific understanding of wind and weather, many attributed the force of wind to a divine force controlled by the Gods. Depending on the culture, a singular or groups of Gods controlled the winds. Most notable are the Greek gods of wind or "Anemoi" which include: the North (Boreas), South (Notus), East (Eurus) and West (Zephyr) winds. Their personalities were used to describe the forces of the winds. As an example, the north wind, Boreas, is described as a mature, strong, and violent man with wings who creates storms while the west wind, Zephyr, is depicted as a handsome, winged youth who is the god of spring. In the first century B.C, the Tower of Wind was constructed as a manifestation of the gods and deities in Athens, Greece. Eight deities were included and personified as people with different personalities. It was built to be a water clock, sundial, and weather vane.[18] The eight sides represent what were believed to be the most significant wind directions and personalities. The tower of winds was one of the first architectural representations of the winds.

Stories and legends from Greek mythology were passed on to the Romans and other cultures, who adapted their own versions of the gods of wind. There are Chinese, Japanese, Hindu, North American Indian gods of wind as well as many more that were and still are worshipped.

To this day, regions all over the world have named winds. The same wind may be called by a different name as it blows through different geographical areas and countries, such as the fifty different names used to identify the sirocco wind that originates in the Sahara.[19] While united as an entity, winds are immensely personal.

18. Kienast, *The Tower of the Winds,* 53.
19. Melaragno, *Wind in Architectural and Environmental Design*, 20.

GREEK:
BOREAS

HINDU:
RUDRA

BABYLONIAN/ASSYRIAN:
ENLIL

JAPANESE:
FUJIN

ROMAN:
AEOLUS

CHINESE:
FENG-P'O-P'O

FIGURE 2.9. Various Personifications of the God's of Wind

Early Architectural Theory

100 B.C - 1400 - 1615

In his essay, *The Role of the Winds in Architectural Theory from Vitruvius to Scamozzi*, Allessandro Nova examines how architects Vitruvius, Alberti and Scamozzi, all address issues of wind as architectural concepts, and yet, all end up with very "irreconcilable perspectives." Their individual perspectives demonstrate very different schools of thought from specific periods in history.

Vitruvius was one of the first known architects to have discussed wind and its relevance to the built city. In *De Architectura (Ten Books on Architecture),* written in 30-20 B.C, he relates the eight cardinal wind directions (set by the Greek and Roman gods) to the orientation of the streets, rotating them slightly off axis in order to hide them from the winds that were regarded as a source of disease. These ideas were an attempt to "keep turbulent winds out...[and] to allow harmony of the universe to dominate the chaos of everyday life[20]." Regarding the entire treatise, Vitruvius believed that architects should consider both the theoretical and the practical in design and planning. In 1452, architect Leon Battista Alberti created *De Re Aedificatoria (The Art of Building)* that focused on the physical characteristics of wind and their relation to people. His treaty was humanistic in its approach, stating that "human reason masters the irrational furor of nature and its elements, since their taming is the premise for the well-regulated life of a civilized community[21]." His instructions were more pragmatic and flexible, as they wanted to deal with laws of urban science, that became modern day town planning. He was also credited with the invention of the anemometer, a tool that changed history in weather prediction. Then in 1615 architect Vincenzo Scamozzi, readdresses wind in *L'Idea dell'Architettura Universale (Idea of a Universal Architecture).* The content of this document was based on new ideas of the world, where humanity realized the round shape of the earth. He was not interested in the origins of wind, but instead how "the orientation of the streets remains linked to the directions of the healthy and harmful winds, but the climates of Hungary, Poland and Germany require different solutions from those adopted in Italy.[22]" Unlike his predecessors, he had realized that a single solution could not be applied to all sites equally.

Architects since then have been able to make sense of wind in more ways, but the investigation continues through both scientific and cultural means. While designers study practical applications, the goal to create the Vitruvian vision of a Utopian city that connects people to the cosmos remains.

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20. *Nova, Role of the Winds*, 75.
21. *Nova, Role of the Winds*, 76.
22. *Nova, Role of the Winds*, 82.

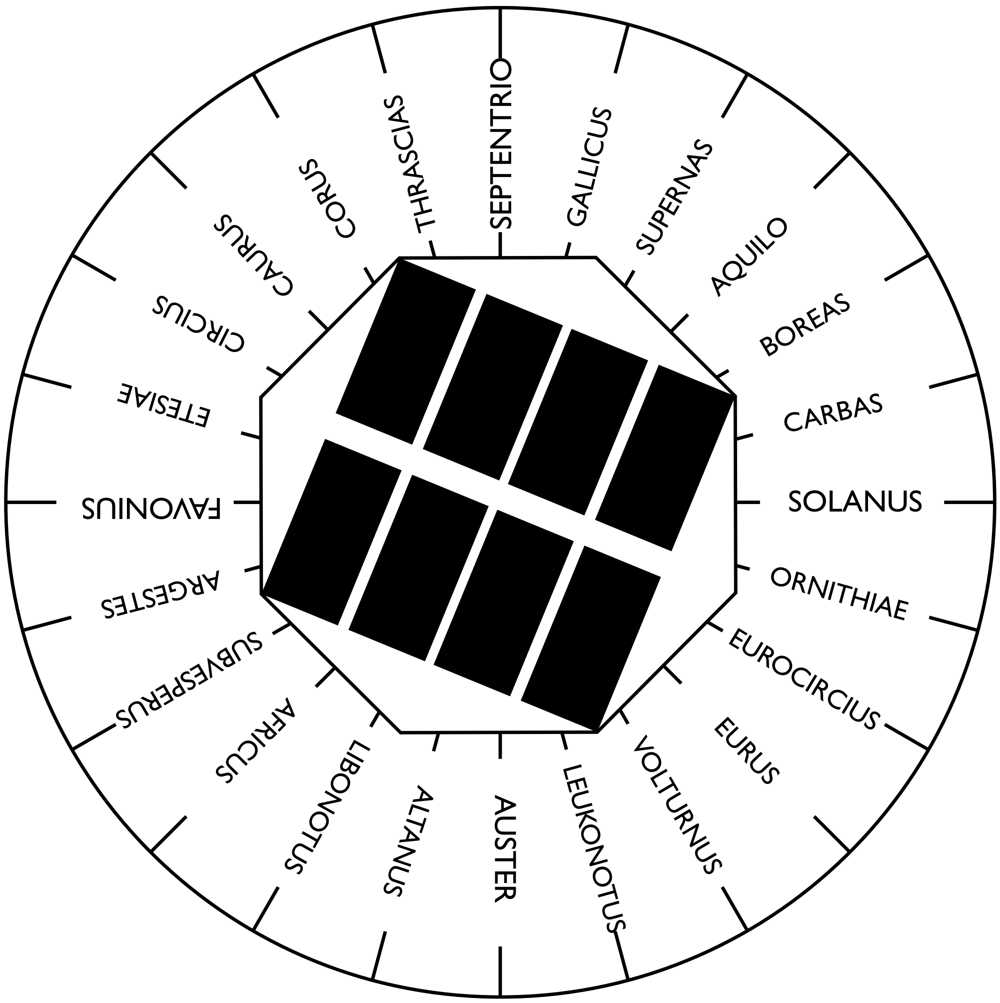

FIGURE 2.10. Hypothetical Layout of a City by Vitruvius

Wind at the Center of the Renaissance

1300 - 1700

In 2006, Western Art Historian Aby Warburg was the first to expose that wind and air had been at the center of Italian Renaissance. In the artwork of the late fourteenth century, wind was used as a tool for a formal means of expression; an external cause of image for pathos and the afterlife. Aby Warburg reinvented the perception of Antiquity and the Renaissanc by placing bodily motion and the displacement of affects at the centre of perception and shifting his focus from the still beauty of Venus to the turbulent edges of her body –- hair, draperies, and breaths of air. The air around the subjects tells its own story about the emotions that are beneath the surface. In works such as the *Birth of Venus*, wind can be seen to send a quiver through space, time, bodies, and souls, connecting outward effects to inward pathos. In this era, the wind does more than simply pass over: it transforms, metamorphoses, profoundly touches people. He goes on to further explain that while the "imaginary breeze" in these art forms seemed to have a spatial incoherence, affecting one form while avoiding another, it was done intentionally. This was not because the artists did not understand wind, but because for the Renaissance man, the "aria" is deeply personal and follows closely to bodily motions.[23]

23. Didi-Huberman, *The Imaginary Breeze*, 280,

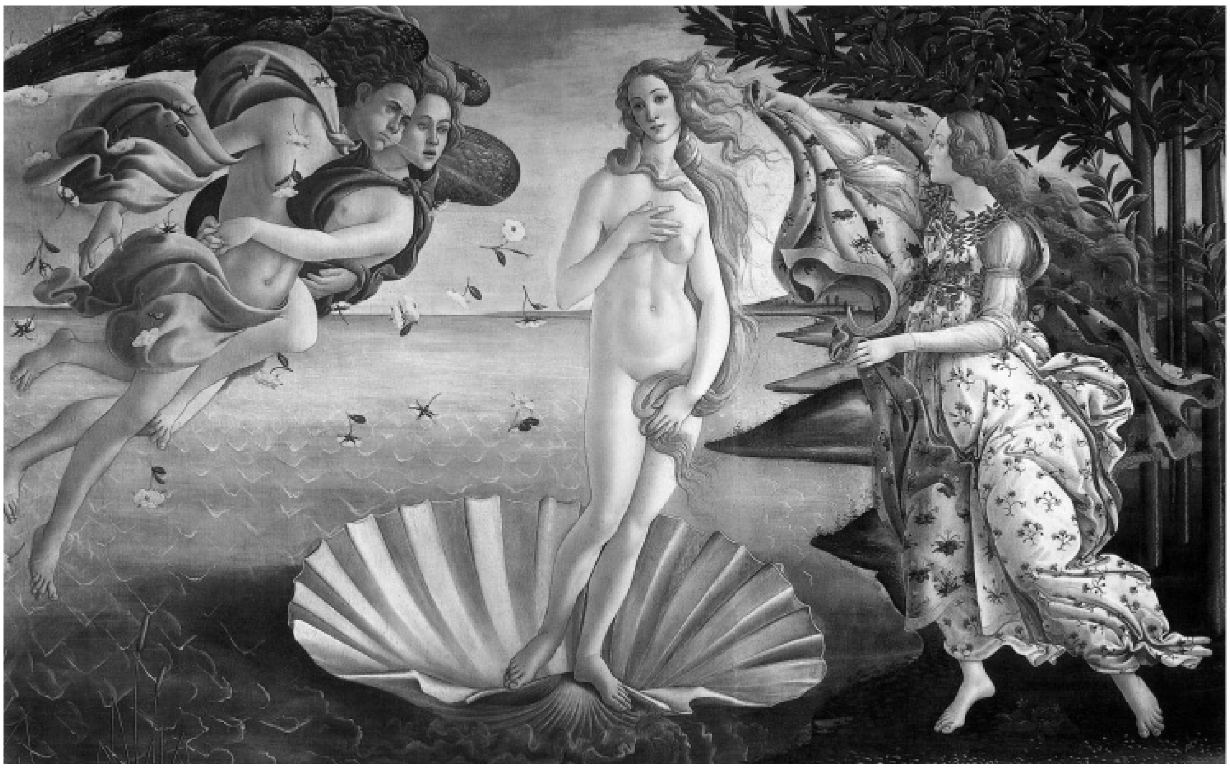

FIGURE 2.11. Wind at the Center of the Birth of Venus - Sandro Botticelli (1484-1486)

The Man Who Loved Fluids

1500

In the 1500's, Leonardo Davinci used a combination of both art (the act of making) and science (logical reasoning) to try to understand the world around him. Considered to be "The Man who Loved Fluids," Davinci investigated many things, including the motion of water and air. He sought after answers in nature, attempting to gain true insight, by "peering beneath the surface of things[24]." His goal was to see what was really there, not what appears to be; to "stop" seeing; to transcend the limitations of the eye[25]." His personal sketches described various flow patterns that are considered to have led to modern fluid dynamics. Scientists would go on to expand upon Davinci's principles, leading to the development of the modern aircraft. "His studies of different speeds of flow in a water channel are the first recorded observations of the conservation of mass flow moving through any cross section[26]," and he is said to have invented a visualization method that includes "fine particles that reflect light suspending in water, or coloured dyes added to part of flow, called streamlines".[27] The importance of Davinci's work goes deeper than methods of visualization. He was one of the earliest people in Western society to suggest that the phenomenon of motion (fluid dynamic) was not chaotic but instead contained persistent forms that could be recognized and that were of value to artists and scientists alike.

24. Ball, *Flow*, 4.
25. Ball, *Flow*, 4.
26. Ball, *Flow*, 8.
27. Ball, *Flow*, 8.

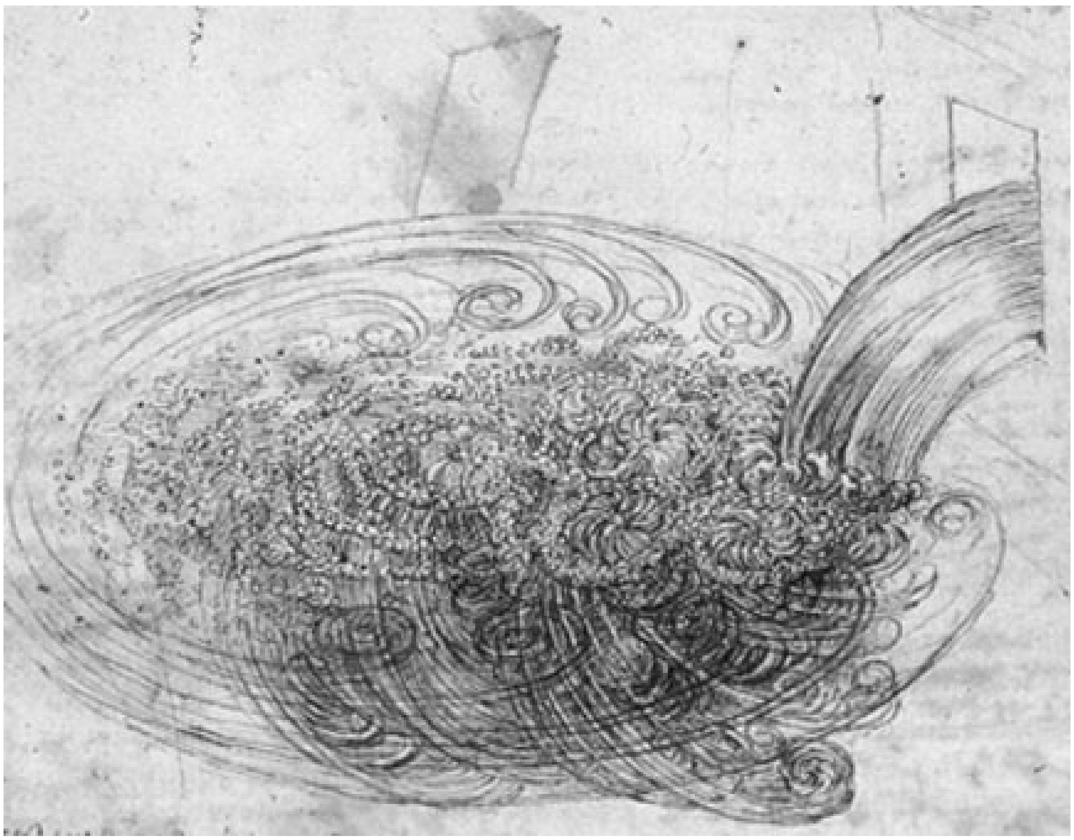

FIGURE 2.12. Davinci's Drawing of Whirling Eddies and Vortices in Water

Scale for the Senses

1805

In 1805, Rear Admiral Sir Francis Beaufort, Knight commander of the Bath, devised a scale for predicting wind effects for sailors at sea. This scale or "reckoner" is called the Beaufort Wind Force Scale. This scale, while arbitrary in its numerical system, used descriptions of a ship's physical response to wind to gauge measurements, instead of measuring the wind itself. Beaufort wanted sailors to look at the ship, not the wind[28]. The visible effects of wind were understood by sailors well acquainted with life at sea. However, when the Navy introduced the scale to a wider audience that was unfamiliar with the ship's motion, they could not agree on measurement or outcome. Around 1955, the use of the anemometer became widespread and mariners correlated measurements with Beaufort's scale. A combination of the telegraph, the anemometer, and a desire for prediction, prompted the creation of a weather network. While rarely used itself, the Beaufort Scale inspired important scales referenced today for severe wind and weather such as the Saffir-Simpson Hurricane Scale and the Fujita Scale for classifying tornado intensities.

In its origins, Beaufort created a scale that allowed sailors to rate and express wind in more than just mathematical terms, by relating them to specific experiences. The significant part of the Beaufort Wind Force Scale is that the senses take priority over a data-driven understanding. A sailor must be familiar with their surroundings, and aware of the forces as they relate to the visible objects. This personal scale, is still valuable today in many instances. For example, an individual sitting near the same office window overlooking a tree for ten years would be able to devise their own scale simply by becoming familiar with the motions of the tree. However, to relate that scale to another individual without numerical values would be difficult. While numerical data creates a reference, ultimately, the senses are the most accessible. To use one senses requires a physical and emotional awareness that relies more on intuition than numbers.

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28. De Villiers, *Windswept*, 133.

Beaufort Number	Description	First Non-Mariner's Description	Wind Speeds knots (kmh)
0	Calm	Calm, smoke rises vertically	<1(2)
1	Light Air	Smoke drift indicates wind direction, still wind vanes	1-3 (2-5)
2	Light Breeze	Wind felt on face, leaves rustle, vanes begin to move	4-6 (7-11)
3	Gentle Breeze	Leaves and small twigs constantly moving, light flags extended	7-10 (13-18)
4	Moderate Breeze	Dust, leaves, and loose paper lifted, small tree branches move	11-16 (20-30)
5	Fresh Breeze	Small trees in leaf begin to sway	17-21 (31-39)
6	Strong Breeze	Larger tree branches moving, whistling in wires	22-27 (40-50)
7	Moderate Gale	Whole trees moving, resistance felt walking against the wind	28-33 (52-61)
8	Fresh Gale	Twigs breaking off trees, generally impedes progress	34-40 (63-74)
9	Strong Gale	Slight structural damage occurs, slate blows off roofs	41-47 (76-87)
10	Whole Gale	Seldom experienced on land, trees broken or uprooted, "considerable structural damage"	48-55 (88-101)
11	Violent Storm	Very rarely experienced; accompanied by widespread damage	56-63 (103-116)
12	Hurricane	Devastation	>64 (118)

FIGURE 2.13. Beaufort Wind Force Scale

BEAUFORT 0

Calm air. Smoke rises vertically.

BEAUFORT 1

A smoke drift indicates the wind direction, while wind vanes remain still.

BEAUFORT 2

Wind is felt on a person's face, leaves rustle, and wind vanes begin to move.

BEAUFORT 3

Leaves and small twigs are constantly moving. Light flags would be extended.

BEAUFORT 4

Dust, leaves, and loose paper are lifted, while small tree branches move.

BEAUFORT 5

Small trees in leaf begin to sway.

BEAUFORT 6

Larger tree branches begin moving, and a whistling in the wires can be heard.

BEAUFORT 7

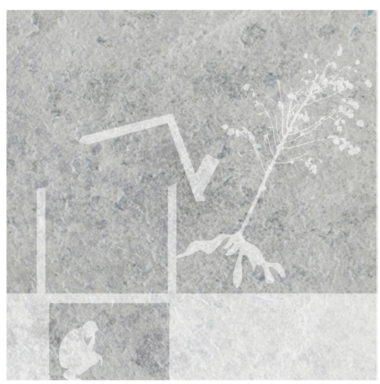
Whole trees begin moving. A resistance is felt while walking against the wind.

BEAUFORT 8

Twigs begin breaking off trees, while the speed of wind generally impedes progress.

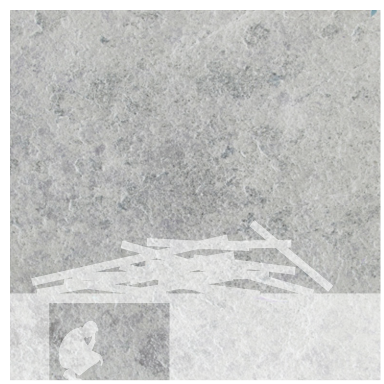
BEAUFORT 9

Slight structural damage occurs, and slate is able to blow off roofs.



BEAUFORT 10

This speed of wind is seldom experienced on land. If it occurs, trees break or are uprooted, and there is "considerable structural damage."



BEAUFORT 11-12

Devastation occurs at this scale. These winds are very rarely experienced, but if they are they are accompanied by widespread damage.

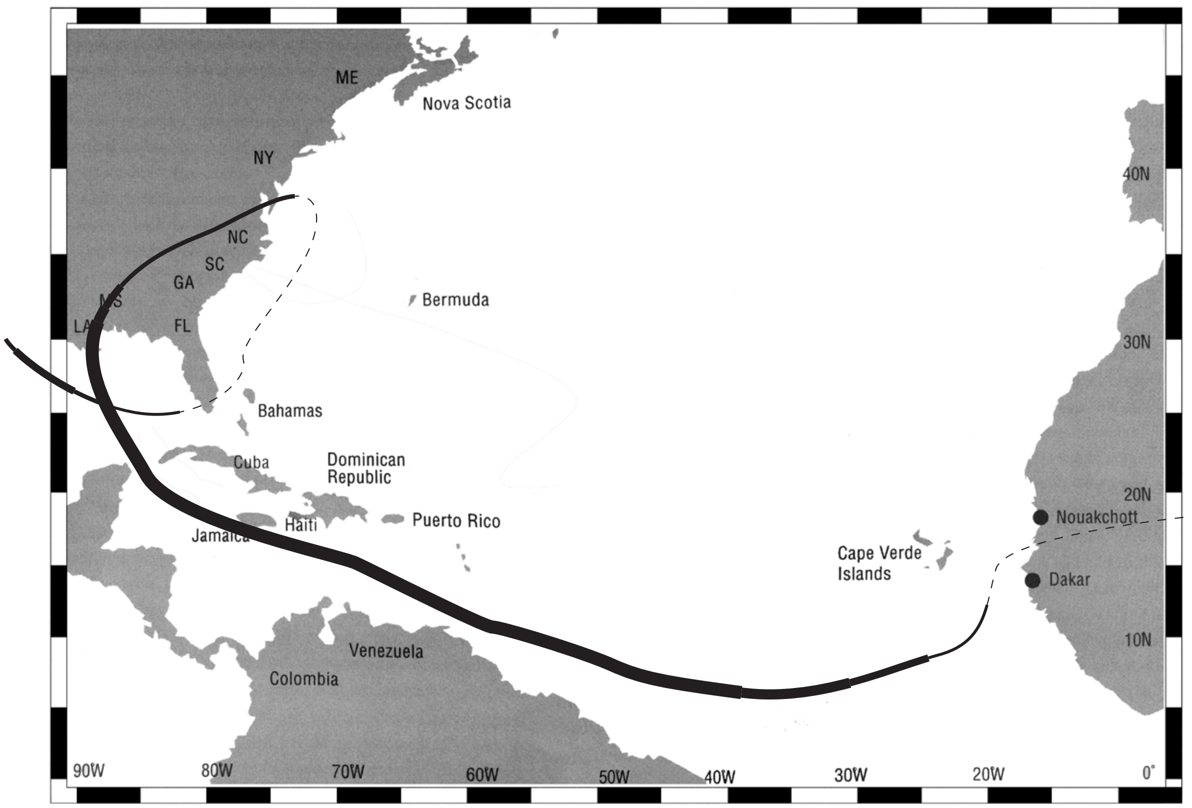
FIGURE 2.14. Beaufort Wind Force Scale - Land Version

The Age of Data

1835

The combination of the invention of the anemometer (1450), the Beaufort Scale (1805), and the telegraph (1837) gave birth to one of the first weather networks, now an ancestor of the World Meteorological Organization.[29] This weather network was dedicated to analyzing earth's atmosphere and its interaction with land and oceans, weather and climate, as well as other things. It was only by 1955 that wind velocities in knots replaced Beaufort numbers, and generally, society began gaining a larger picture of wind and weather, and relied less on personal experiences and chance. The forces of winds, tornadoes, and hurricanes could now be subjected to and measured against numbers to gauge severity. Tools of measurement such as the thermometer (1638), the wind vane (50 BC), the anemometer (1450), the barometer (1643), the weather balloon (1896), the satellite (1957), and of course the advancements of the modern computer all enabled the visualization of realtime patterns that meteorologists had been plotting on their maps. Once data could be shared, the paths of wind that were uncovered were eye opening. The slow, dry winds in the desert that slowly made their way over to the American continent to become an entirely different force, made of the same matter, were now able to be tracked. Although wind and weather prediction can be traced back to the Mesopotamians in 600 BC where short-term weather changes correlated to cloud cover and haloes, it was not until the 21st century that a major effort was put in to develop numerical forecasting[30]. Since then, weather forecasting has drastically improved over time with predictions as accurate as 3-4 days in advance.

29. De Villiers, *Windswept*, 133.
30. De Villiers, *Windswept*, 133.



Info from http://www.nhc.noaa.gov/.

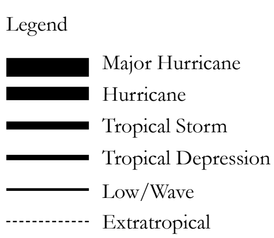
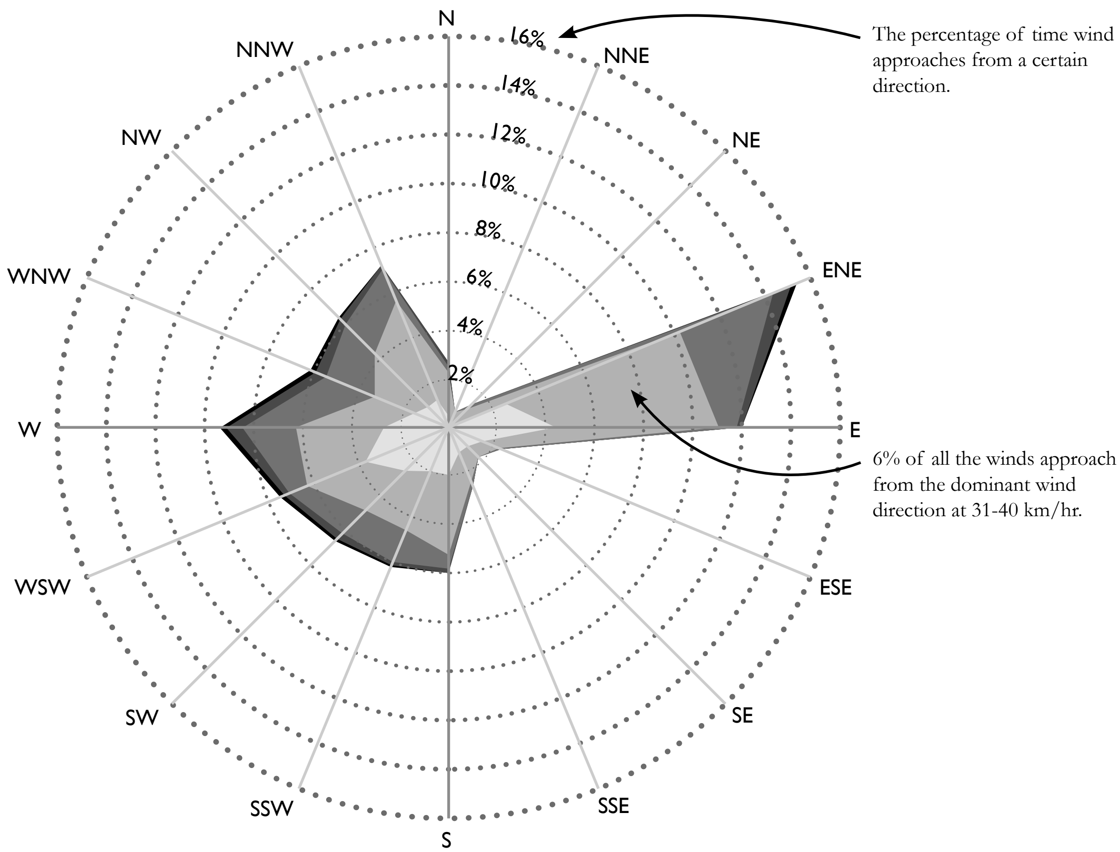


FIGURE 2.15. Path of Hurricane Ivan in the Atlantic Basin in 2004

The Wind Rose

As data began to be collected and stored, visual representations were created to simplify and organize the information in an accessible way. The most common visual representation created and still used today is the wind rose: a visual representation of the average speed and direction of wind over time. Data entered into the wind rose is generally taken from an anemometer, that can document wind speed and direction. They are generally located at airports, where they benefit from the open fields away from drastic topographic changes such as mountains or cities. They are placed at about ten meters above the ground in order to catch the free flowing air at gradient height (its maximum speed). Many parameters affect the information in a wind rose including: such as the time intervals when wind speeds are collected (1 or 3 second gusts), the number of wind directions included (36 or 16 wind directions) and the date when the wind rose was established. If a singular anemometer collects 1 second gusts from 1920 to 1950 and the 3 second gusts from 1950-present day, only the results from 1950 onward can be averaged, as including the earlier ones would skew the information. Furthermore, authors of the paper *Predicting Design Wind Speeds from Anemometer Records* raised questions on the accessibility, validity, and identity of wind records, and stated how it is important to verify the nature of the information being used. They exposed the problems associated with not knowing the anemometer type and exposure characteristics, incorrectly assuming the averaging time of the wind speeds, and carrying out an assessment using only one meteorological site[31]. If this information is not understood and used incorrectly, the resulting wind rose is useless. Since designers only deal with the resulting wind rose, it is important to question and confirm the quality and relative accuracy of the information in the wind rose.

31. Burton, *Predicting Design Wind Speeds from Anemometer Records*, 1.



LEGEND

Wind Speed (km/h)	Probability (%) Summer	Winter
Calm	5.5	2.6
1-10	28.4	15.8
11-20	44.2	37.7
21-30	17.7	26.2
31-40	3.5	11.8
>40	0.8	6.0

FIGURE 2.16. The Wind Rose - Courtesy of RWDI

Larger Patterns

Generally, the wind rose details annual information regarding a specific geographic location, at specific intervals of time, at a specific height, and over a specified amount of time. The information can be divided further to show average winds during summer and winter, during all four seasons and even between day and night. Since the information is so specific, it is difficult to apply it to another site without knowing how the data is collected or what is taken into account.

A combination of wind roses over a larger area can hint at overall patterns, if the information is available. Wind patterns not only differ over long distances but also over different heights. Contextual characteristics such as the presence of body of water, mountains, cities, as well as different altitudes also contribute to changes in wind flow. Some wind roses can also show wind speeds in relation to direction and over a period of time. The direction that typical winds come from is not always the main source of high speed winds. In these cases it is important to pay close attention to the specifics of the information.

Meteorlogical (MET) data is not required to perform initial computational simulations or tests within a wind tunnel or waterflume. Generally, ratios of different wind speeds are solved in computational and physical simulations and then the numbers are calibrated to properly represent the MET data. This final step is necessary to ground any project, attributing and relating effects to a specific place over a certain period of time. As designers are visual learners, the visual nature of a wind rose is vital. Designers only have MET data to rely on to gain information on wind conditions of a particular a site. It is for this reason that it is important to understand the nature of the data itself, how to work with it, and what types of information can be relied upon.

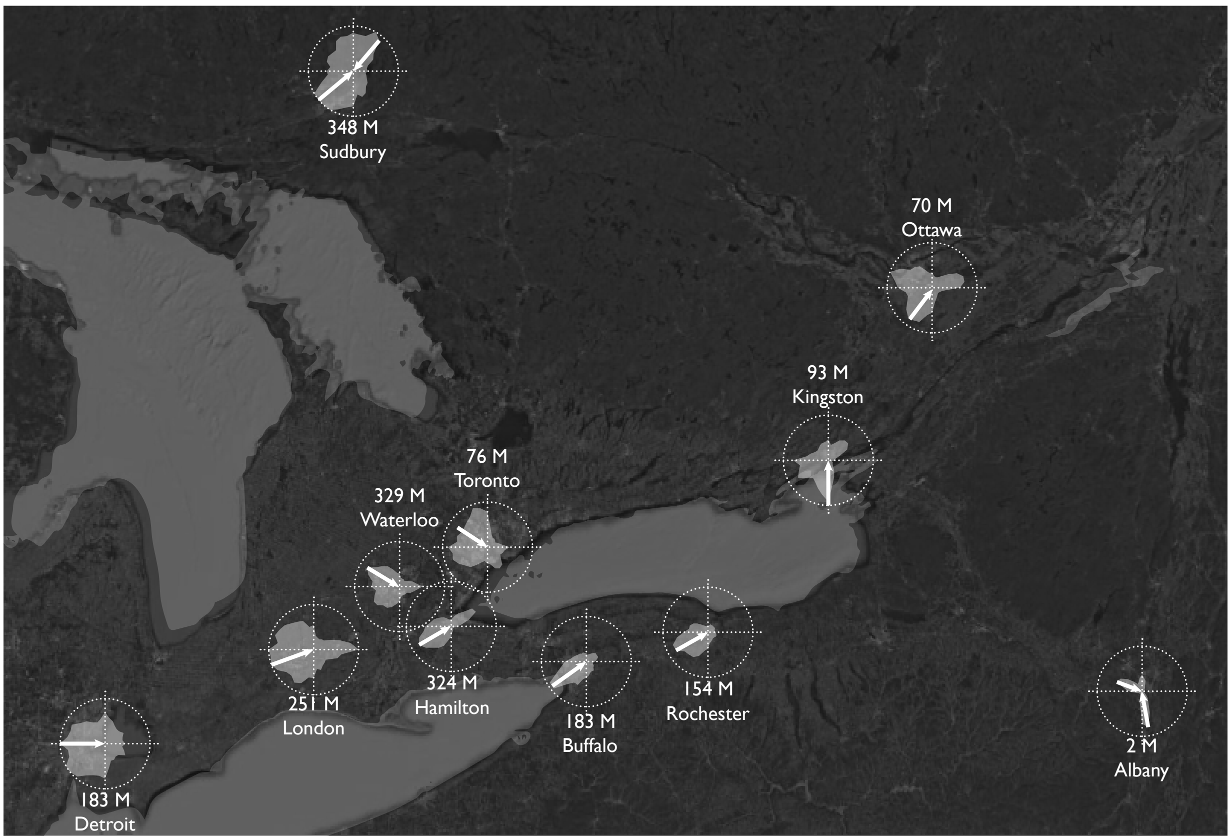


FIGURE 2.17. Combination of Wind Roses Demonstrating Changing Winds

The Boundary Layer

1904, 1909-1912

In the early twentieth century, German scientist Ludwig Prandtl discovered the concept of the boundary layer that enabled the testing of buildings and bridges. Before this, aerodynamicists had made assumptions that air moved the same way close to the ground as it did high into the sky in order to simplify equations. It was in 1904, that Ludwig Prandtl suggested that due to the viscous (syrupy) qualities of air, upon first contact with the surface, a first layer of air particles stick and get caught on the surface due to roughness (however minuscule). A second layer slides over the first and slowly increases in speed at the intersection of this first "stuck" layer ("it shears past at a very slow velocity, dragged down by the [first layer]."[32] This stratification of air and its varying speeds are what make up the boundary layer, where humans live. Prandtl applied these principles to aeronautics, while engineer Gustave Eiffel built upon this research and examined different building shapes in wind tunnels.

Gustave Eiffel was one of the first individuals to factor in the importance of the effects of wind on tall structures. Although the wind calculations of the Eiffel tower were considered to be conservative, Gustave Eiffel had told the French newspaper *Le Temps* that the primary concern in the design was wind resistance.[33] He applied his ideas by not only designing and constructing the world famous Eiffel Tower completed in 1887, but by then using that same structure to host other experiments associated with wind. Around 1889 he created a drop-test device that accurately measured drag by dropping various bodies along a vertical cable from the second level of the Eiffel tower[34]. Between 1909 and 1912, he built a wind tunnel at the tower's base and confirmed that air moving around a stationary body produces the same drag as the body moving through still air. Gustave Eiffel produced the most accurate data of the time and confirmed the theory of fluid flow. His laboratory was to become a model for future practice.

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32. Roberts, *Wind Wizard,* 15.
33. Roberts, *Wind Wizard,* 16.
34. Roberts, *Wind Wizard,* 17.

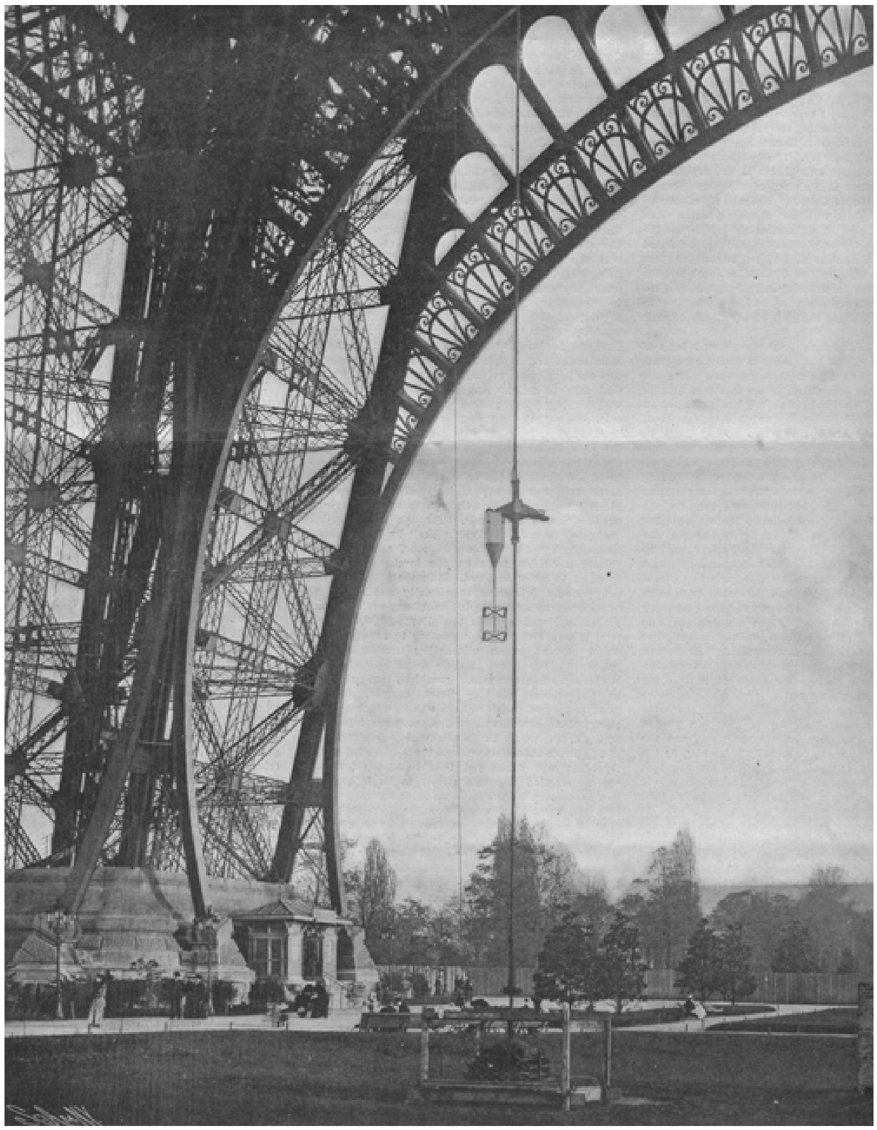

FIGURE 2.18. Gustave Eiffel's Drop-Test Device Setup on the Second Level of the Eiffel Tower

Seeing the Unseen

1899 - 1903

While many scientists were working to numerically describe the behaviour of wind at grade, French Scientist Etienne-Jules Marey was pioneering chronophotography that enabled him to capture the motion of bodies in time, that led him to wind. Constantly pursuing ways of observing the invisible, his work is said to be one of the best examples of inter-disciplinary learning and studying. While the majority of his work studied the gallop of horses, the flight of birds, the gait of elephants, the swim of fish, and the organic motion of many other creatures, it was not until 1899 that he produced what is said to be the climax of his work,[35] the smoke machine. While the first smoke machine built in 1899 had twenty smoke trails, in 1901 the United States funded Marey to construct a smoke machine with fifty-eight smoke trails. Between 1899 to 1909, he photographed the movements of air and in turn invented what was said to be one of the first aerodynamic wind tunnels. Marey confirmed Gustave Eiffel's findings, stating that "From the point of view of the resistance experienced, whether the solid body be in motion in calm air or whether it be immobile in an air animated with movement is indifferent."[36]

Étienne-Jules's investigation using smoke to visualize flow inspired a major industry. Although scientific in its use, his initial intentions were simply to observe motion of different bodies over time.

35. Naughton, *Étienne-Jules Marey (1830 - 1904)*, ctie.monash.edu.au/hargrave/marey.html.
36. Musée d'Orsay, *Movement of Air Etienne-Jules Marey*, musee-orsay.fr/en/events/exhibitions/in-the-musee-dorsay/exhibitions-in-the-musee-dorsay-more/page/1/article/mouvements-de-lair-etienne-jules-marey-1830-1904-photographe-des-fluides-4216.html?cHash=d5c6f3a521.

FIGURE 2.19. Étienne-Jules Marey,
Tilted plane, 30-degree angle, fourth and last version of the smoke machine equipped with 57 channels

Buildings, Bridges, and People

1963

While the first aeronautical wind tunnel had been used since 1871,[37] it was almost 100 years later that the first boundary layer wind tunnel came into existence. In 1964, Alan Davenport and Jack Cermak, said to be fathers of modern day wind engineering, worked with Les Robertson to create a "unique meteorological wind tunnel at Colorado State University that had the capability of creating turbulent boundary layers[38]" that was used to test the New York World Trade Towers for the first time. Alan Davenport would go on to create the first dedicated boundary layer wind tunnel in 1965, for civil engineering structures including buildings and bridges. This tunnel, located at the University of Western Ontario, was used to test a version of the New York City World Trade Centre towers, Citicorp Tower, Chicago's Sears Tower, Boston's John Hancock tower, Shanghai's World Financial Centre, Toronto's CN Tower, many of the world's longest bridges, and odd occurrences such as the ones found at Amen Corner (a golf course in Florida where winds would switch direction halfway between the hole and the starting point due to tree positioning).[39]

This occurred the same decade that saw the invention of the computer mouse, the Internet, hand held calculators, the ATM, Apollo 8, string theory, and a time when a newfound consciousness on environmental sustainability was developing[40]. This was also eighty years after the construction of the Chicago's Home insurance building, considered to be the first modern skyscraper at the time, that lead the way for skyscraper development.[41]

Davenport was said to often use the Tacoma Narrows Bridge collapse of 1940 (due to unanticipated flutter in response to wind motion[42]) as an example to emphasize Shakespeare's notion of "what is past is prologue"; that disasters were precedents that revealed new information to be remembered and applied to future designs.

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37. Baals, *Wind Tunnels of Nasa*, grc.nasa.gov/www/k-12/WindTunnel/history.
38. Cochran, *Early Days of North American Wind Engineering,* 3.
39. Rogers, *Wind Wizard*, 4.
40. Rogers, *Wind Wizard*, 4.
41. Janega, *The Skyscraper*, chicagotribune.com/bluesky/series/chicago-innovations/.
42. Pasternack, *Strangest Bridge Collapse*, motherboard.vice.com/read/the-myth-of-galloping-gertie.

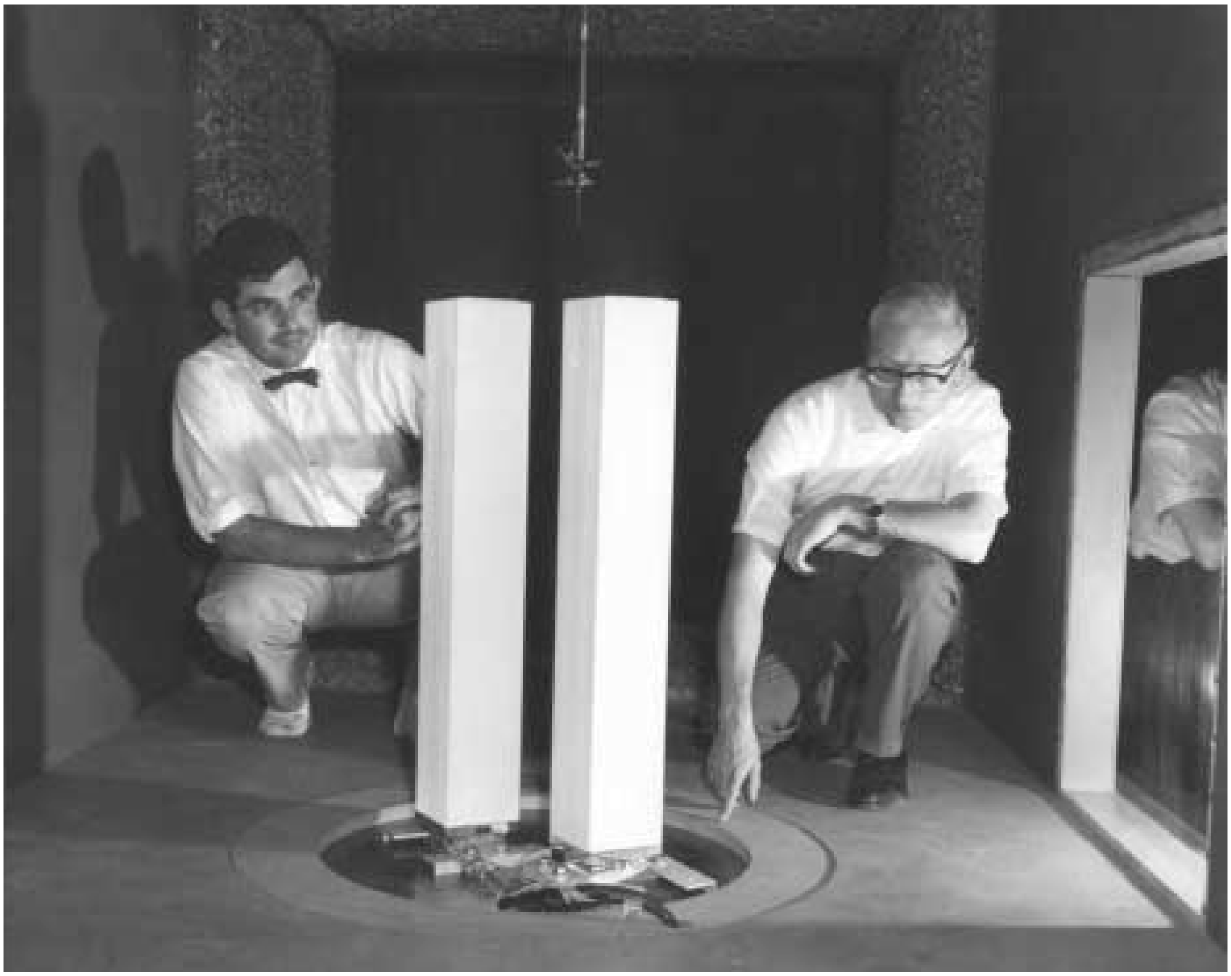


FIGURE 2.20. Drs. Davenport and Cermak with Aeroelastic Models of the World Trade Center in the Meteorological Wind Tunnel at Colorado State University in 1964.

Advancements in Wind Engineering

Others would go on to expand and contribute to the field of wind engineering and fulfill a commercial demand for wind tunnel testing. In 1972 Bill Rowan, Colin Williams, Anton Davies, and Peter Irwin, co-founded the company RWDI Inc. in Guelph, Ontario, Canada that would be known as "the world's largest wind engineering consulting firm". In 1981, Dr. Jack E. Cermak, who contributed greatly to defining the tools and methods on which modern day wind engineering was founded, partnered up with Dr. Jon Peterka, (and three years later) with Dr. Ron Petersen to co-found Cermak Peterka Petersen and Associates. Since then, many other companies that claim to provide expert wind tunnel testing and professional expertise have formed all around the globe.

The inclusion of the study of wind engineering within universities and commercial practices allowed for the development of methods of measuring and visualizing the flow in wind tunnels. The application and use of wind in design expanded far beyond simple wind loading calculations on the structure of buildings and bridges to include testing on: the strength of facades, pedestrian level comfort, air quality, acoustics and noise, snow, rain and sand accumulation, and even tornadoes, hurricanes, and downbursts (a strong downward current of air) at facilities such as the Wind EEE Facility at the University of Western Ontario.

Today, there is still a large amount of research needed to narrow down wind engineering science, and to expand ways to work with wind. There is much more to be uncovered, especially in the coming age of super-tall and mega-tall buildings.

CALM WIND

LIGHT AIR

GENTLE BREEZE

LIGHT BREEZE

MODERATE BREEZE

FRESH BREEZE

COMFORT CATEGORY	SPEED (KMH)	DESCRIPTION
Sitting	≤9	Calm or light breezes desired for outdoor restaurants and seating areas where one can read a paper without it blowing away
Standing	≤12	Gentle breezes suitable for main building entrances and bus stops
Strolling	≤ 16	Moderate winds that would be appropriate for window shopping and strolling along a downtown street, plaza or park
Walking	≤19	Relatively high speeds that can be tolerated if one's objective is to walk, run or cycle without lingering
Uncomfortable	>19	Strong winds of this magnitude are considered a nuisances for most activities, and wind mitigation is typically recommended
Safety Risk	>90	Excessive gust speeds that can adversely affect a pedestrian's balance and footing.

FIGURE 2.21. Pedestrian Comfort Criteria of RWDI-Guelph

REVEALING WIND

Despite the mass amounts of information available to describe wind, there remains a need to sense the wind in order to truly understand it. In a few cases, individuals possess the capacity to interpret conditions from a distance such as Lauchie McDougall "the human wind gauge" (1896-1965) who could sense storms and suggest the delay of trains in NFL Canada[43]; or Herb Hilgenberg of Burlington, Ontario who uses a single sideband radio to broadcast to ocean travellers who need help navigating the unpredictable weather of the Atlantic ocean[44]. For the rest of humanity, even engineers, while intuition based on experience can be useful, testing and using a combination of computational, physical simulation, and full scale measurements is necessary to achieve accuracy.

Learning from failure is a primary way that wind becomes visible, from the 1839 damage to the Menai Suspension Bridge, the 1854 failure of the deck of the Ohio wheeling suspension bridge, the 1879 failure of the Tay rail bridge, the 1889 Niagara Falls suspension bridge, the 1940 Tacoma Narrows incident, and the modern day Walkie Talkie tower downwashing disaster. Each of these instances are precedents for future design. Alan Davenport believed that people should look for wind in unexpected places and learn from failure. For example, Alan Davenport described that while humans confront the wind by leaning forward and relying on gravity, palm trees adapt to strong winds by rolling up their branches to reduce wind resistance. They can do this because they have developed a tough fibrous trunk with excellent fatigue resistance.[45]

While wind can be found in unexpected places, many artists over time have been revealing parts of wind that science has not been able to fully describe, especially characteristics related to the senses. Although the interaction between people and wind is typically considered a minor annoyance, many artists have used their work to monumentalize these encounters, instead of allowing them to remain unnoticed.

43. De Villiers, *Windswept*, 115.
44. De Villiers, *Windswept*, 161.
45. Roberts, *Wind Wizard*, 18.

FIGURE 2.22. Artists Christo and Jeanne-Claude Test their Project *Over the River* at RWDI's Wind Tunnel in Guelph, Ontario, Canada.

WIND VEIL
NED KAHN
2000

BEAUFORT 1: DISPERSAL ZONE, 2015
TIM KNOWLES
2015

Ned Kahn uses the elements of air, water, fire and earth in his installation work. Some pieces are incorporated into building facades and add a dynamic dimension to an otherwise still architecture. In the *Wind Veil* specifically, Kahn uses small metal elements that are tethered on one edge and free to flip back and forth on the other. These elements move with the gusts of wind to produce an effect that mimics ocean currents.

In the city, exhaust from buildings and automobiles can reveal the patterns of wind. The installation, *Dispersal Zone*, created for Nuite Blanche 2015 in Toronto, Ontario, was composed of rings of heat placed around a street lamp bulb, that would emit smoke. The combination of light and smoke traced out patterns of the wind in a common setting. At a one to one scale, the pedestrian was enabled to "see" the wind that they feel moving around them.

46. Echelman, *1.8 London*, http://www.echelman.com/project/1-8-london/.

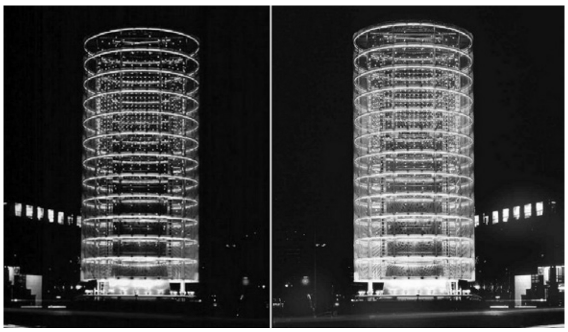
THE SINGING RINGING TREE
MIKE TONKIN AND ANNA LIU
2006

1.8 LONDON, UK
JANET ECHELMAN
2016

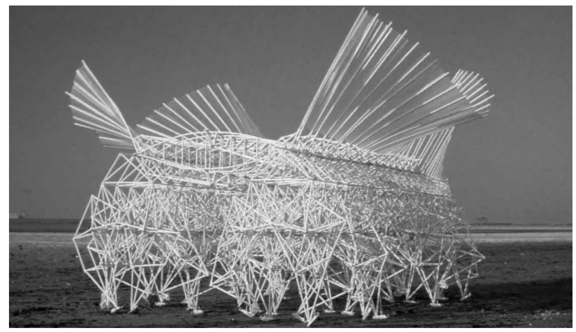
The sculpture, *The Singing Ringing Tree*, utilizes orientation, location and form in relation to winds to produce an "eerie, melodius hum". The pitch and frequency of the sounds are directly related to the strength and direction of the wind surrounding the sculpture. The pipes are tuned according to their length and cover several octaves. While the sound of the wind as it flows between typical objects found in a city setting might produce an undesired effect for certain individuals, this project attempts to control that sound for a desired effect.

Janet Echelman's installations, created from high-tech fibre developed originally for NASA spacesuits, are described as "living and breathing" because they billow and change shape in the wind. The name of the project, *1.8*, refers to the "length of time in microseconds that the earth's day was shortened as a result of... the 2011 earthquake and tsunami that emanated from Japan.[46]" Many of her sculptures allow the ephemeral forces of wind to bring the work to life.

FIGURE 2.23. Artistic Expressions of Wind



TOWER OF WINDS
TOYO ITO
1986

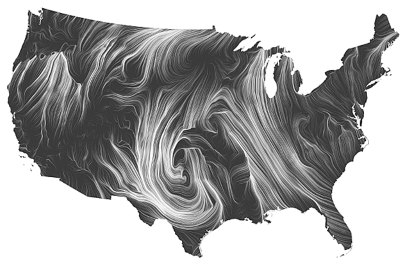


STRANDBEEST
THEO JANSEN
1990

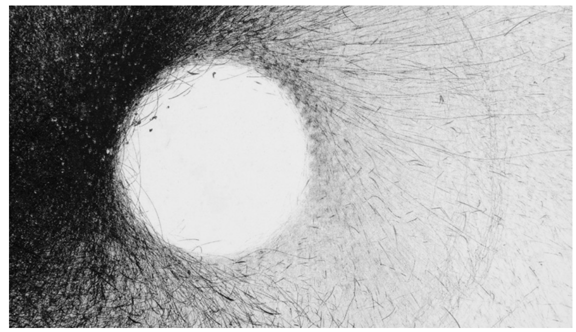
The *Tower of Winds* by architect Toyo Ito, is a project that uses technology to establish a relationship with nature that is then shared with the surrounding city. At night, real-time data from the surrounding landscape translates sound into color and wind into light through sensors. Adding on to an existing infrastructure that is a water tank, Ito aims to connect the natural with the technological.

Theo Jansen's Strandbeest's "walk on the wind" and miraculously bring life to inanimate objects. These "animals" are said to have become "better at surviving the elements" and eventually, the artist would like to place the animals "out in herds on the beaches, so they will live their own lives[47]." The wind's energy is translated into motion. In a way, these animals illustrate the beauty and force of the wind; using it for their very livelihood.

47. Jansen, *Strandbeest.* http://www.strandbeest.com/.



THE WIND MAP
FERNANDA VIÉGAS AND MARTIN WATTENBERG
2013



WIND DRAWINGS
CAMERON ROBBINS
2008

Many artists have utilized simulations to reproduce patterns and data into stills or animations. *The Wind Map* - also called a "living portrait" - uses real-time data from meteorological stations spread out over the USA to reveal the unseen patterns of wind. The visual nature of this work allows the individual to see the direction and force of winds and the relationship between different parts of the country through wind.

Other methods of utilizing data to visualize wind have been to insert an instrument, at times paint dust, or simply a pen fixed to a wind catching object and to let the wind draw itself, such as Cameron Robbins *Wind Drawing* instruments. The instrument used to create these works consists of an anemometer tied to the drawing utensil and a wind vane controlling the drawing pad. As the wind approaches the instrument at a certain direction and with speed, the anemometer and wind vane move in response, resulting in these pieces of wind drawn art.

FIGURE 2.24. Artistic Expressions of Wind

"[In] the age of technology and age of ecology, the machine is a symbol of necessity and wind a symbol of possibility. "Wind" denotes a condition and event of things called air as well as the field of flow where the phenomenon occurs. A field transcends the place where the work of architecture exists, that is, the domain, and extends endlessly."

- Hara, *"Machine" and "Wind"*, 8.

LAWS OF MOTION

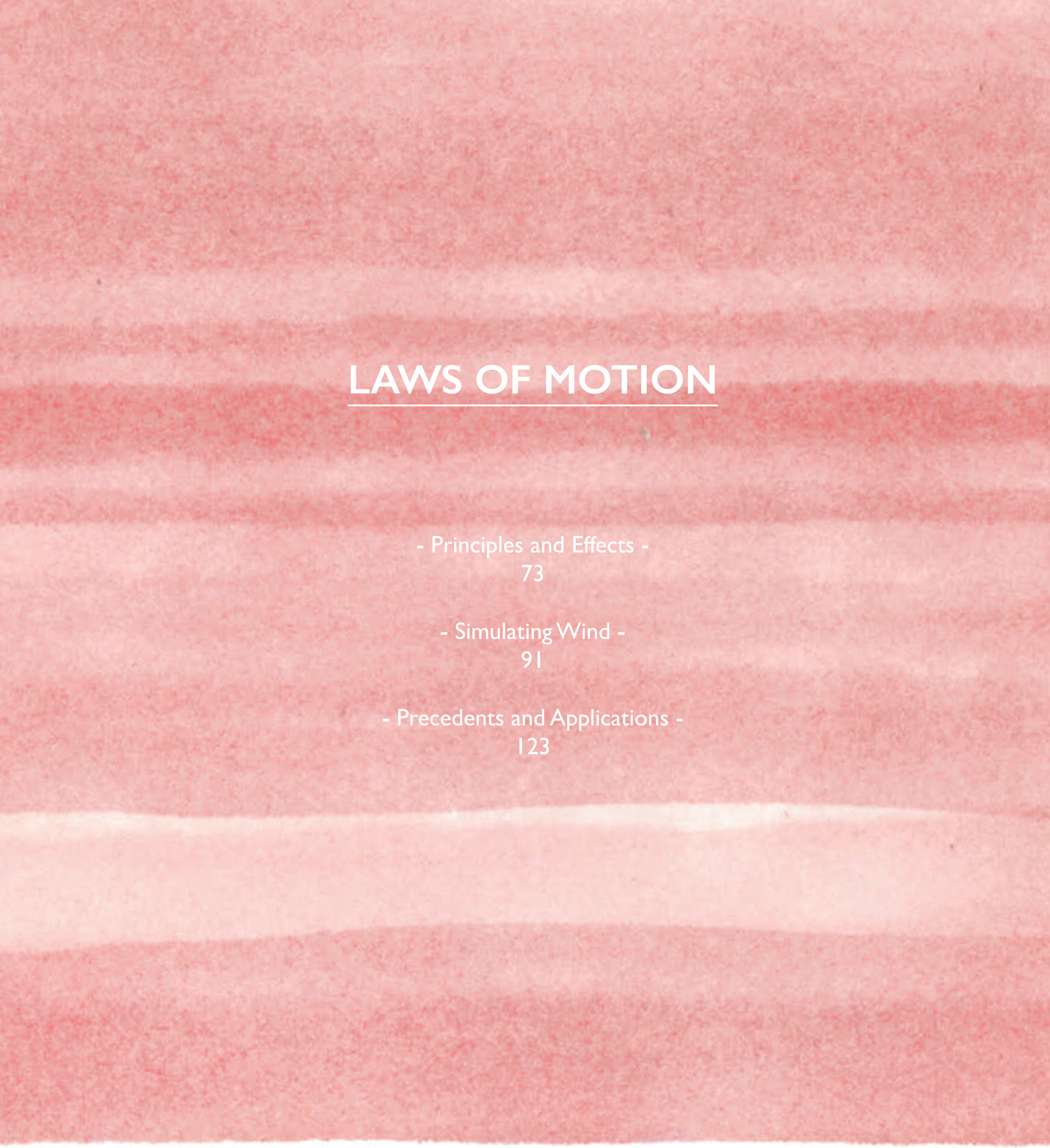


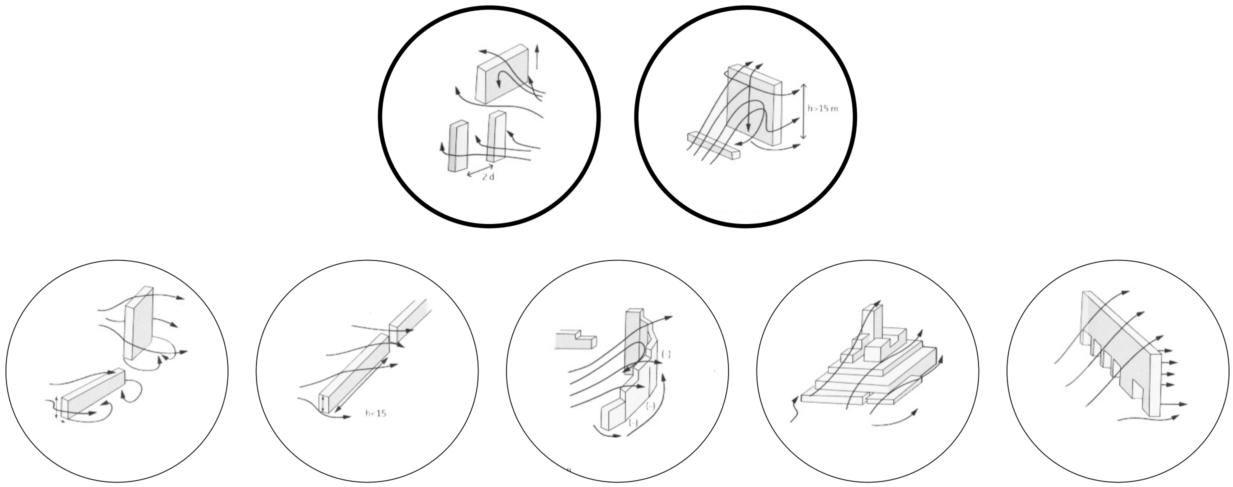
FIGURE 3.1.

PRINCIPLES AND EFFECTS

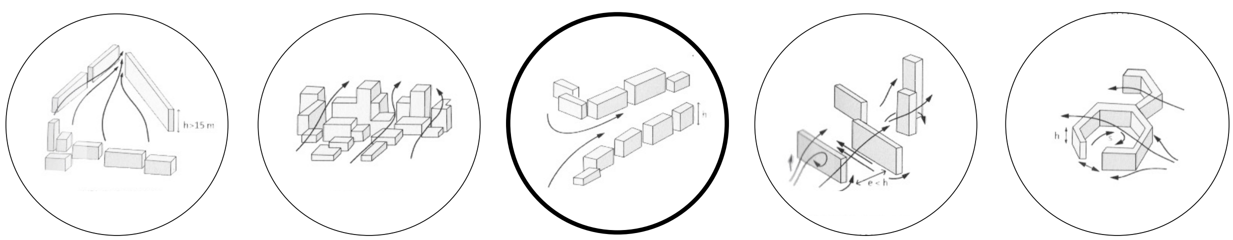
In 1973, J. Gandemer produced a document outlining twelve aerodynamic effects that occur at pedestrian levels. He stated that "wind flow at ground level is the result of complex interaction between the wind (incidence, mean vertical speed gradient, turbulence), and the buildings themselves (shapes, sizes, settings)[1]". These twelve effects can be categorized into isolated building effects as well effects caused by a combination of buildings. Many of these effects can occur simultaneously or in succession.

The study of these forms is specific, simplified, isolated, and extracted from their context and therefore cannot be generalized. Instead, these effects provide a basic understanding of the complex interactions between building and wind.

1. Gandemer, *Discomfort Due to Wind Near Buildings*, 1.



OBJECT: FORM, SHAPE, SURFACES, EDGES BASED EFFECTS

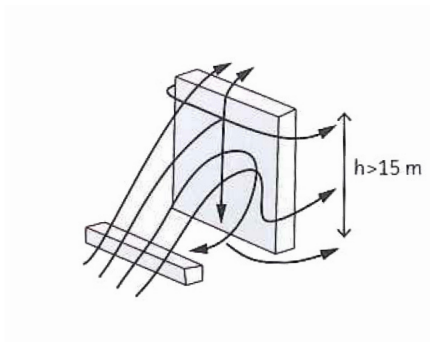


SPACE: ORIENTATION, PROXIMITY BASED EFFECTS

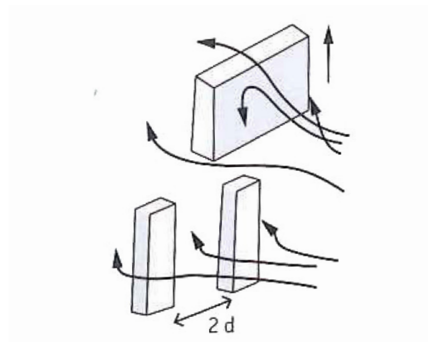
FIGURE 3.2. Twelve Aerodynamic Effects - By Gandemer

SURFACE

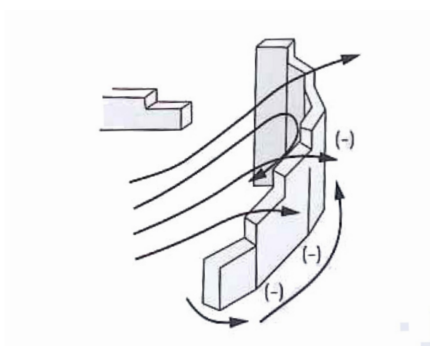
EDGE



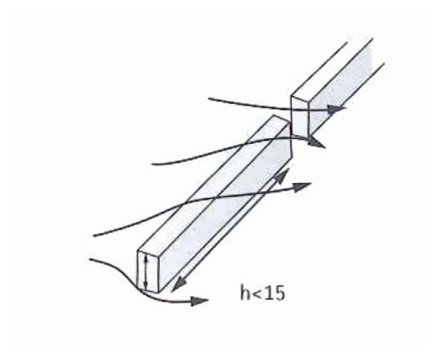
DOWNWASHING



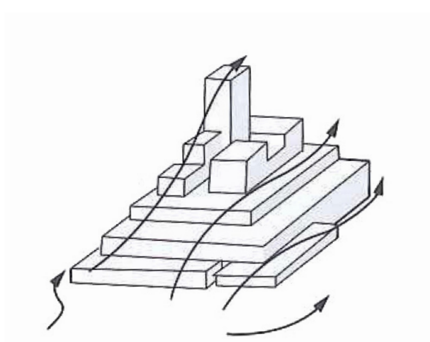
CORNER ACCELERATION



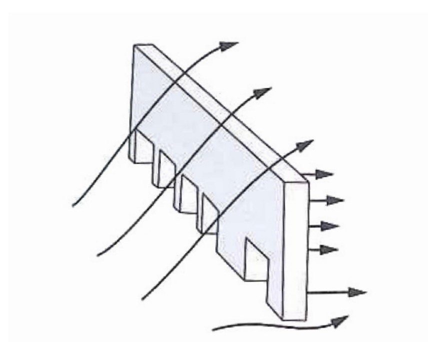
VARYING HEIGHTS



BAR EFFECT



PYRAMID EFFECT



GAP EFFECT

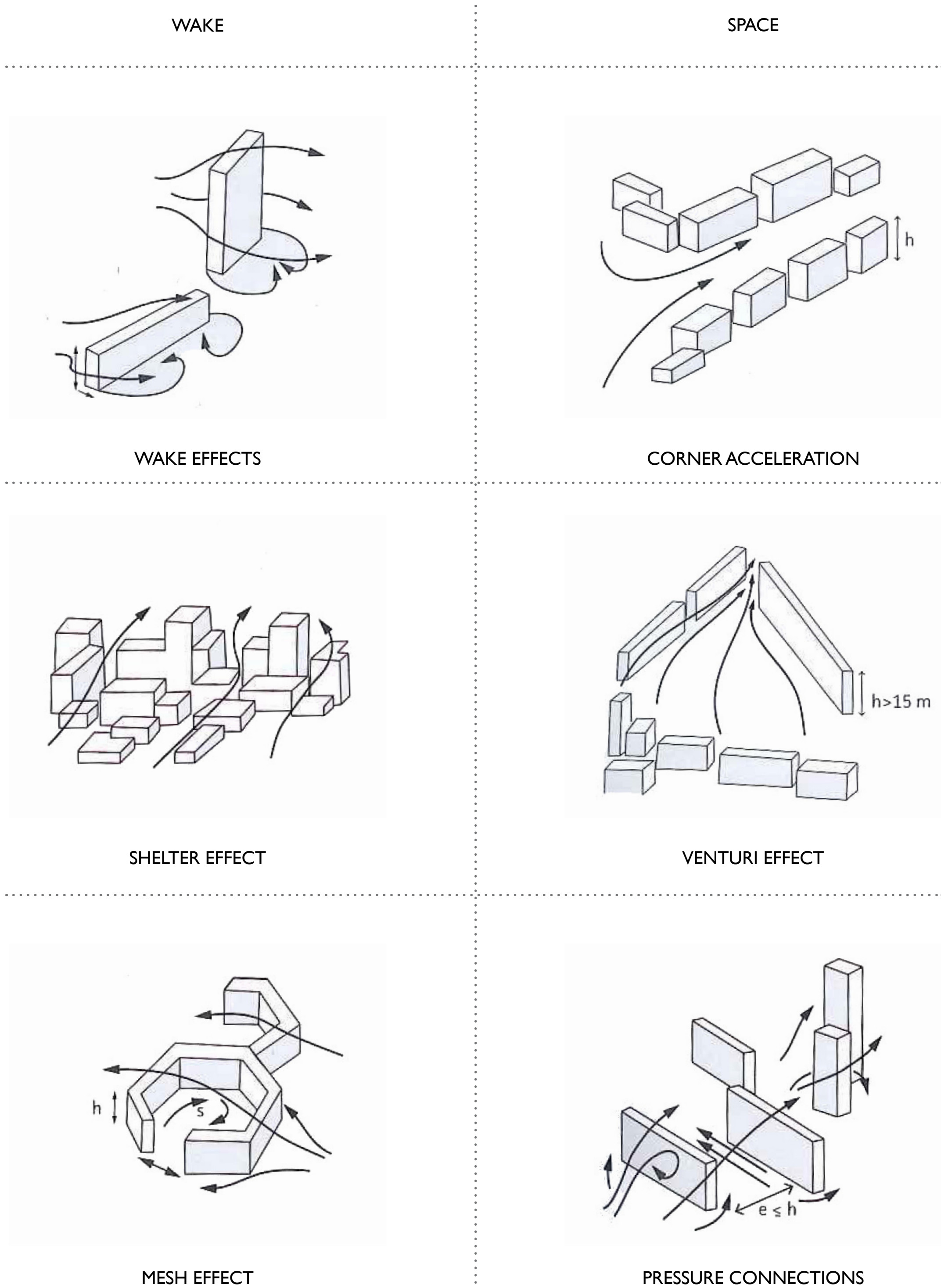


FIGURE 3.3. Twelve Aerodynamic Effects

Interaction

Three principles designers must remember about wind, as listed in the book *Sun Wind and Light*, are: air moves slower along the surface of the earth, wind (generally) continues to move in the same direction around an obstruction and finally that air moves from areas of high pressure to areas of low pressure[2]. When wind approaches an obstruction (also known as a bluff body), such as a mountain, a building, or a tree, it can either be deflected, guided or broken down. Winds can be deflected by groups of trees, solid buildings, mountain ranges, chimneys and other objects. Typically, areas of negative pressure are created downwind (or behind) a building (depending on the wind direction). The pressure results in a suction effect that can lead to issues at corners, edges, and in between buildings. Curvilinear buildings, or buildings in areas of low wind speeds, can gently guide winds around them, without creating significant areas of negative pressure. Buildings, groups of buildings, fences, or trees can be used to break down fast winds into smaller gusts that are able to pass through the obstacles, slowing them down in the process.

Through form (material, shape, size), and space (orientation and location in proximity to other forms) architecture effects the motion of wind. Objects that alter wind can vary in scale, from the size of a building to a wall, a canopy, a screen, trees, shrubs, or sculptures. Any form that alters the topography and profile of the surface of earth contributes to the effect produced. The designed form and the space surrounding contribute to the diversion, guiding or disassembly of wind that can occur while the intensity of these effects depends on the characteristics of the flow (speed and direction, along with parameters of the surrounding climate). Endless combinations of form, space and wind can either encourage or discourage aerodynamic effects depending on the outcome desired for a specific climate. Due to this, the following section will include a list of general effects that can be used to encourage or discourage winds.

2. Brown, *Sun, Wind, and Light*, 2001.

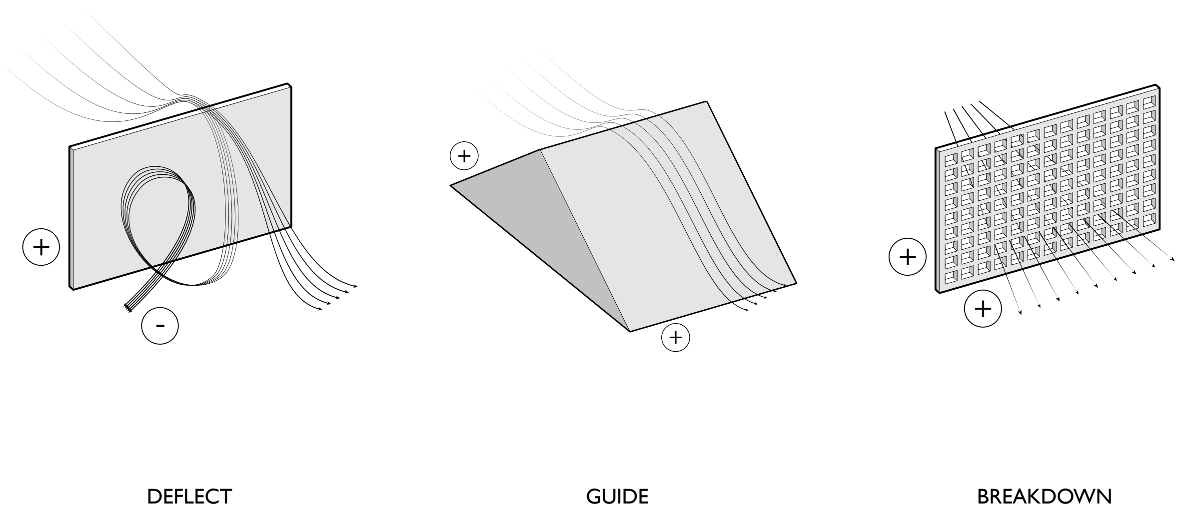
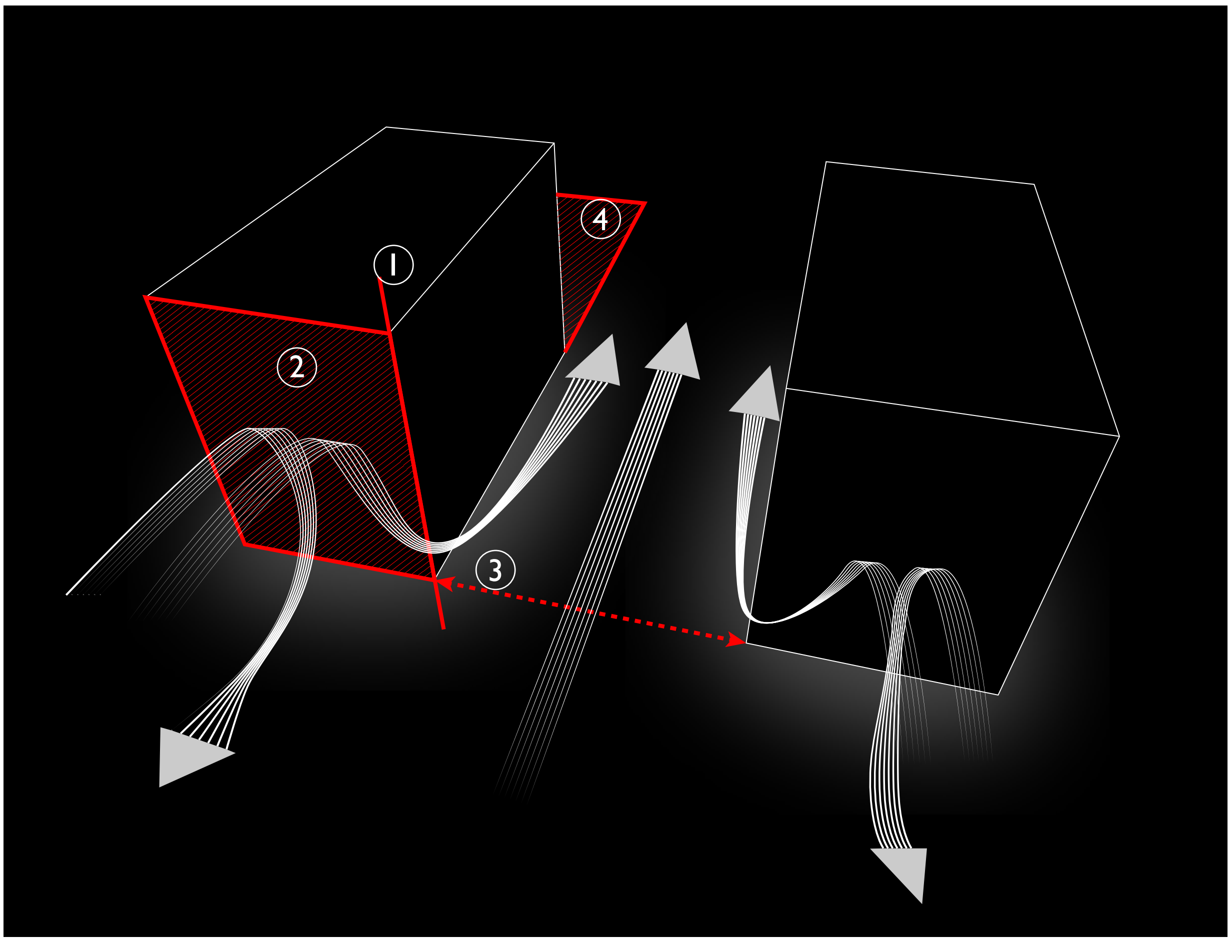


FIGURE 3.4. Types of Wind Interaction

Areas of Impact

The designer must consider certain components or areas of buildings in relation to the dominant directions of wind approach. The four key areas that can be used to influence form to guide, deflect or break up winds are: the edges, the windward surface (facing the oncoming wind), the gap between buildings, and the wake (space downwind or leeward of the building).



1. EDGE
2. WINDWARD FACE
3. GAP BETWEEN BUILDINGS
4. LEEWARD AREA OR WAKE

FIGURE 3.5. Areas of Impact

Windward Surface: The orientation, smoothness, and size of this surface can foster many wind effects. Two pressure differences can occur on the windward side of the building: a difference in vertical pressure that brings high speed winds down, and difference in horizontal pressure (the edges and centre of the face) that can cause a vortex in front of the building[3]. The windward surface is significant when dealing with tall buildings because as theys grow taller, they interact with fast moving winds and direct those down to grade. Generally accepted by wind engineers, at about two thirds of the building height (where a vertical pressure differentiation occurs), high speed winds can be directed down to street level. This two-thirds point is called the stagnation zone, and is characterized by high pressures above and below it, a velocity of zero, and the area of a building where winds flow up and over, or down and around the building form. That being said, if buildings are tall and slender, winds are able to flow around the building prior to reaching the ground.

Edges: The windward edges are generally the location where flow separates. For an isolated building, high pressures that might be found on the windward side create low pressures on the leeward side that in effect suck the front vortex around the edges and along the sides of the building. The smoothness of this edge condition effects how smoothly the flow travels from the front to the back. The amount of suction determines the speed of this acceleration. When dealing with smoother edges, the location of this "edge" condition or separation becomes harder to determine.

Wake: The wake area is dependent upon a building orientation, size, proximity to other structures, as well as the speed of wind. Generally, low wind speeds occur in the wake zone as the body of the building blocks and diverts winds away from this area. However, the wake zone is not always sheltered, as separated flows can reattach here and negative pressures can create suction and vortex effects.

Spacing: The space between buildings is determined by the orientation, size and conditions of adjacent buildings to produce different effects. The amount of space between buildings is significant because realistically, there are no isolated buildings. Effects created by an isolated building can be altered when combined with effects from surrounding buildings.

3. Wu, *Pedestrian-level Wind Environment around Buildings*, 40.

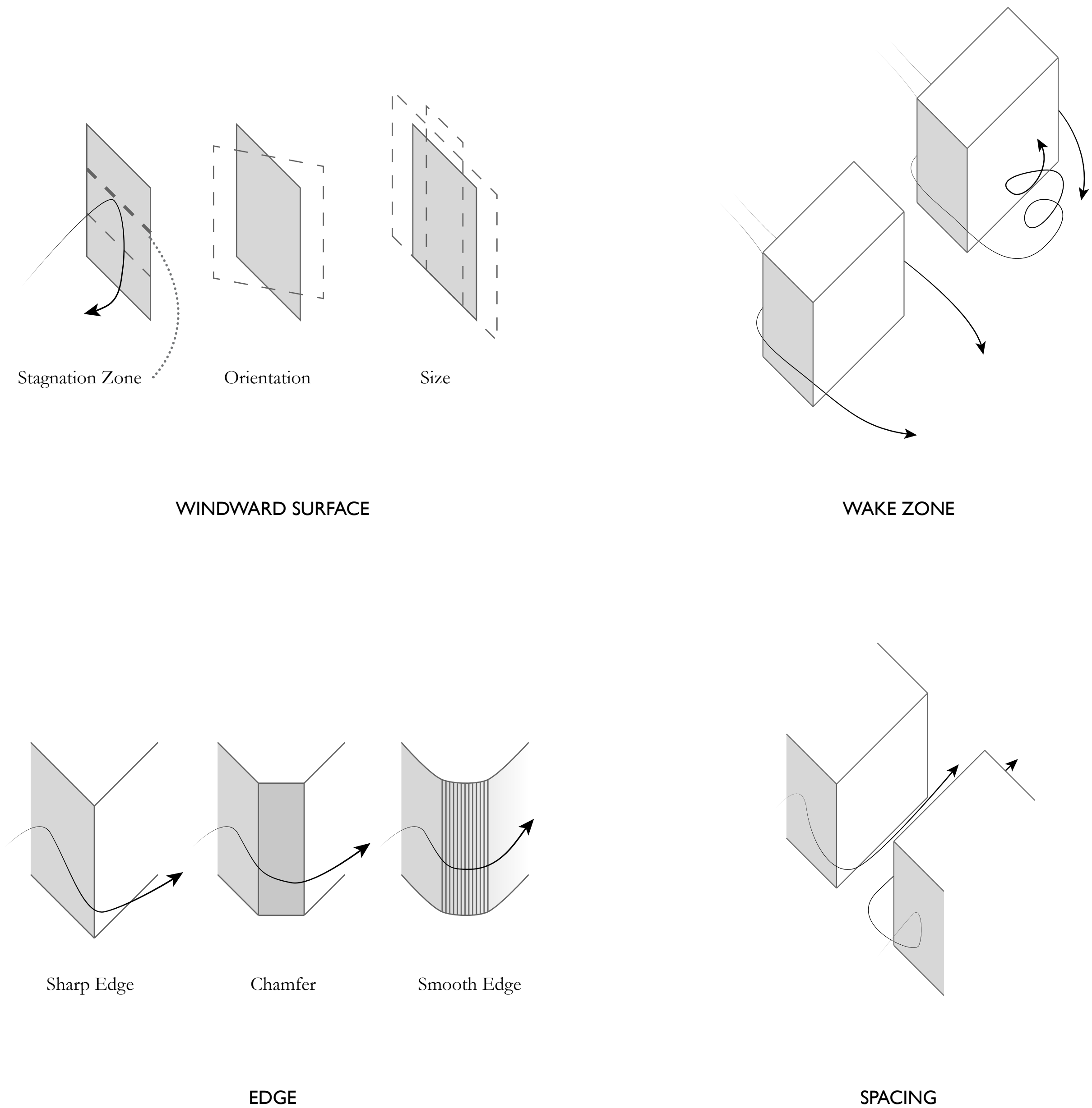
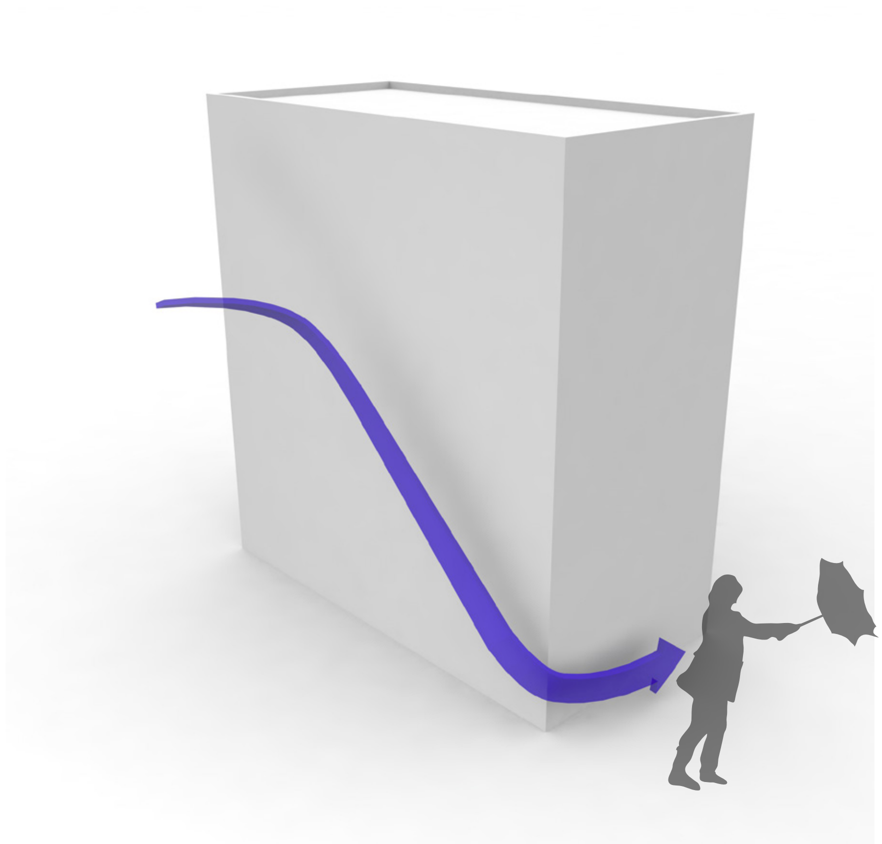
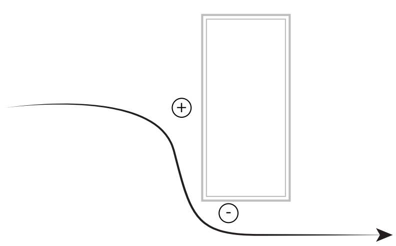


FIGURE 3.6. Changes to Areas

Edge Condition: Corner Acceleration





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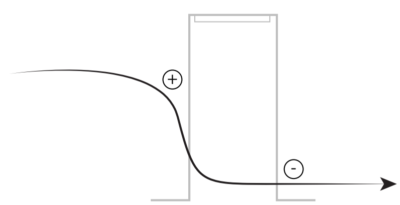
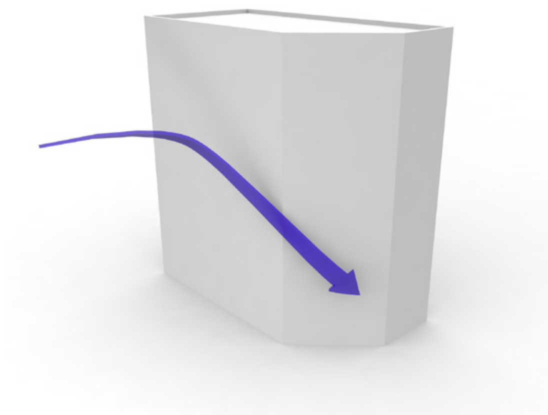


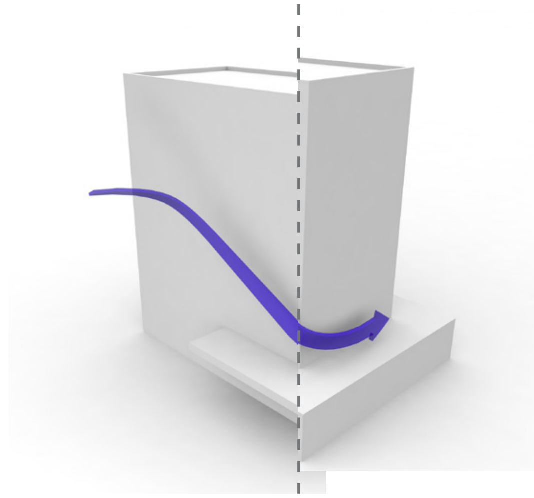
ELEVATION

Corner acceleration depends on the speed of the wind in combination with properties of the structure including sharpness and length of the edge condition. As winds hit the windward surface, they flow down and accelerate around sharp corners to reach the wake area (that may have a strong negative pressure or suction effect.)



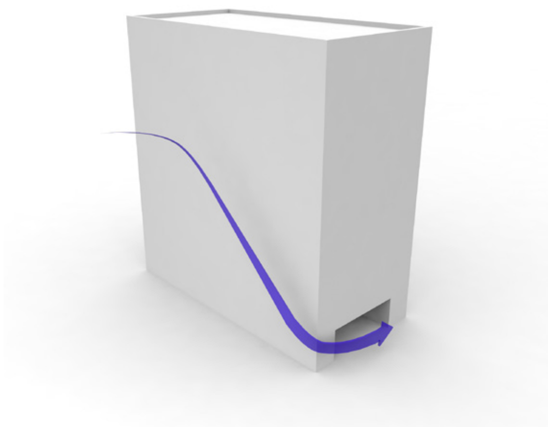
CHAMFER

Cutting off the end of the corner smooths out the transition for the wind from the front of the building to the back, guiding winds instead of deflecting them.



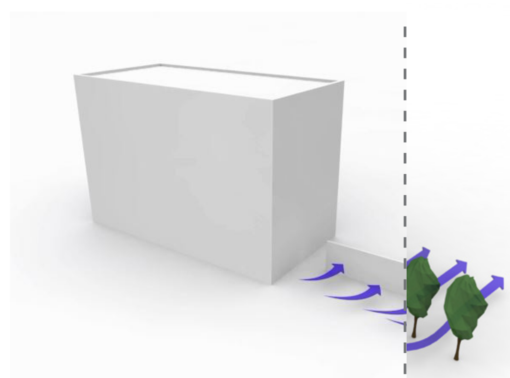
CANOPY OR PODIUM

By adding a canopy or podium, the flow coming down and increasing in speed around the corner is diverted before it can reach grade.



SETBACK ENTRANCE

While this does not reduce the effect of corner acceleration, setting an entrance back in from the outer wall will shield people as they enter or exit the building.



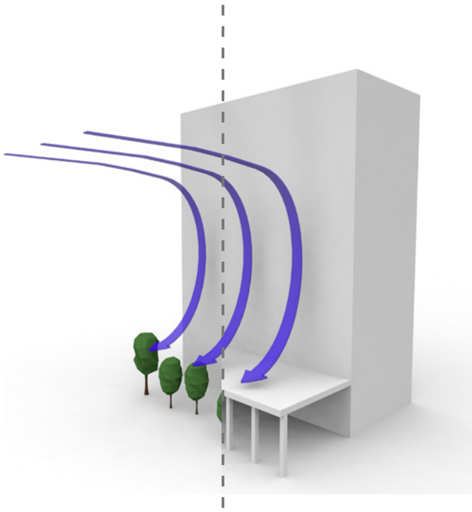
SCREEN OR LANDSCAPING

Porous screens and shrubbery located at the side of the building can slow down and break up the strong winds into weaker vortices as they accelerate around the corner.

FIGURE 3.7. Corner Acceleration and Mitigation Strategies

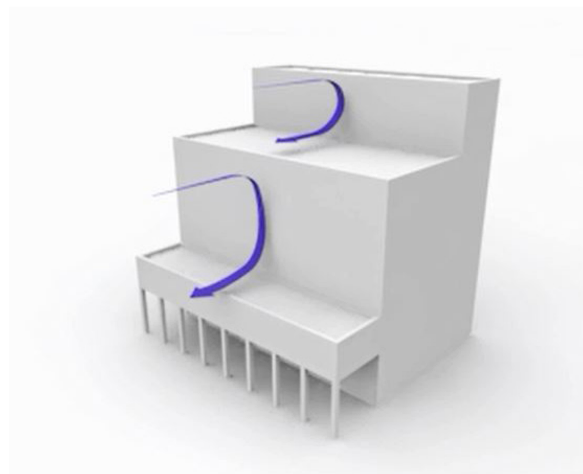
Surface Condition: Downwashing

Downwashing is the effect of a negative pressure area at grade that creates suction that pulls winds down along the windward surface of a building. If a building is tall and skinny, the surface area does not always force winds all the way down to grade, but allows them to pass around the building before reaching the ground.



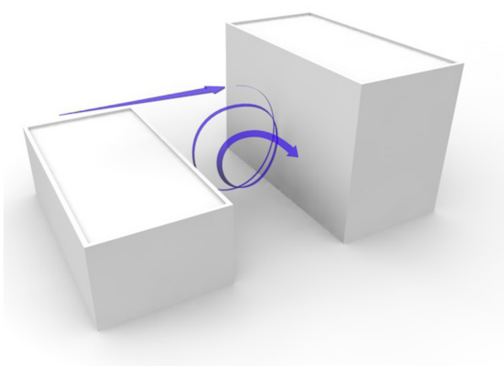
TREES OR CANOPY

Adding trees or a canopy at the base of a building can either break up or divert winds (depending on the porosity of the element), before they reach pedestrian level.



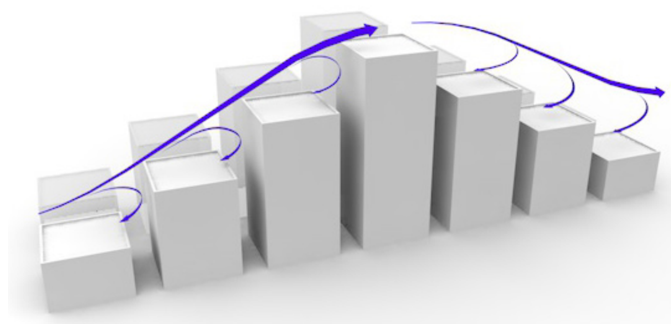
STEPPING FACADE

Stepping the building facade breaks up the downwashing, reducing the overall impact. However, if there are balconies on these levels, they will be extremely windy.



POSITIONING

A low building located upwind of a taller building can create a condition where winds are pulled down and channel into the street corridor at an accelerated speed.

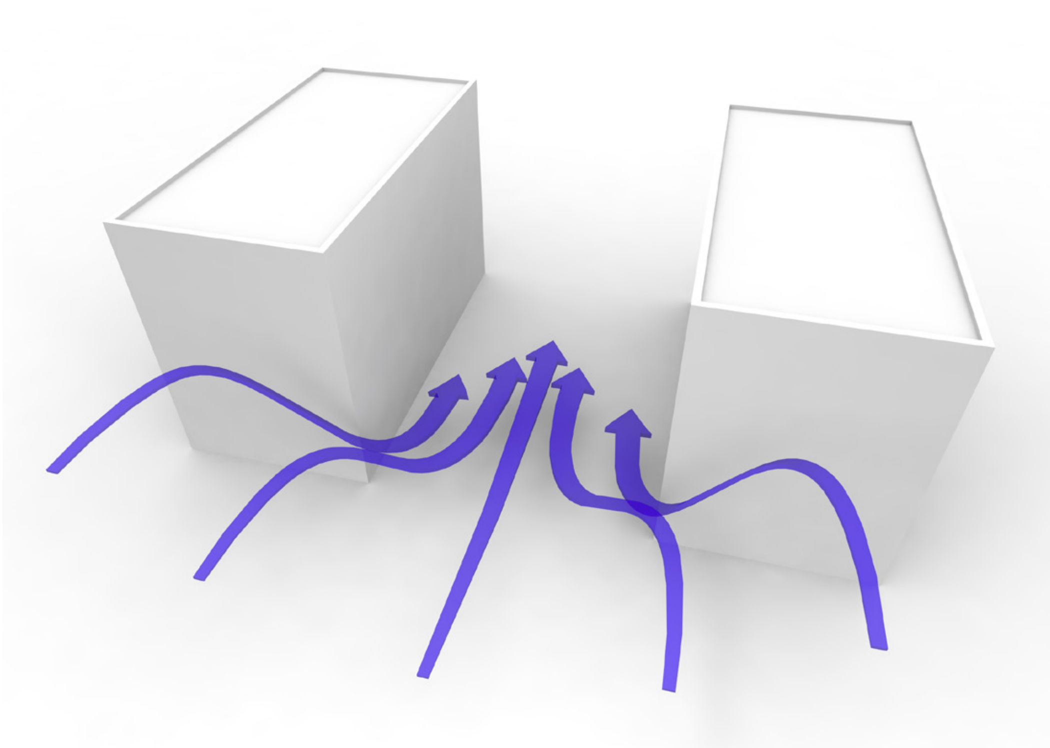


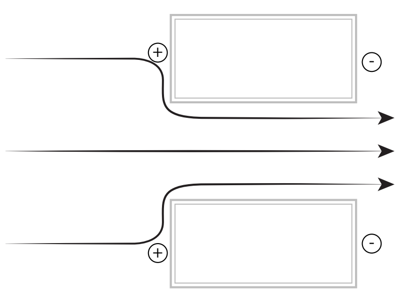
CITY LAYOUT

If buildings in a city are constructed in a stepped fashion (similar to the stepped building facade) with the tallest buildings at the center, the larger flow will be broken up into slower and weaker gusts.

FIGURE 3.8. Downwashing and Mitigation Strategies

Space Condition: Channelling





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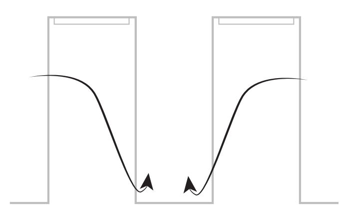
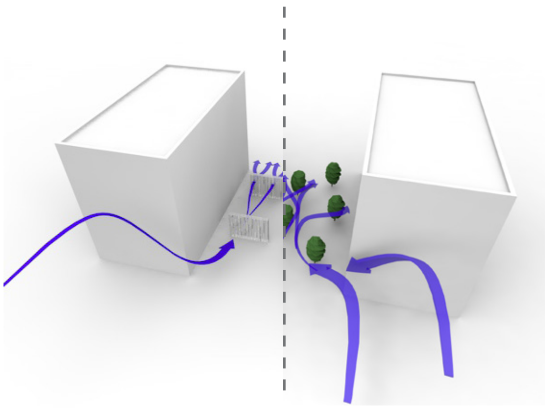


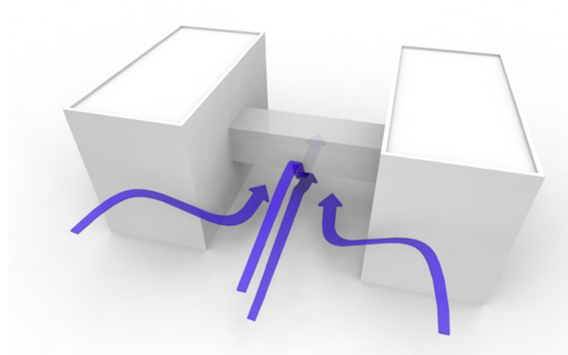
ELEVATION

Channelling occurs when negative pressures are created on the leeward side of buildings, that pull flows down and in between the buildings at an accelerated rate. This can happen when winds wash down and accelerate around the edges of the buildings on either side of an open corridor as well. Similar to effects seen in water, channelled winds are "funnelled" and accelerate as they are squeezed together. However, unlike water, wind is not always forced to squeeze through openings as winds can escape from many directions. A particular spacing and condition creates this effect.



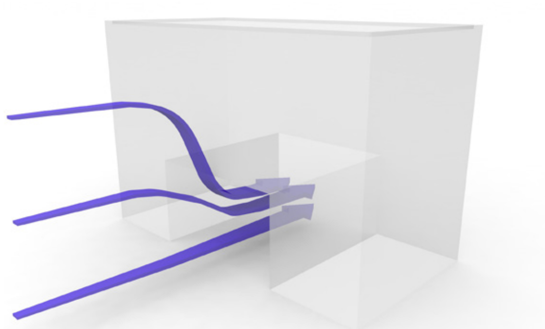
POROUS SCREENS OR TREES

Adding porous screens or trees helps to slow down winds and break them up into smaller vortices.



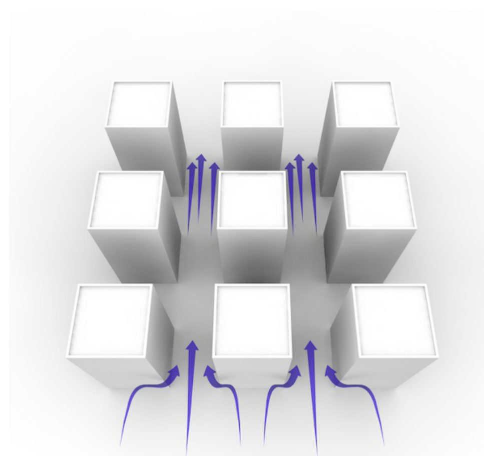
SPANNING BRIDGE POSITIONING

If a bridge connecting two buildings is designed, its location must be carefully analyzed. If the bridge is located close to the windward faces of the buildings it may further accelerate high speed winds. Generally, a setback as well as screens or trees are necessary to reduce this effect.



OPENINGS

Openings through buildings can also channel winds through them. Depending on the size and shape of the building, the opening may provide the winds an opportunity for the negative pressure behind the building to create suction and pull winds through.

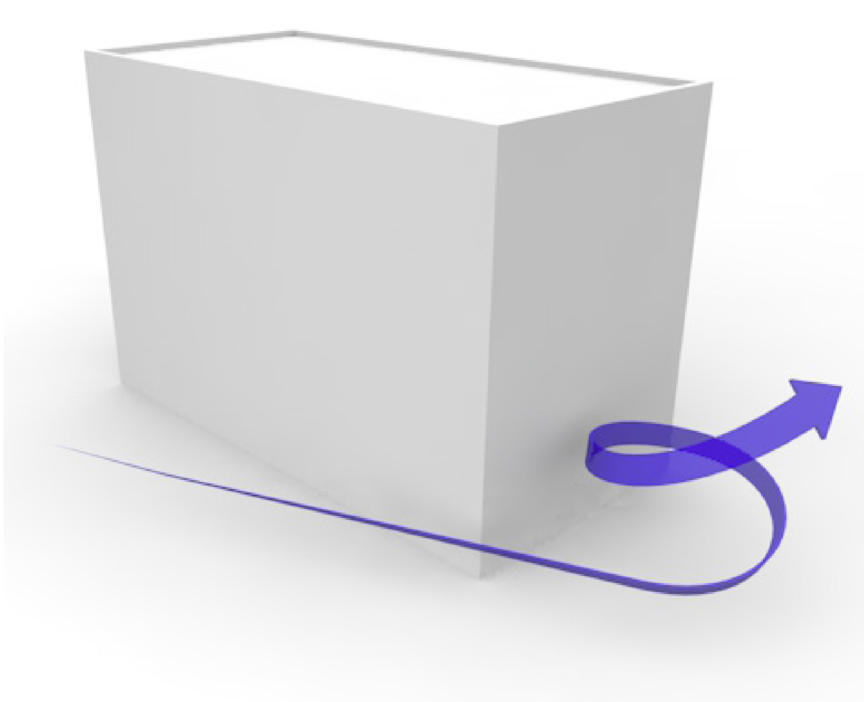


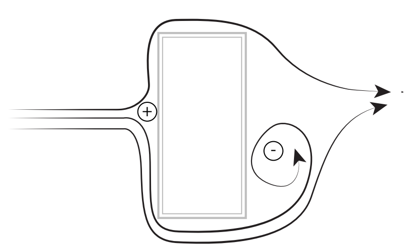
CITY PLANNING

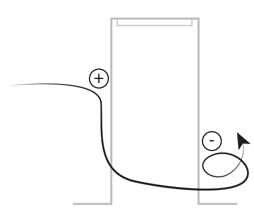
At a larger scale, winds can be channelled the length of entire city blocks. This effect is not always negative, as these winds can be used to ventilate and carry pollutants out of the city.

FIGURE 3.9. Channeling and Mitigation Strategies

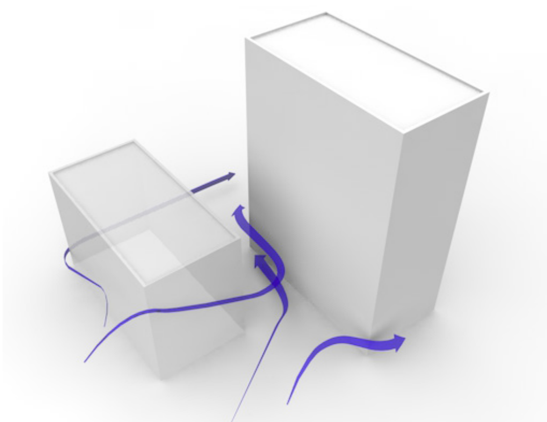
Wake Zone

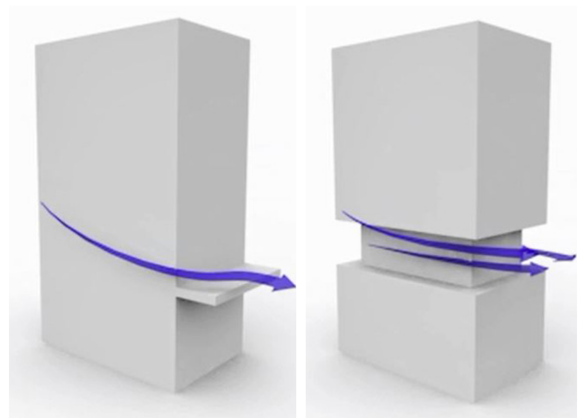






Wake zones are typically associated with negative pressures. After flows separate around a building, the negative pressures downwind determine how and where the flow reattaches and if winds are pulled back toward the back of the building. Although the areas downwind of a building are thought to shelter, it is not uncommon to experience vortex effects or high wind speeds in these locations. The form of the building and its position in relation to other buildings determines the effects in the wake zone.



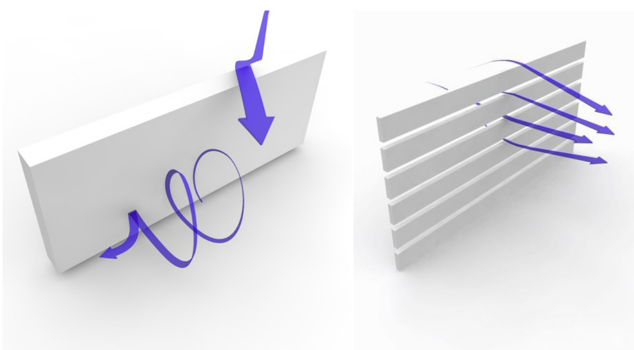


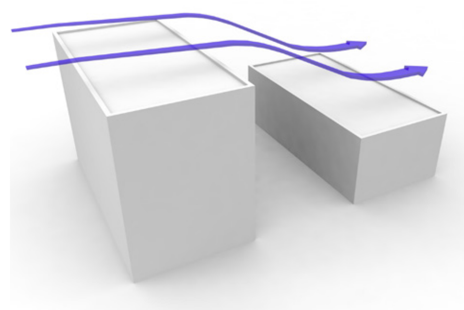
PRESSURE EFFECT

When buildings are combined unexpected effects and a change in the direction of flow can occur. The wake zone of one building can alter the expected effects on a building downwind and even connect to another wake zone. These scenarios alter typical effects and at times create strong areas of negative pressure that can pull winds against the common direction of flow.

CANOPY OR CUTOUT

For tower scenarios where there are issues with wake vortex generation, canopies and setbacks can help to mitigate those issues.





OPENINGS

Solid walls can produce negative pressures in the wake zone downwind of the flow, causing reattachment that can cause winds to swirl and accelerate. For this reason, porous walls or screens are recommended instead as they do not restrict or divert winds, but break them down and slow their speeds. This allows the pressures in front and behind the screen to remain equalized, and avoids the creation of a suction effect.

CITY PLANNING

Shorter buildings placed downwind of taller buildings typically encourage calm winds and comfortable conditions at street level. However, if a negative pressure were created between the buildings at grade, wind would be forced down by the resulting suction force.

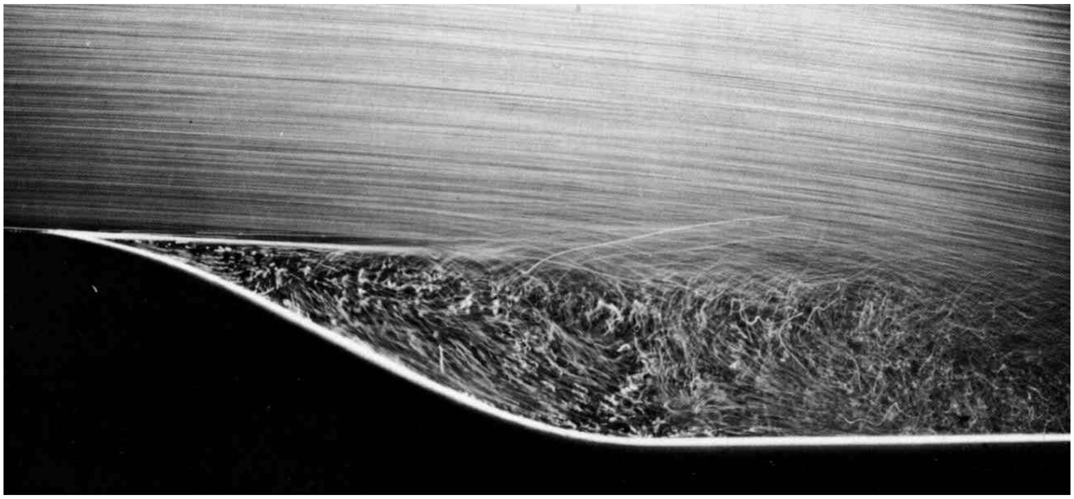
FIGURE 3.10. Wake Zone Effects and Mitigation Strategies

SIMULATING WIND

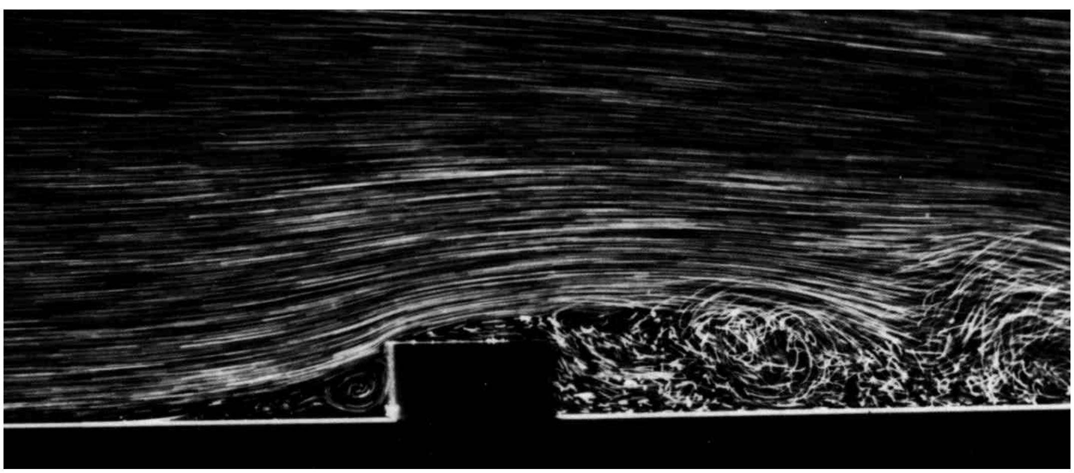
There are many steps involved in the simulation and prediction of wind and its effects. There are three main aspects to consider: what to look for (a focus and approach), how to look for it (tools and techniques), and how to interpret and understand the data[4]. The focus can be anything from testing pedestrian comfort, structure, snow drift, ventilation or air quality and the approach can be to provide preliminary predictions or move ahead to tunnel testing. The tools can include wind tunnels or water flumes in combination with pressure sensors or smoke needed to gain qualitative or quantitative data or virtual simulations. The steps within the simulation process are all of significance, as each is linked and alters the subsequent steps.

In order to interpret or translate the data, an understanding of how the information is represented and how to use available meteorological data is necessary. The proper utilization of computational fluid dynamics programs (CFD) heavily relies upon the data input to achieve useful information. Designers can avoid redesigns and the costs associated with them by having a basic understanding of these concepts and by working with wind engineers earlier on within a project.

4. Adamek, *The Process of Wind Visualization*, 2015.



LAMINAR SEPARATION FROM A CURVED WALL



TURBULENT SEPARATION OVER A RECTANGULAR BLOCK ON A PLATE

FIGURE 3.11. Images of Separation by ONERA referenced by Milton Van Dyke

Unique Complications of Wind Testing

Although aeronautical wind tunnels have been used since the nineteenth century and many computational programs can simulate winds at higher altitudes, the simulation of winds that interact with the earth's surface are much more complicated. The main difference between wind at high altitudes and wind at lower altitudes is that at the surface, friction causes wind to slow down until it comes to a stop. Even wind at eye height of an individual is faster than the winds at grade. This layer where winds slow down due to surface friction is known as the planetary boundary layer. The boundary layer and the frictional relationship between the speed of the wind and the roughness of objects (the Reynold's Number) are just a few of the reasons simulating wind effects around buildings is complex. The roughness of the earth's surface made by mountains, cities, suburbs, and other obstacles, alter the height that the wind can reach its gradient speed (maximum). This is known as the gradient wind profile (or boundary layer profile). There are many different profiles including: water, open terrain, suburban and urban. In open terrain, wind can smoothly increase from 0% to 100% of its speed, whereas winds that flow past a city must increase in speed over a shorter distance and do not reach gradient (maximum) speed until a higher elevation, compared to wind flowing across a smoother terrain.

In reality, there are many factors that wind engineers must take into account to simulate and predict wind and its effects. For designers, applying many of these principles to design is not only unrealistic and unfeasible, but unnecessary. Instead, basic knowledge of these principles and their significance in relation to designers is of greater importance. The following pages include a list of eight significant principles of wind simulation that play a significant role in design including: the boundary layer (including turbulence intensity and spectral density to simulate the correct distribution of big gusts and little gusts of wind), the mean velocity profile, a streamline versus a bluff body, laminar versus turbulent flow, the Reynolds Number, Bernoulli's equation, the Navier-Stokes equations, and vortex shedding.

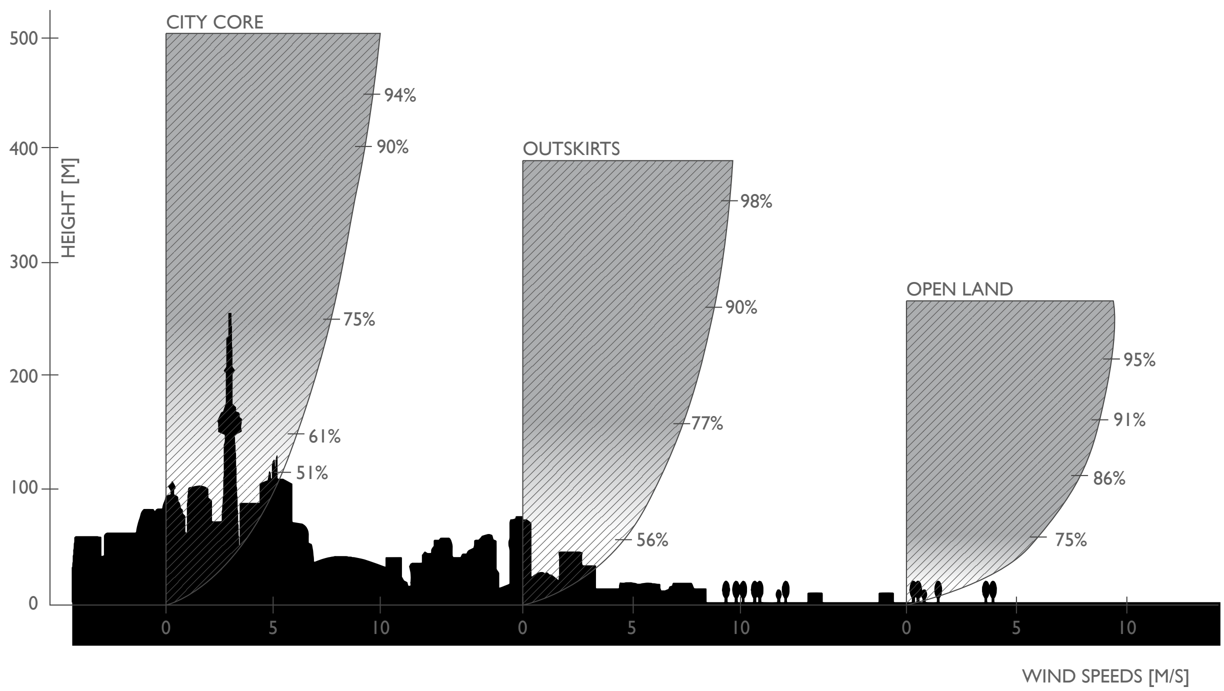
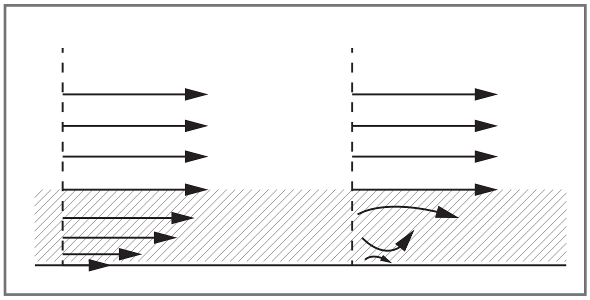


FIGURE 3.12. Gradient Wind Profile

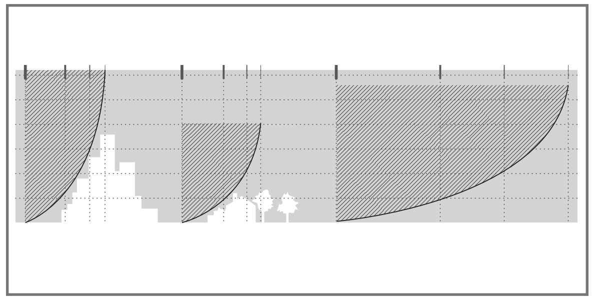
Key Principles that Apply to Architectural Aerodynamics



BOUNDARY LAYER

The atmospheric boundary layer is the threshold where the velocity of wind changes from 0 at the surface to the maximum free stream value away from the surface. Buildings exist within and alter this layer depending on the profile.

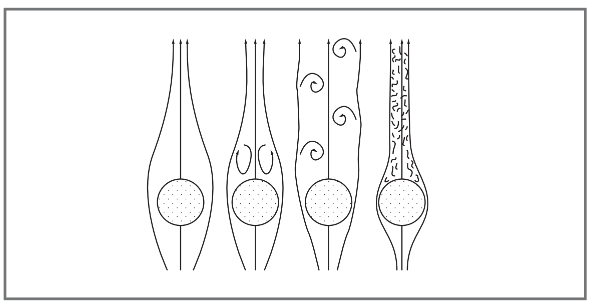
Significance: The difference in testing buildings and bridges compared to aeronautical tunnels used for aircraft design is due to the boundary layer. This also determines what type of computational program can be used. Winds are more complex closer to the surface of the earth.



MEAN VELOCITY PROFILE

The mean velocity profile is the decrease of wind speed caused by the friction with different surface conditions such as water, open terrain, suburbs and urban developments.

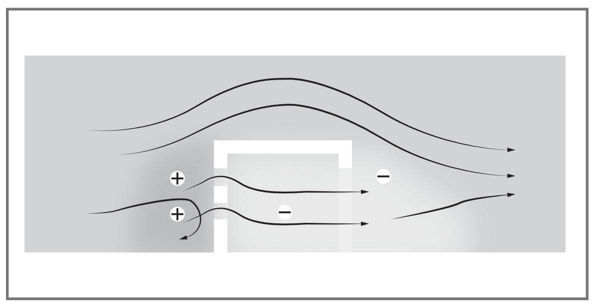
Significance: When predicting how wind approaches a site, the profile alters the speed at which winds enter the city. The context is important.



REYNOLD'S NUMBER

The Reynold's number is a dimensionless quantity of the relationship between inertial and viscous forces. "Most architectural aerodynamic flow occurs at high Reynold's numbers[5]." The Reynolds number is an important parameter that describes whether flow conditions lead to laminar or turbulent flow and where separation of the fluid will occur around streamline or bluff bodies.

Significance: The Reynold's number is necessary to test aerodynamics in full scale to a relative accuracy. When models are scaled down and wind speeds are reduced, the relationship between the building skin (roughness) and the viscosity of wind is difficult to retain because wind itself cannot be scaled down. This is why wind tunnel facilities are large and facilities alter the roughness of a building to try to match the ratio determined by the Reynold's number.

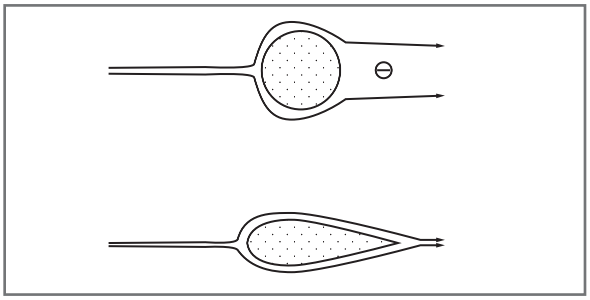


BERNOULLI'S EQUATION

This equation describes the relationship between the velocity and pressure exerted by a fluid. As velocity increases, pressure decreases, creating a greater suction effect.

Significance: This principle outlines how as wind velocity increases around a building, an area of negative pressure is created. The negative pressure is the root cause of the increase in velocity and an increase in uncomfortable wind conditions and is directly related to building form and orientation.

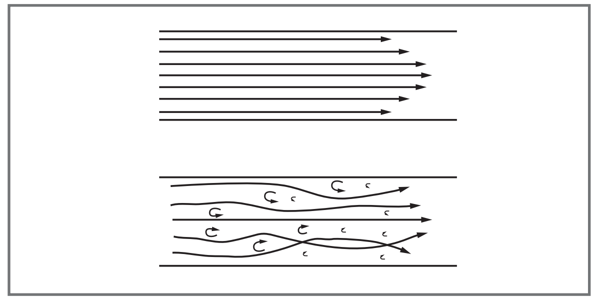
5. Aynsley et al. *Architectural Aerodynamics*, 63.
6. Physics Classroom, *Newton's Second Law*, physicsclassroom.com/newtlaws/Newton-s-Second-Law.
7. Blocken, *Sport and Building Aerodynamics MOOK*, Part 3.



STREAM LINE AND BLUFF BODY

A stream line body is one that offers the least resistance to fluid flow such as an airplane wing, while a bluff body is the opposite, one that offers resistance to fluid flow.

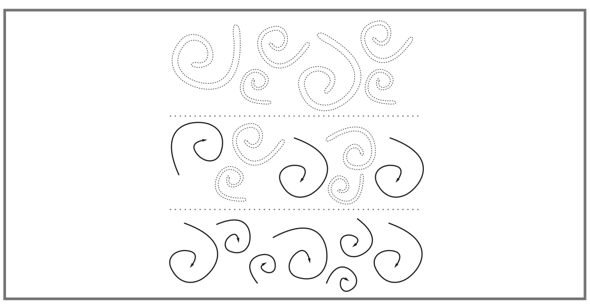
Significance: All buildings can be considered bluff bodies, with the capacity to be streamlined depending on the direction and nature of the relative local winds.



LAMINAR AND TURBULENT FLOW

Laminar (streamline) flow is when a fluid flows in parallel layers, with no disruption between the layers. Turbulent flow is when the fluid undergoes irregular fluctuations, or mixing. Both of these types of flow depend on the viscosity and speed of the fluid.

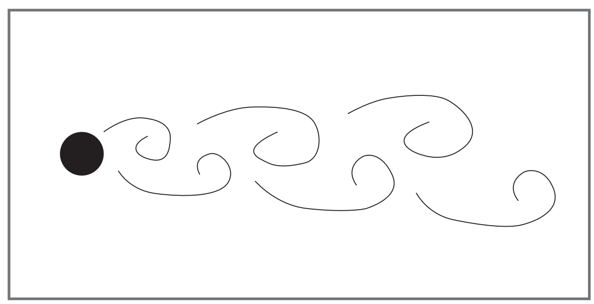
Significance: The boundary layer is for the most part turbulent because of the surface of the earth. In computational models, viscosity and speed are complicated to model and solve.



NAVIER-STOKES EQUATIONS

This equation is based on Newton's second law of motion: "The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object[6]". These equations were made to describe the flow of a fluid.

Significance: Computational fluid dynamics programs (CFD) are based off of Navier-Stokes equations. However, to completely solve all equations fully -- to solve all vortices and eddies, not just model them -- it takes significant computational memory and power that is not easily accessible. A simplified version where only the mean flow is solved (Reynolds Averaged Navier-Stokes) is the most commonly used equation. It is not exact and is less accurate but remains applicable as it demonstrates the effect of turbulence on the main flow that is modeled[7].



VORTEX SHEDDING

Vortex shedding (Von Kármán Vortex) is a repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid around bluff bodies. The creation of vortex shedding is dependent upon the velocity of the fluid, as it flows past a specific sized and shaped bluff body building.

Significance: Tall buildings with a uniform shape are susceptible to this phenomenon. The effects can be seen on objects such as flagpoles, that sway back and forth. However, densely packed urban structures lead to turbulence that stops and breaks up the initial formation of these vortices. The first tall building in a low-rise area or a tall building separate from a group of tall buildings is at risk to this occurrence.

FIGURE 3.13. Key Principles

Physical Simulation

In the field of wind engineering, the combined use of wind tunnels and computational fluid dynamics systems, is the established method for performing wind simulations and analyses. The combination of physical and digital modelling systems is necessary to compensate for the limitations of each system.

The most accurate, efficient, and common method of simulating wind at grade is done using the boundary layer wind tunnel. Critical characteristics of the simulated boundary layer include the velocity profile (wind speed correlated to a certain height), turbulence intensity profile, and turbulence spectral density (that determines the spacing of small and large gusts). Today, the testing of thirty-six wind directions on a single site (for either qualitative or quantitative results) is performed faster by physical rather than computational methods. The difficulty in simulating wind is due to the fact that the particles of air cannot be scaled down, so other factors must be altered in order to reproduce the relationship between the surface and the flow of air (Reynold's number). For smoother, non-rectilinear buildings, the point where wind separates is difficult to predict as the Reynolds Number must be achieved accurately. These relationships can be modelled more accurately at larger testing facilities. Wind engineers must have the necessary space and knowledge to configure and operate these scaled simulations. The wind tunnel, in combination with other tools, has the ability to provide both quantitative and qualitative results. Variations on typical tools are developed by each facility, such as a 6x8x20m sized wind tunnel that uses hydrogen bubbles, a smoke machine, ribbons, sensors, or CFD models that show vectors, colors or numerical information. In addition, the sectional size of the tunnel (ex. 2x2m) is significant as the blockage ratio (the ratio of the area of the vertical cross-section of the test model to the cross-sectional area of the wind tunnel) affects the pressures surrounding a test model and can affect how the wind flows around the model. Using these tools, the techniques to collect quantitative or visual information and then interpret the meaning of this information can occur quite differently.

The water flume is another physical simulation that is used by wind engineers typically for visualization purposes only, as water is not compressible and has a different viscosity than air. However, general flow patterns can be visualized in this system as water and wind are governed by similar fluid dynamic principles.

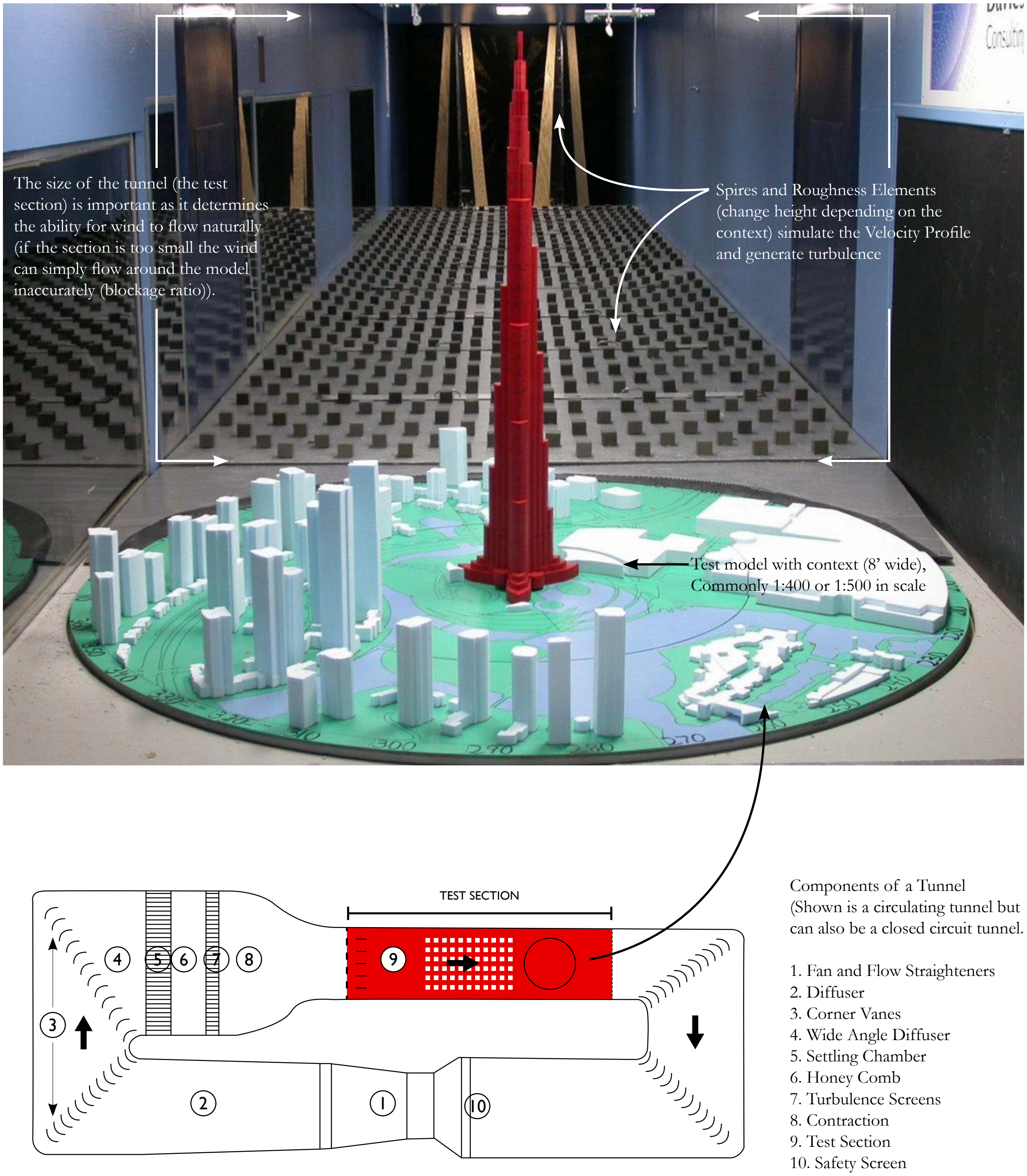


FIGURE 3.14. Example of a Circulating Boundary Layer Wind Tunnel

Virtual Simulation / Computational Fluid Dynamics (CFD)

Within the past decade technology has significantly changed the field of design and has allowed designers to test many kinds of environmental parameters that were not available before. For designers and engineers alike, digital tools that can simulate long term effects such as sun/shadow angles and wind conditions is highly desired. While there are many computational programs available to simulate wind, knowledge of basic aerodynamic principles is needed to not only run simulations, but to interpret the data that the simulations produce. Results can be calibrated, interpreted and calculated incorrectly if they are not accompanied by an understanding of these principles. It is the goal of many developers, scientists, engineers, and programmers to look for ways of making wind engineering more marketable and accessible. For now, these digital tools are used by wind experts exclusively to visualize and support quantitative data collected by studies within the wind tunnel. While CFD programs allow projects and their associated aerodynamic parameters to be quickly setup, the results can take a significant amount of computer power and time to be calculated. Another danger is that the user has complete control over the factors and the results they produce, therefore if any parameters are overlooked they might go unnoticed. Information can be excluded or over simplified if not investigated properly.

There are many programs that feature the option to include wind as a parameter, such as plug-ins for Rhino, Cinema 4D, Vasari, Autodesk Ecotect, Autodesk Flow, Autodesk CFD, as well as a collection of personalized programs created in-house by certain companies. These open source programs make visualizing wind and its affects seem simple. The real issues arise when attempting to read or interpret the information. Many programs do not give the option to adjust surrounding conditions (that alter the boundary layer profile), direction, size of model, speed, and standards of speed. For this reason, it is necessary to understand the data being used and the results produced in order to use the programs correctly. In addition, any programs require third party processing in order to take the collected data and organize it comprehensively.

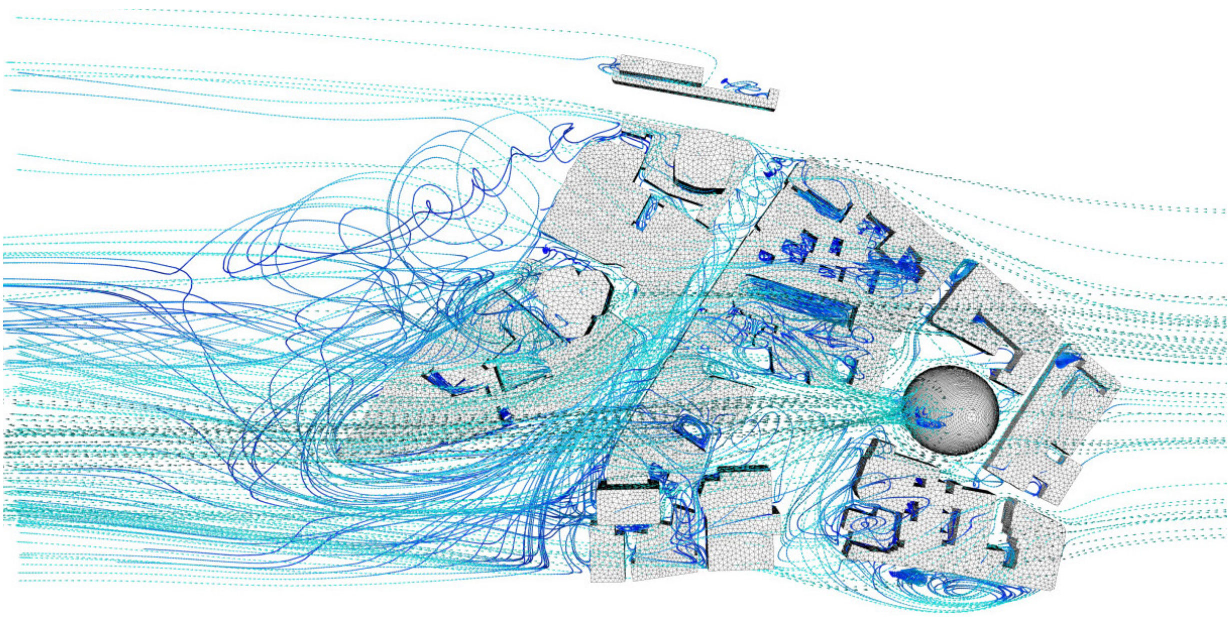


FIGURE 3.15. Computational Fluid Dynamics Simulation by Samuel Wilkinson

Today, virtual simulation is simply used for visualization purposes. Due to its accessibility, it appears to be an ideal method to help designers apply wind principles to projects. However, the use of these programs requires a sufficient understanding of the basic principles of aerodynamics.

Although in computational methods the Reynold's number can be met, the surroundings and focus areas can be modelled, and the wind speed and direction easily set, there are still some downfalls. Computational methods require powerful virtual memory to produce site analyses of larger areas. There are also different capabilities, depending on the program and the computer power available. Assumptions regarding the complexity of the laws of physics can be made to gain average results in a shorter period of time, or more laws can be applied that require more computer power and time. The complexity of these equations are broken down into three types: RANS (Reynolds Averaged Navier-Stokes, LES (Large Eddy Simulation), or DNS (Direct Numerical Simulation). DNS completely solves all equations (which takes an extreme amount of time), DNS simplifies larger vortices and RANS simplifies all flow based on smaller properties and is the most used equation. It will take more time for the results to be processed if more parameters are required to be solved. These programs must also be calibrated to match full-scale or wind tunnel studies in order to semi-accurately predict flow patterns.

Although CFD is available to architects and other designers, there is currently no intuitive way to understand the principles to apply and how to use them to test design iterations. Although many believed that CFD would provide more accurate results by the twenty-first century, it has not been able to replace analogue methods.

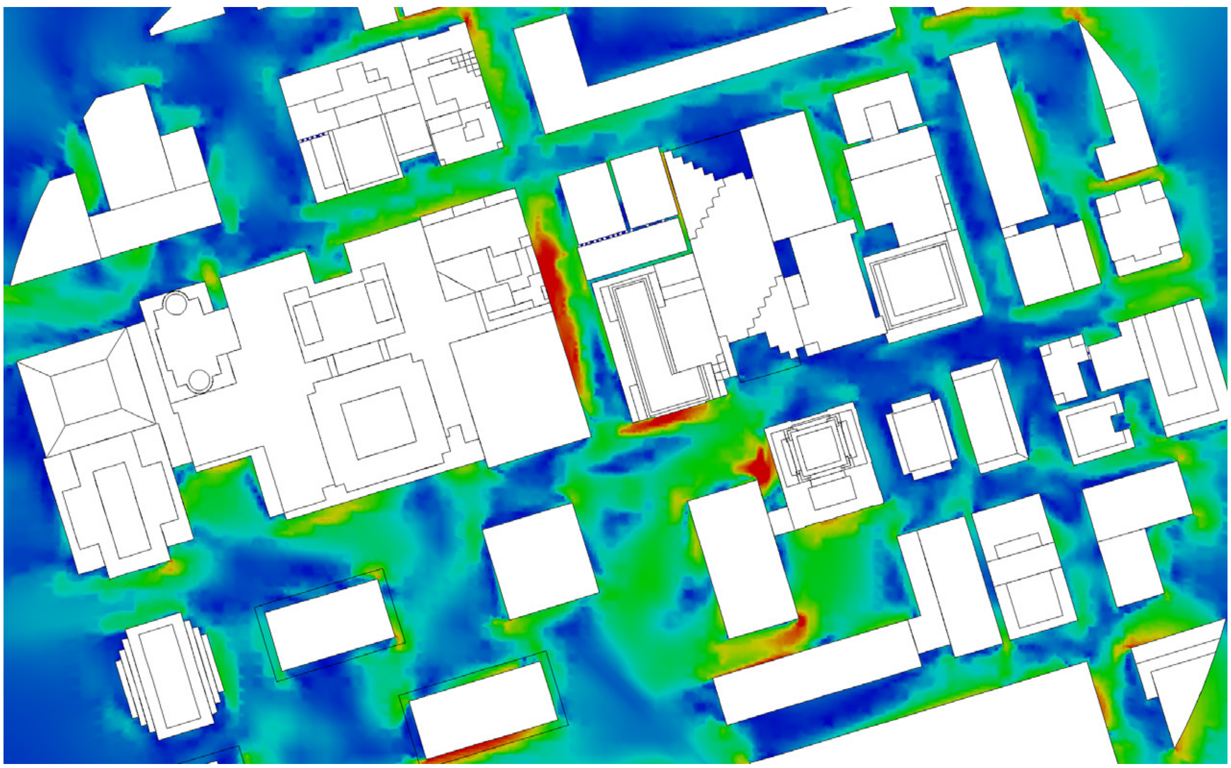


FIGURE 3.16. RWDI's *Virtual Wind* Simulation

Simulation of Different Forms in a Water Flume

A study completed in 2012 entitled, *Experimental Investigation of Aerodynamic Forces and Wind Pressures Acting on Tall Buildings,*[8] examined and compared the aerodynamic forces and wind pressures acting on 4-5 different forms of 6 different shape configurations. These configurations included: basic, corner modified, tapered, helical, opening, and composite models. The main goal of the study was to examine the relationship between the wind and the structural form, and determine the most aerodynamic shape. However, safety and habitability were included in as parameters to consider as well. The conclusion showed that there were varied benefits to each form (ex. square or cylinder) and modifications to each form (ex. chamfered or smooth edge). In an analysis performed within a wind tunnel to test the response of the structures, the corner modified, helix and composite models demonstrated good performance in safety design. However, the corner and composite models have less floor area and habitability, therefore the helical model showed superior aerodynamic behaviour in both safety and habitability[8]. The following pages are a visual guide to the forms of this previous study. The exercise emphasizes the relationship between the resulting wind flow and the shape of the buildings.

The form and relative surroundings of the BMO tower located in Toronto, Ontario, act as the focus of this study. The BMO tower is the tallest building in the Financial District and its chamfered profile slows winds down as they pass by. For this visualization study, seven forms from the journal noted above were selected and tested. Three basic model shapes: a cylinder, square and eye shape; one corner modified shape: the chamfer, one tapered model: the setback, one helical shape: 180 helical square, and one opening shape. All of the shapes are symmetrical in order to simulate flow coming from any direction.

Direction: The flows were only examined from one direction of flow. Only a few mid-rise buildings are located upwind of the studied geometry.

Methods: The testing was performed within a water flume at RWDI's facilities in Guelph, Ontario. The qualitative visualizations resulting from this method are specific to water, however they can be compared to patterns in air.

8. Tanaka, *Experimental Investigations*, 190.

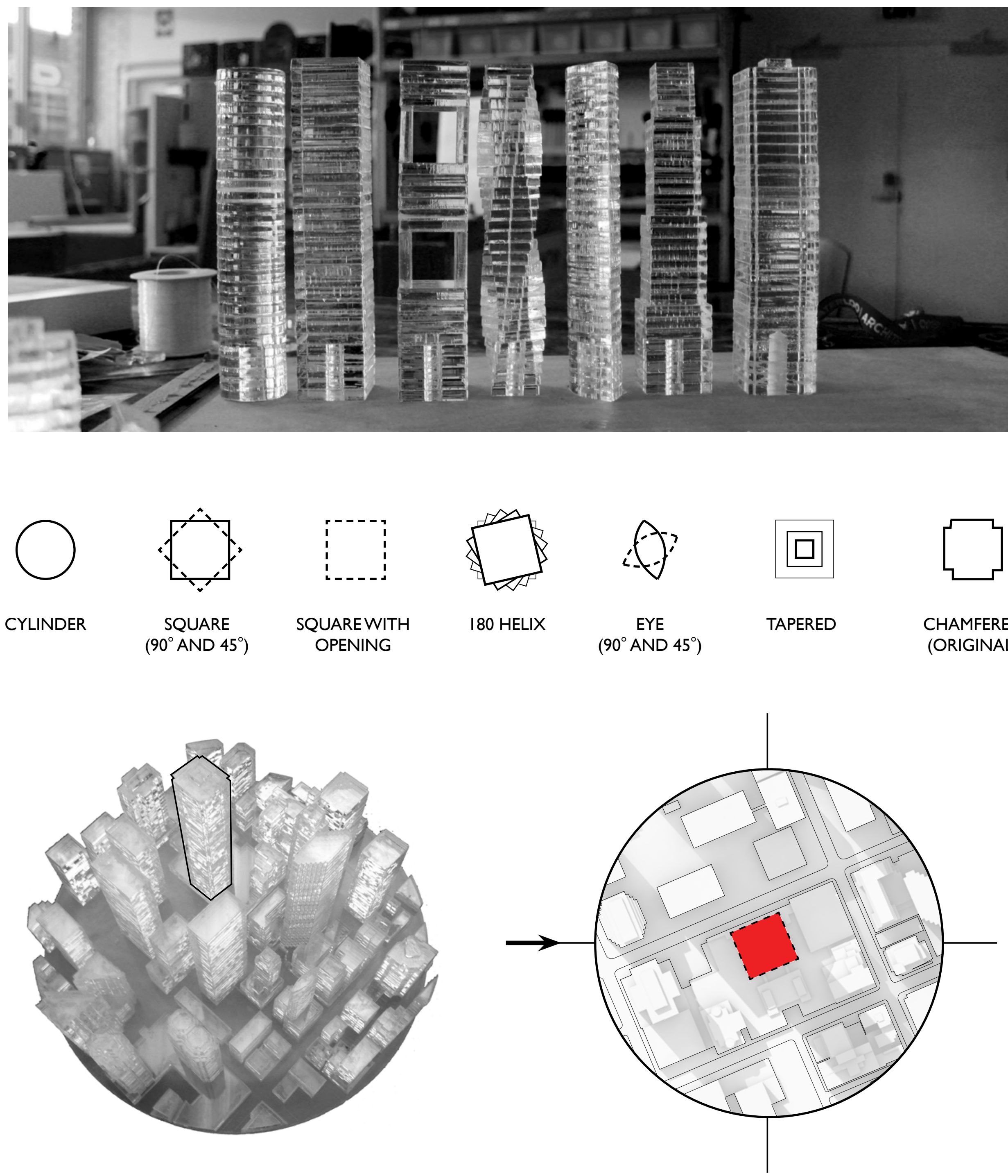
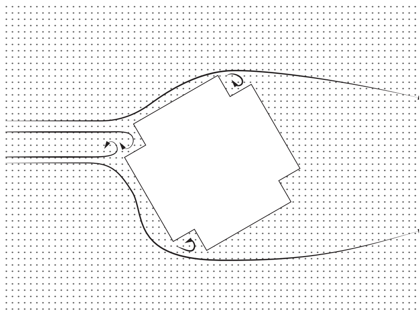
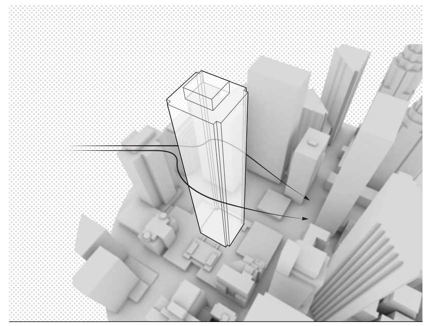


FIGURE 3.17. Setup of 1:1500 Scale Model to Test the Relationship between Form and Wind

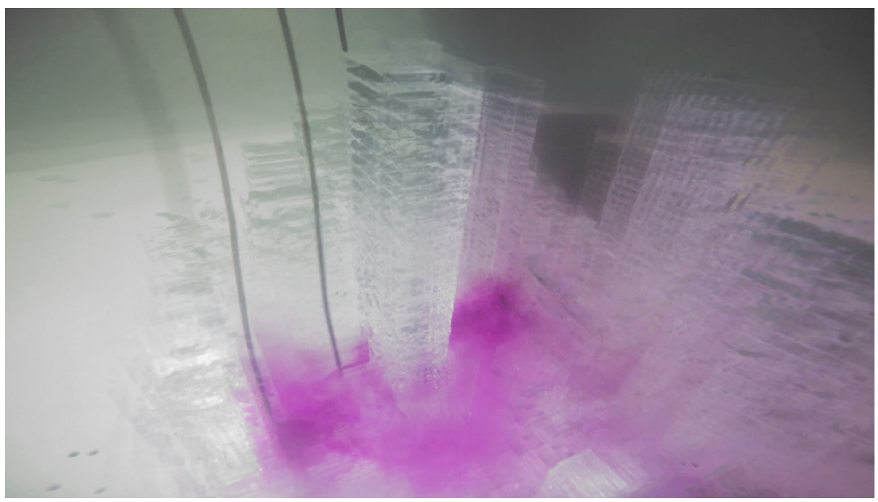
Chamfered (Original)



PLAN



PERSPECTIVE



OVERALL EFFECT

The approaching flow wraps around the building smoothly. The chamfer breaks up the winds at the corners (into smaller gusts), and allows the winds to gently pass around the building without being deflected at the edges.

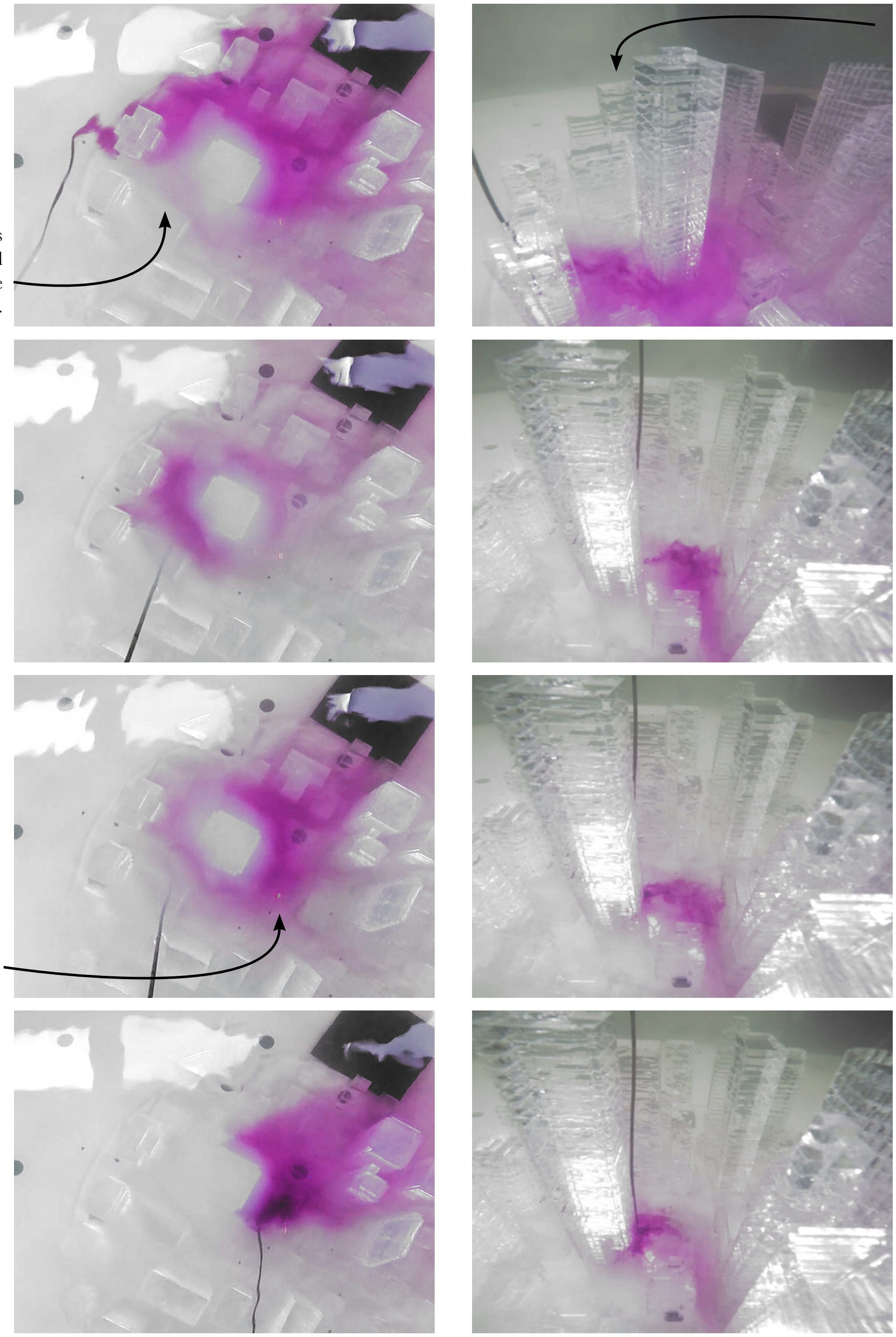
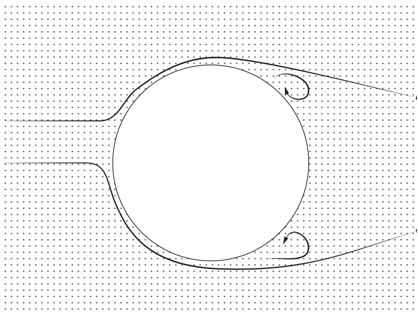
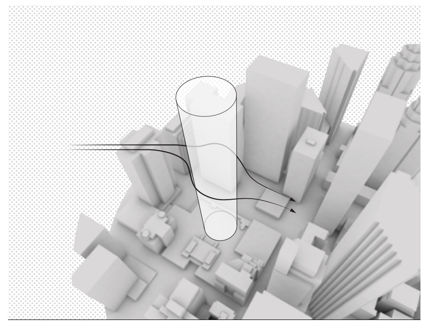


FIGURE 3.18. Video Sequence of Flow Around Chamfered Form

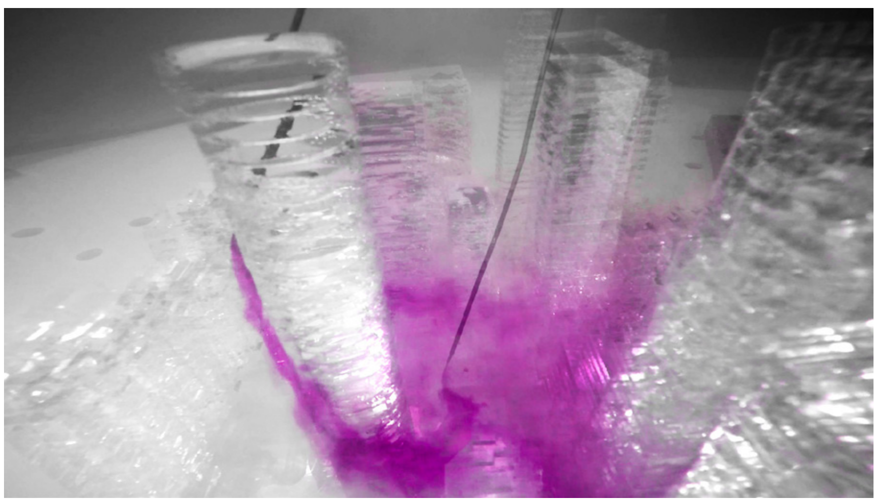
Cylinder



PLAN



PERSPECTIVE



OVERALL EFFECT

The cylindrical body guides winds along the facade. On the leeward side of the building, a vortex effect is created where flows are pulled up behind the structure.

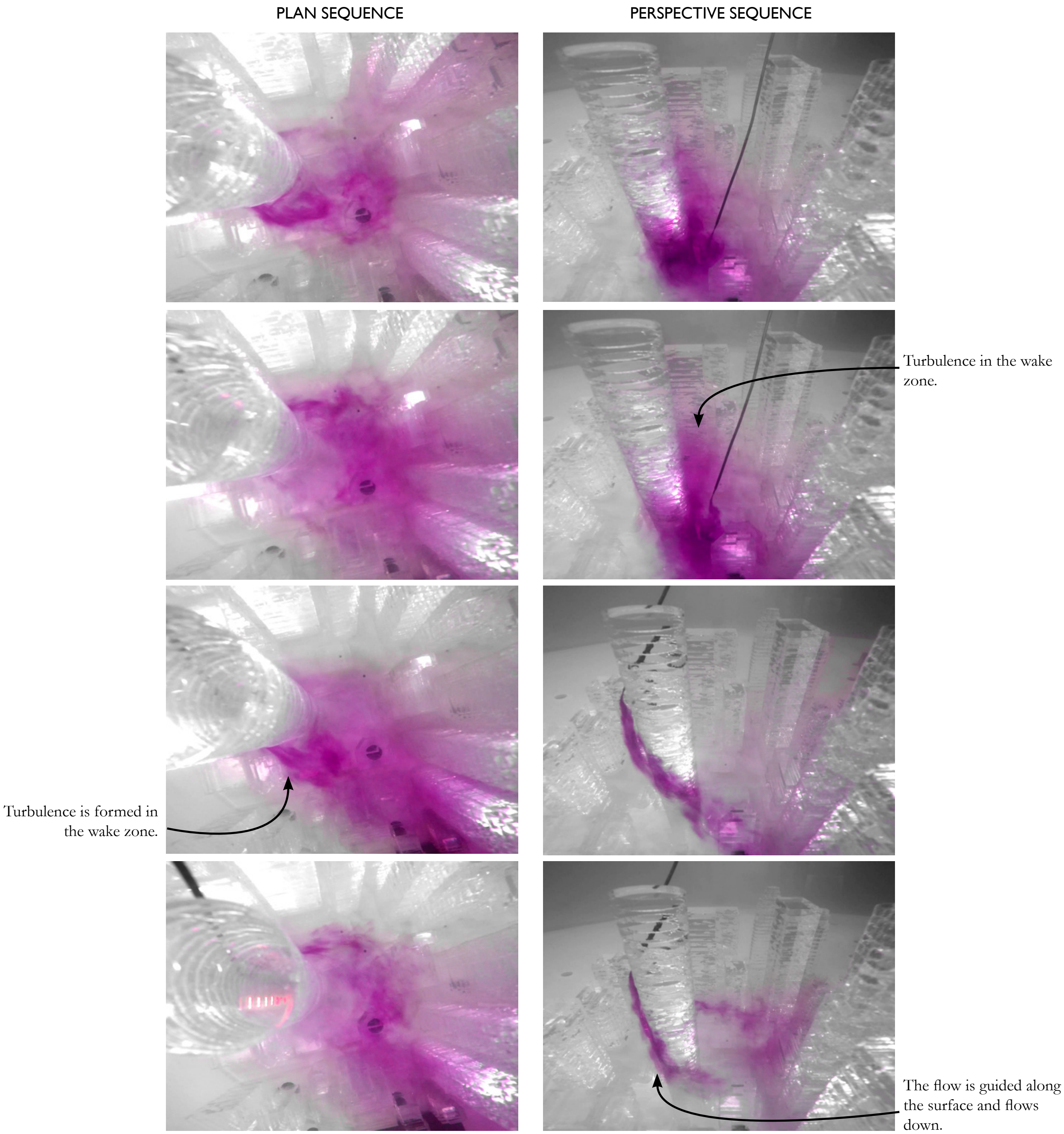
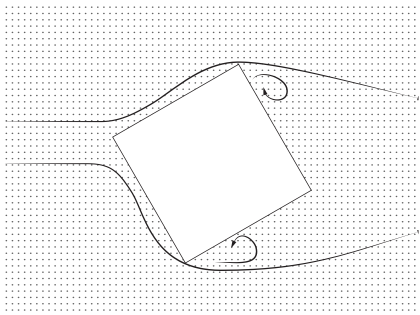
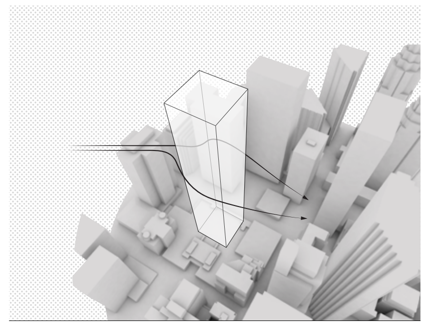


FIGURE 3.19. Video Sequence of Flow Around Cylinder

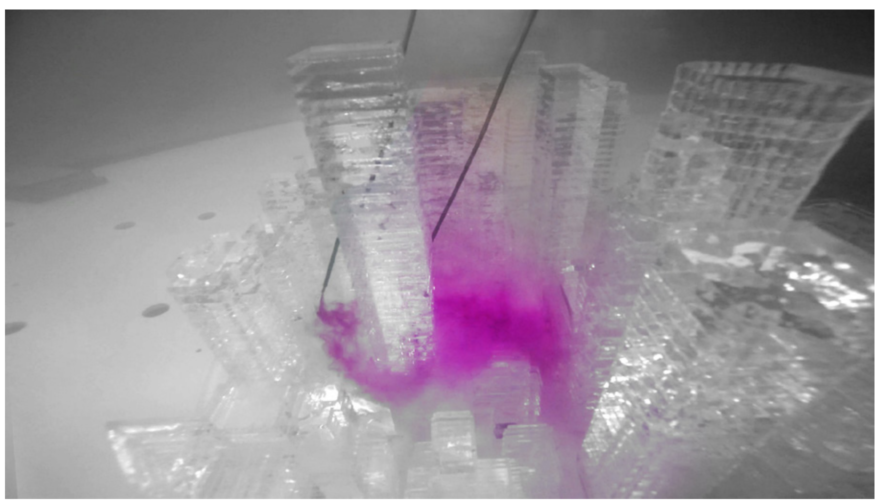
Square



PLAN



PERSPECTIVE



OVERALL EFFECT

Winds separate at the front edge of the square and flow smoothly from the front to the back of the building, creating only a small wake area.

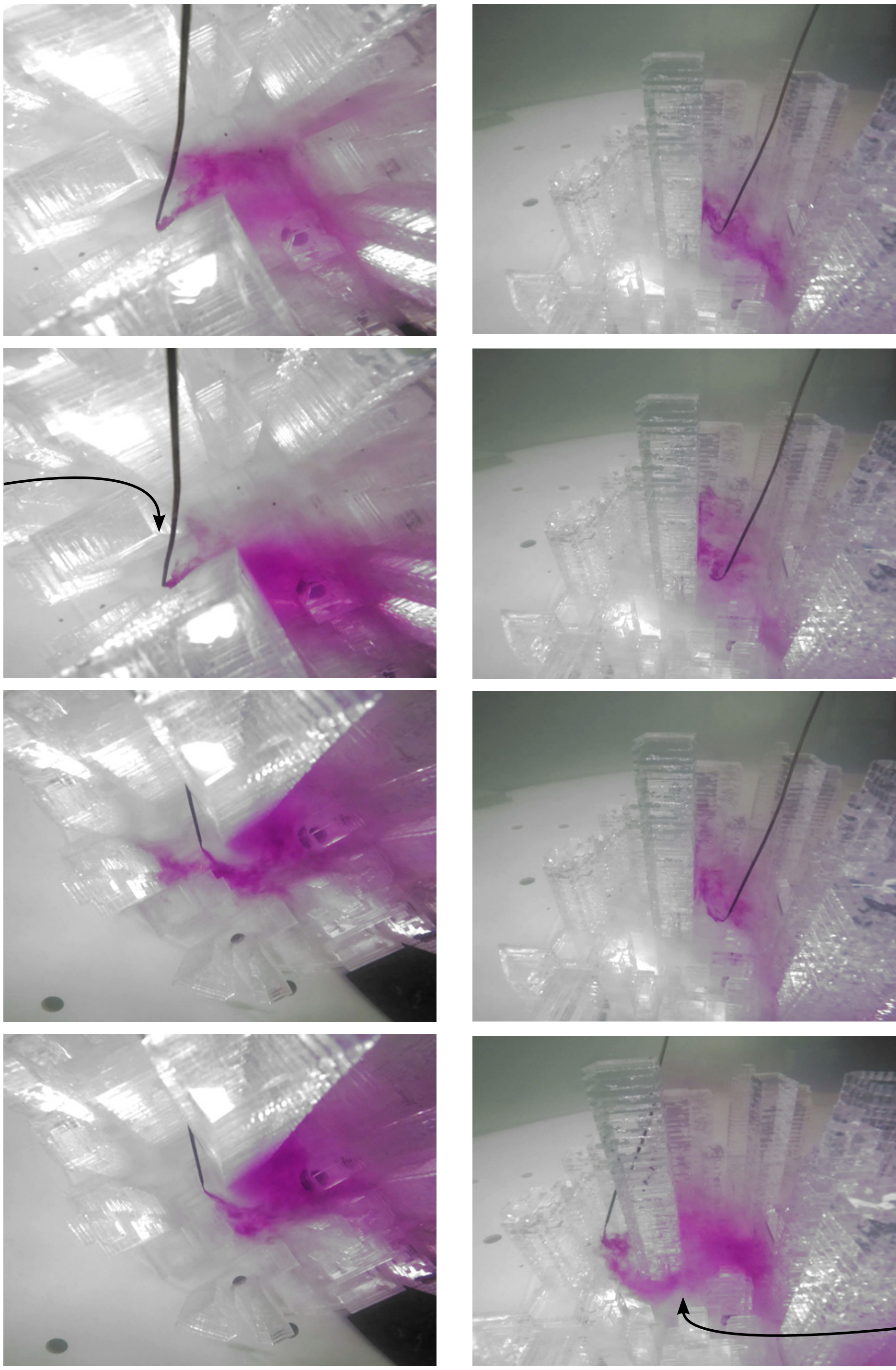
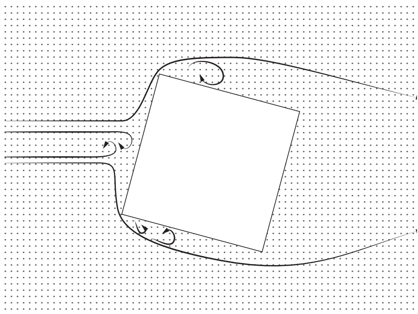
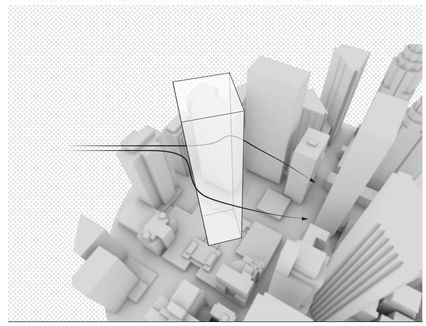


FIGURE 3.20. Video Sequence of Flow Around Square

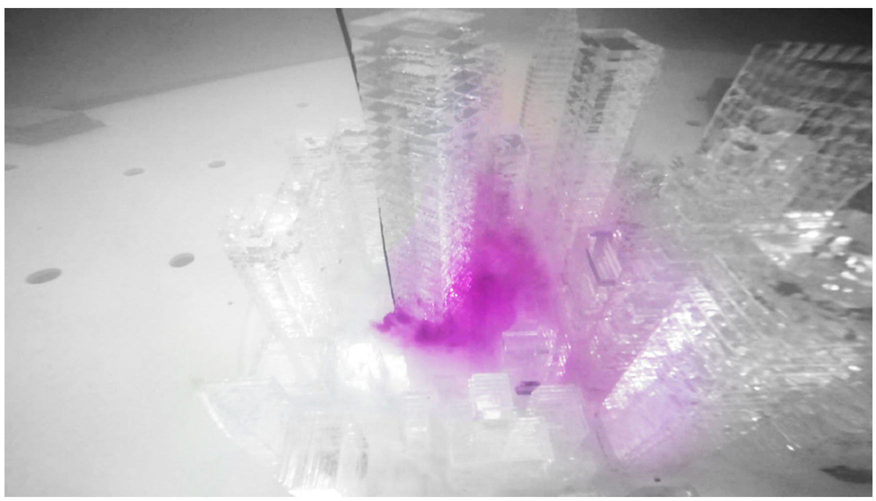
Square 45°



PLAN



PERSPECTIVE



OVERALL EFFECT

The flow washes down the front face of the square and accelerates around the corners. A negative pressure zone is created on the leeward side of the form. This creates a suction effect that pulls winds up the backside of the facade.

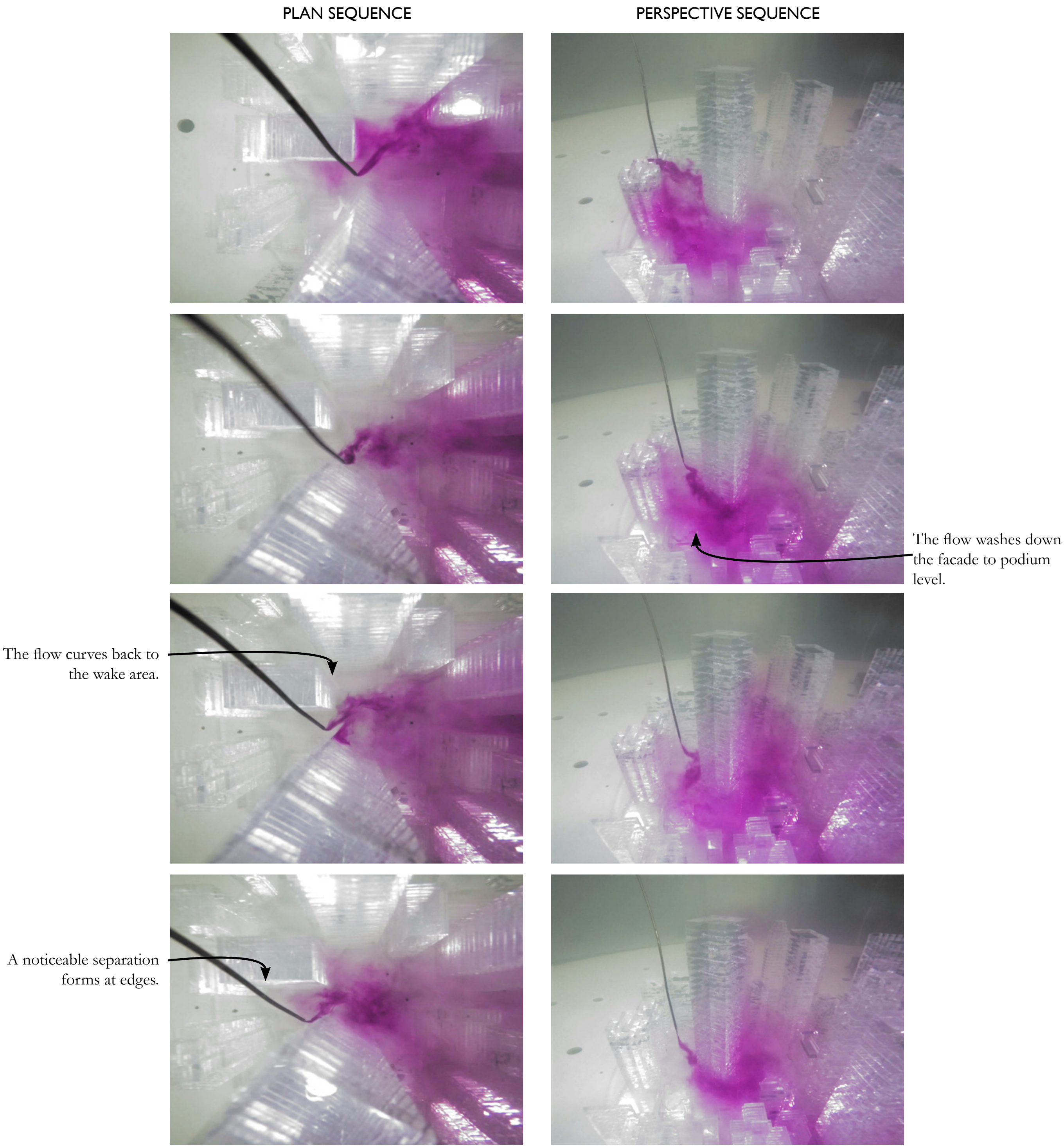
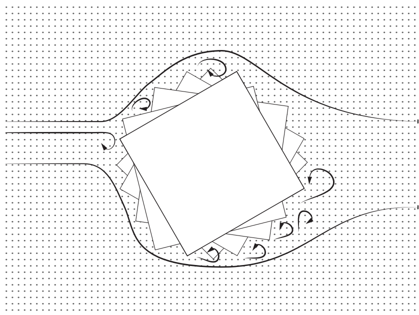
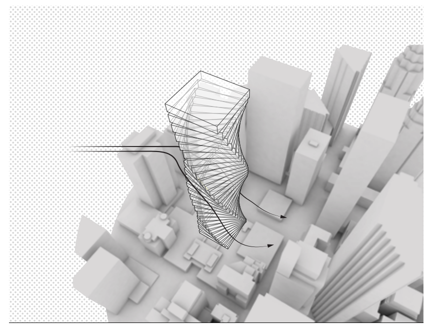


FIGURE 3.21. Video Sequence of Flow Around Square Rotated 45°

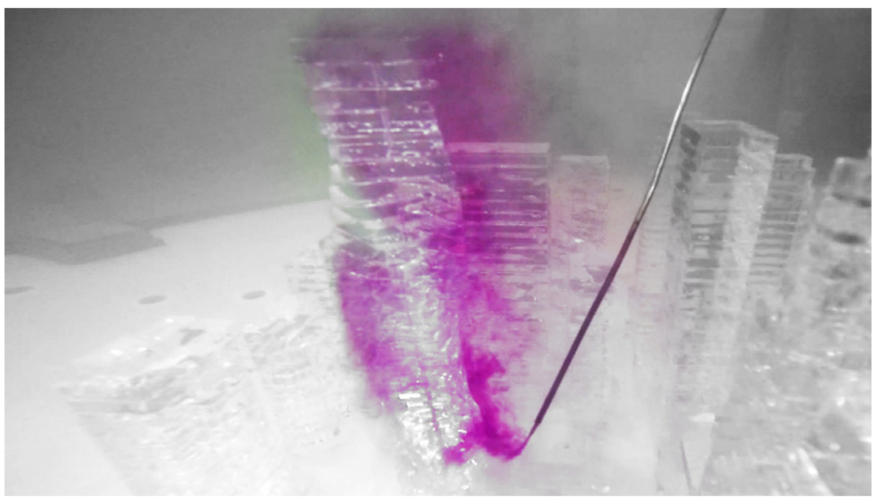
180° Helix



PLAN



PERSPECTIVE



OVERALL EFFECT

The flow around the helical tower is smoothly guided from the windward to the leeward side of the tower without being deflected or severely separated. Due to the changing cross-section over the height, the winds are continuously broken up and guided around the building without being deflected or impeding on flows in other regions.

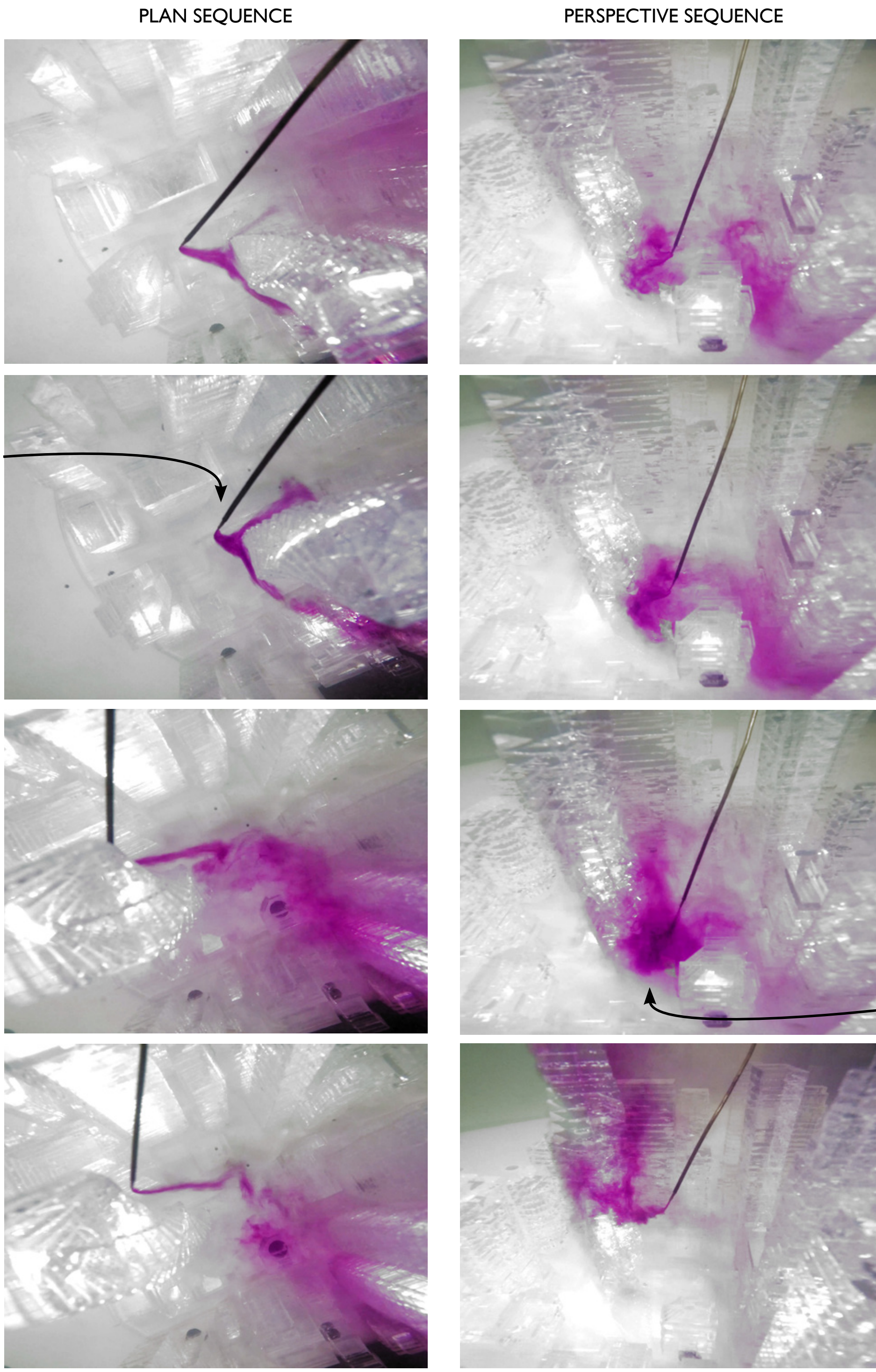
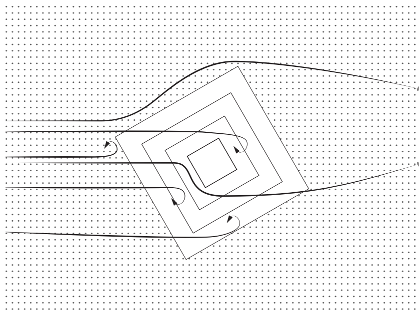
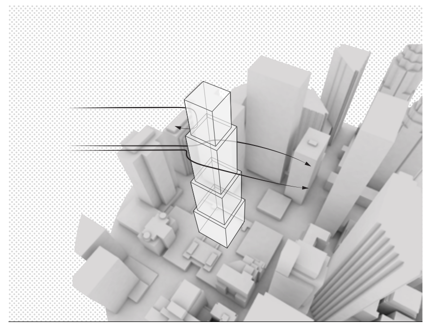


FIGURE 3.22. Video Sequence of Flow Around 180° Helix

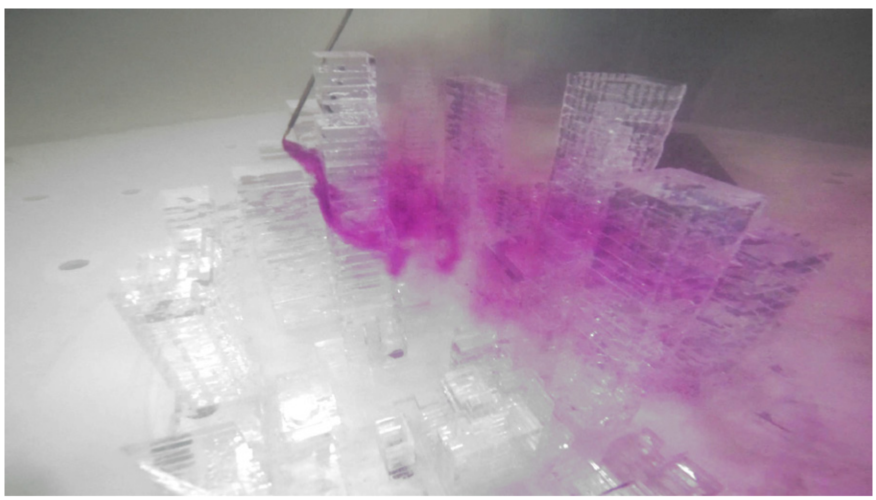
Stepped



PLAN



PERSPECTIVE



OVERALL EFFECT

The winds are broken up along the height of the stepped form, similar to the flow around the helical form. Winds that might be directed down by the taller part of the building are broken up at the step back locations.

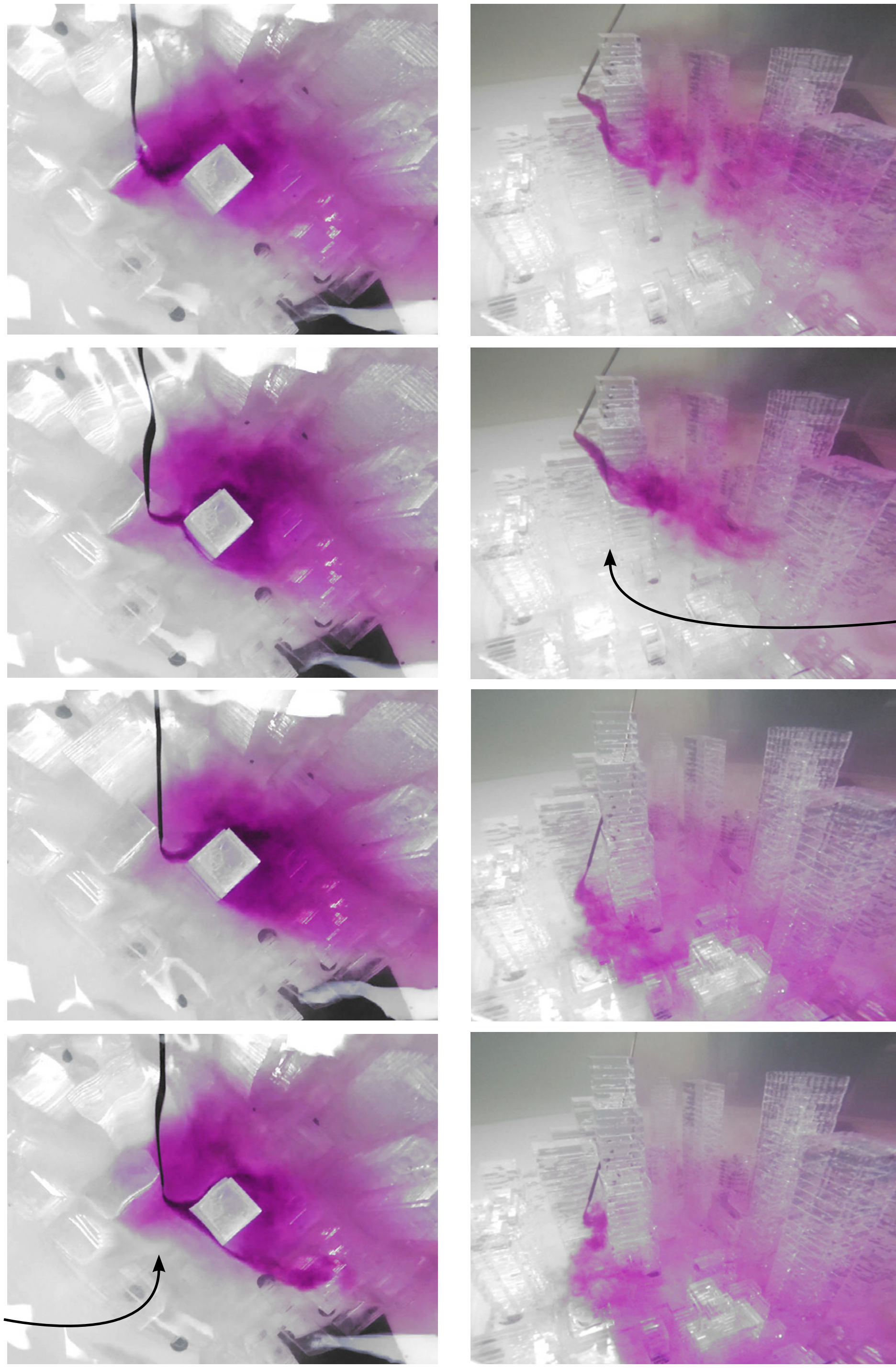
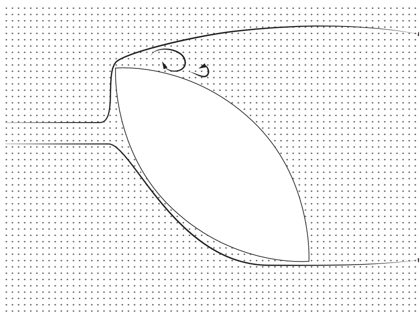
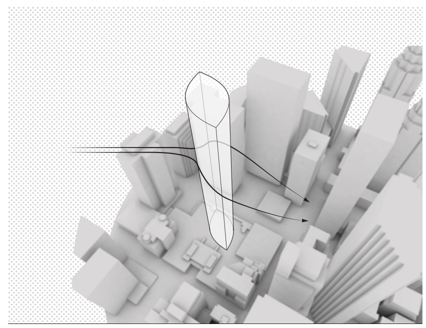


FIGURE 3.23. Video Sequence of Flow Around Stepped Form

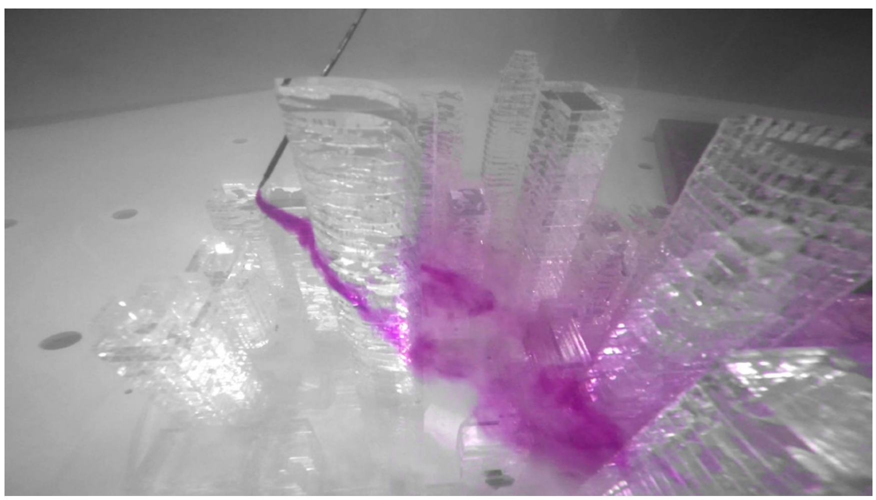
Eye



PLAN



PERSPECTIVE



OVERALL EFFECT

When the pointed edge of the eye shape is oriented toward the main direction of flow, the wind is smoothly guided along the surfaces. With no obstructing surfaces for the winds to wash down and no edges for winds to be deflected out from, the flow can smoothly separate and reattach.

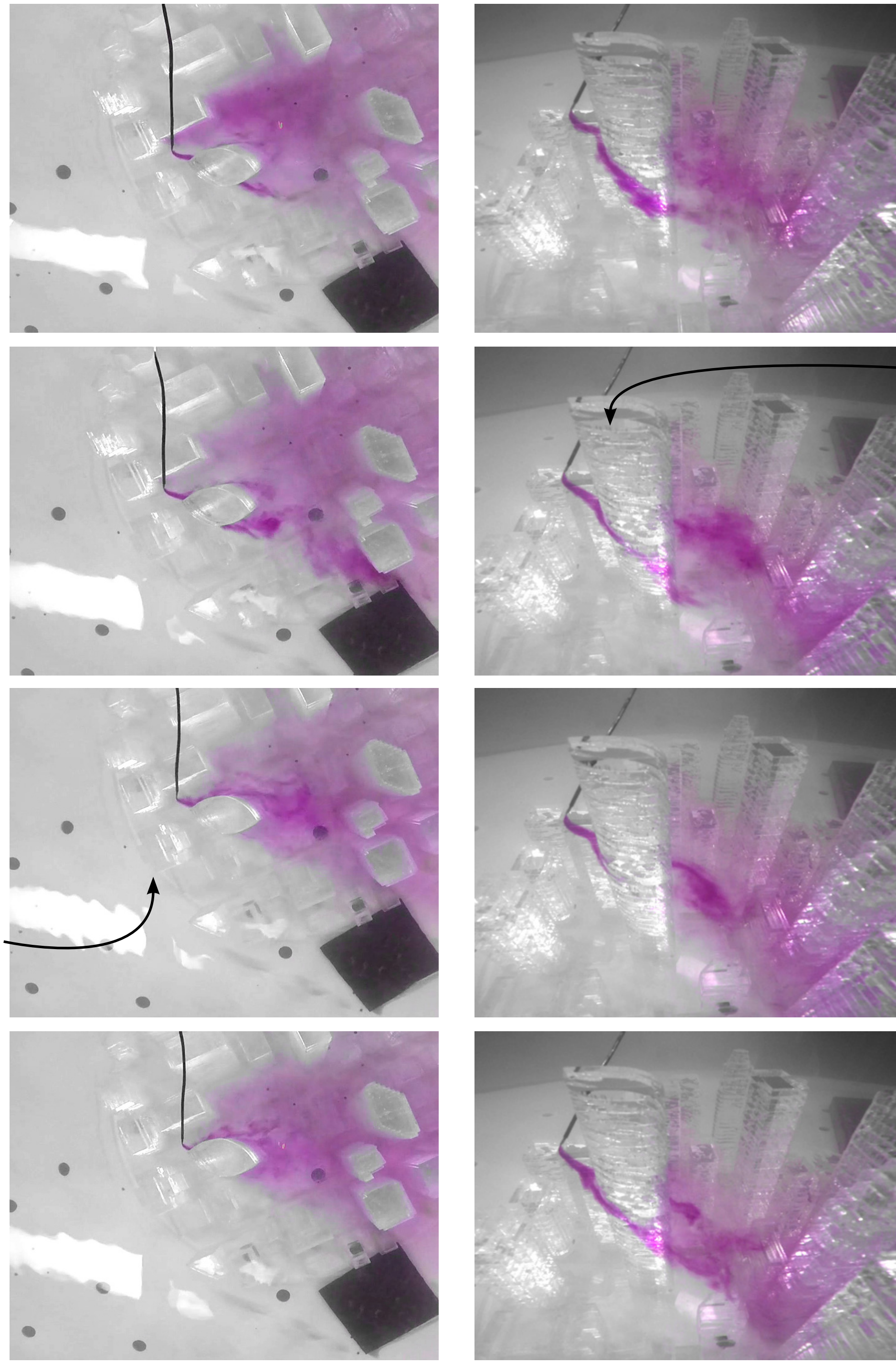
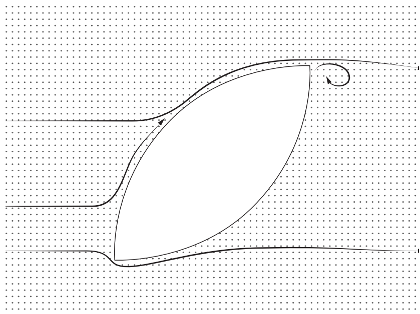
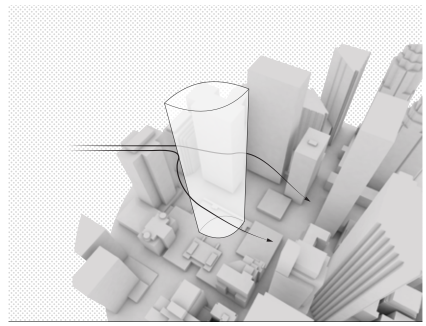


FIGURE 3.24. Video Sequence of Flow Around Eye Form

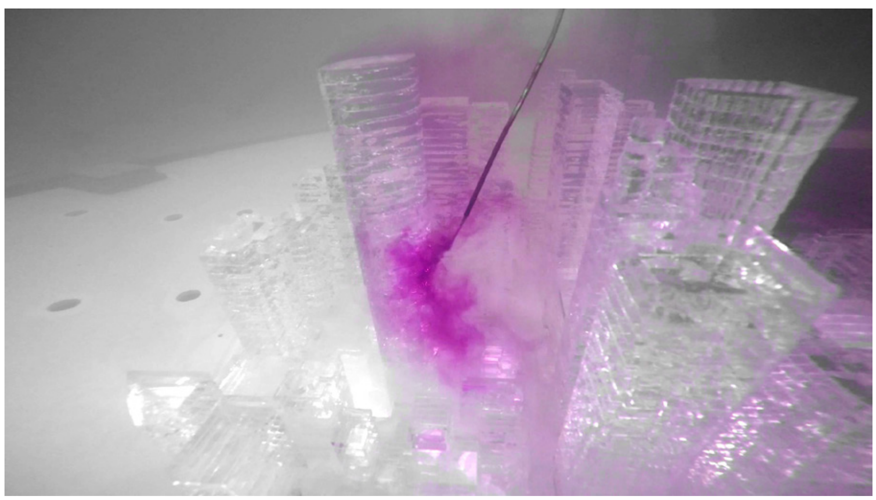
Eye 45°



PLAN



PERSPECTIVE



OVERALL EFFECT

If the wider face of the eye is oriented toward the main direction of flow, the large surface impedes winds and they separate at the corner edges in an oscillating fashion. A large wake region is created leeward of the building. Strong gusts are projected outward from the edges and have the potential to alter the safety of the surrounding buildings.

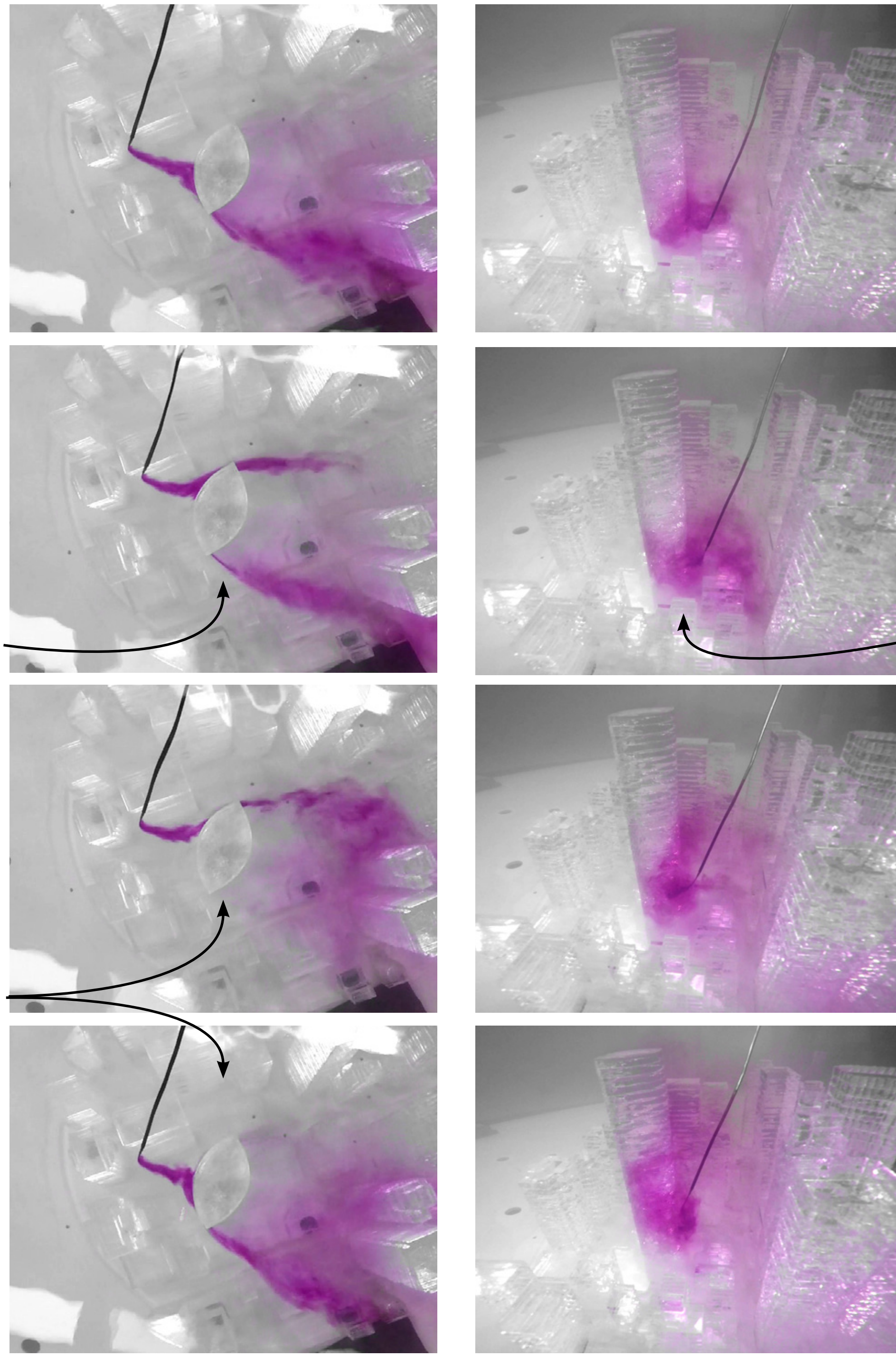
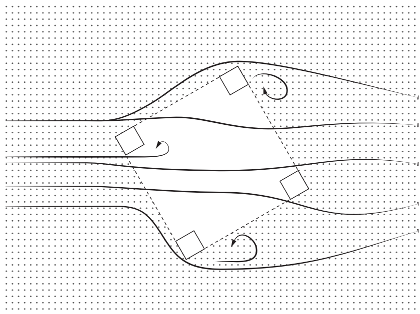
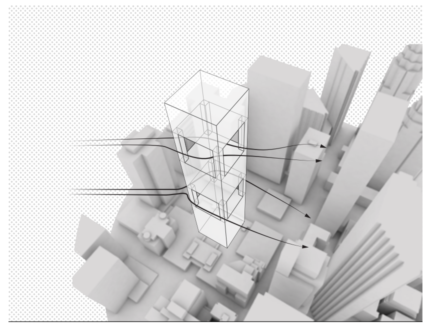


FIGURE 3.25. Video Sequence of Flow Around Eye Rotated 45°

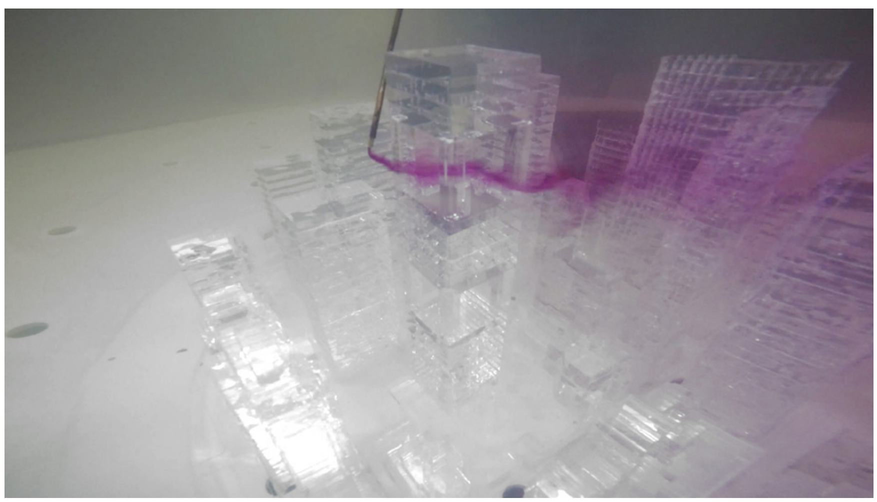
Square Form with Openings



PLAN



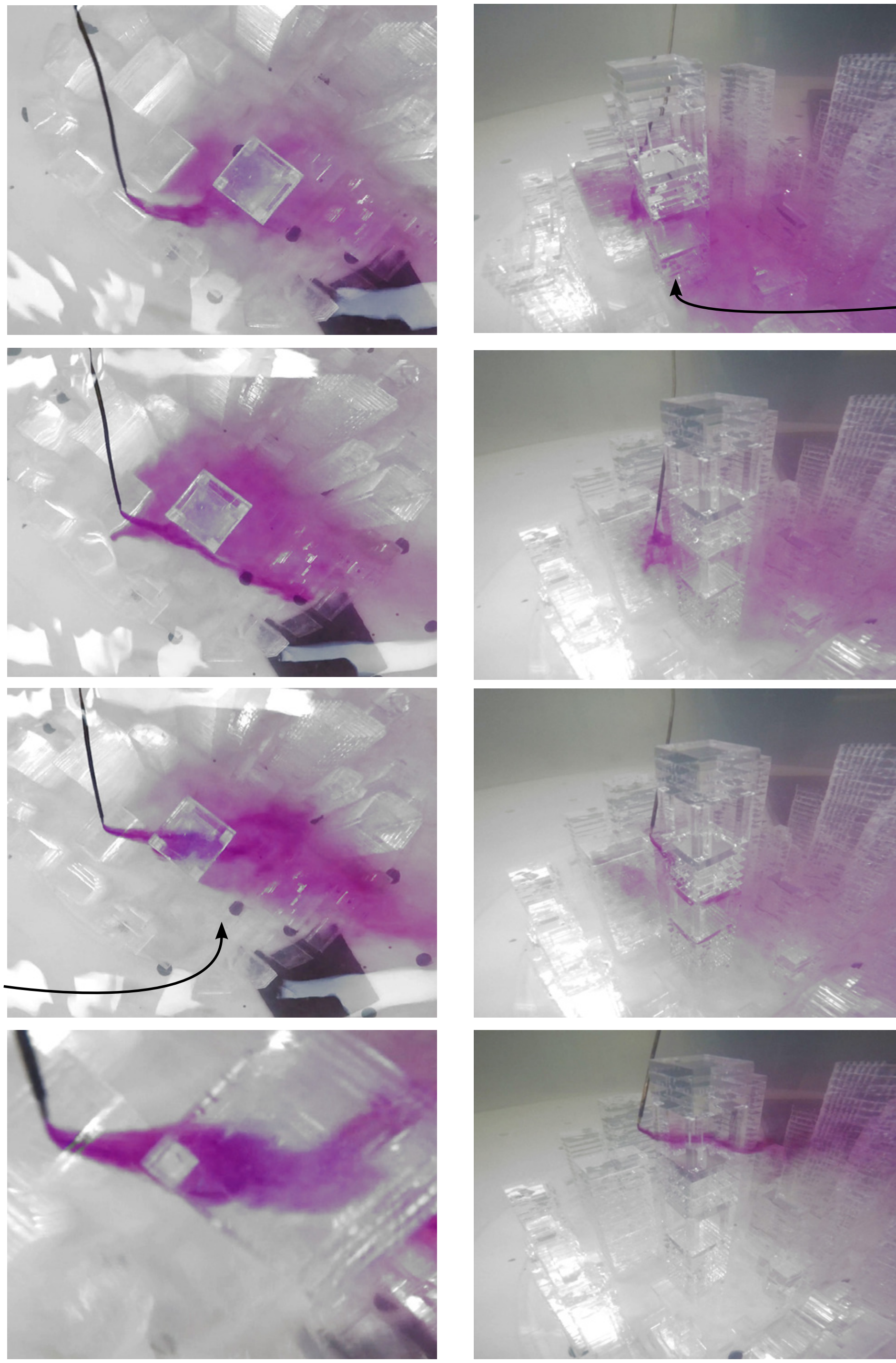
PERSPECTIVE



OVERALL EFFECT

The flow does not enter the lower opening of the form due to the mid-rise buildings that block them from flowing freely. However, the flows at higher elevations smoothly enter and exit the top opening. Overall, the openings allow winds to smoothly pass without creating zones of negative pressure that would pull the winds to grade.

PLAN SEQUENCE | PERSPECTIVE SEQUENCE



The flow does not accelerate through the opening at the lower level.

With no obstructions upwind, the flow accelerates through the higher opening.

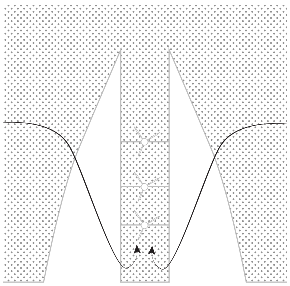
FIGURE 3.26. Video Sequence of Flow Around Square Form with Openings

PRECEDENTS AND APPLICATIONS

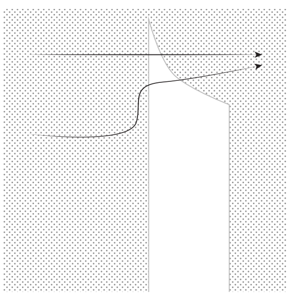
In many design professions, it is not common to find designers that use winds for anything other than ventilation. Once in a while, a new application for wind is incorporated into a building design, however these projects are typically located outside of cities or in isolated parking lots. As cities develop, the potential to use wind in design grows. The following pages examine the different ways that building form, orientation and positioning have been designed to utilize winds.

FIGURE 3.27. Turbulence Fields of the Donghai Bridge Wind Farm, China

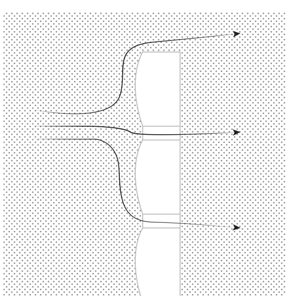
Energy



The Bahrain World Trade Center is composed of two triangular towers connected by three wind turbines. The wind turbines make use of channelling effects created by the two towers to generate energy. A study from the Technical University of Eindhoven has shown that if the towers were rotated 180 degrees and the wind turbines setback a few more metres, the design would be more efficient at collecting wind[9].



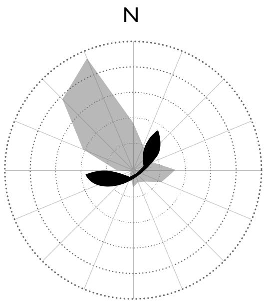
The original design for the Strata SE1 Tower in London, England aimed to generate 8% of the total energy for the tower by incorporating wind turbines into the facade. The concept was to channel the high speed winds at higher altitudes into three wind turbines. However, noise and vibrations affected residents and the turbines were shut off between the hours of 11pm and 7am each night. According to locals, the turbines are seldom seen rotating[10].



The sculpted body of the Pearl River tower was designed to direct wind toward funnel-like openings located at one-third and two-thirds of the building height. Integrated wind turbines and other mechanical systems are located within those openings. The building shape is oriented toward the prevailing winds and is designed to make use of relatively mild winds from multiple directions[11].

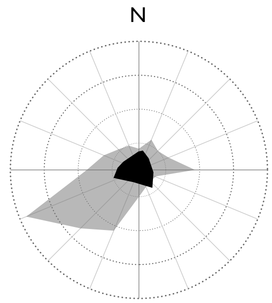
To harness the wind for energy, many parameters must be taken into account such as: future developments in the surrounding areas, structural costs, the possibilities for noise and vibration, the prevailing winds, and the accuracy of wind tunnel testing and computational models available. As technology advances and designers become more familiar with architectural aerodynamics, there will be more opportunities to build efficient buildings that harness wind energy.

9. TU/e, *Bahrain World Trade Center*, tue.nl/en/university/news-and-press/news/23-04-2014-bahrain-world-trade-center-is-exactly-the-wrong-way-round/.
10. Urban75, *Rarely Spinning Turbines,* urban75.org/the-rarely-spinning-turbines-of-the-strata-tower-south-london/.
11. Quick, *World's Greenest Skyscraper*, gizmag.com/pearl-river-tower/14696/.



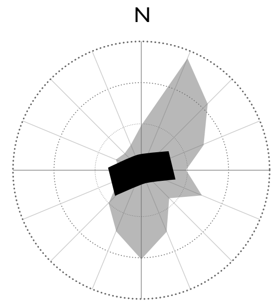
BAHRAIN WORLD TRADE CENTER

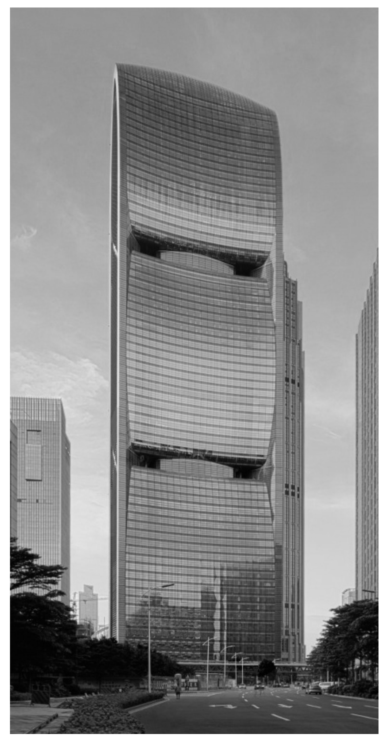
Location: Manama, Bahrain
Constructed: 2008
Designer: Atkins



STRATA SE1

Location: London, England
Constructed: 2010
Designer: BFLS



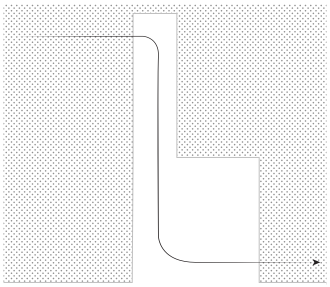


PEARL RIVER TOWER

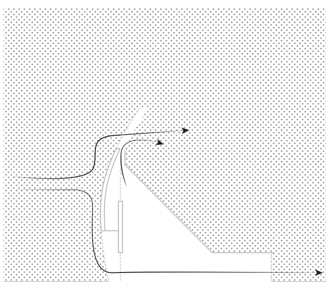
Location: Guangzhou, China
Constructed: 2011
Designer: SOM

FIGURE 3.28. Towers Designed to Generate Wind Energy

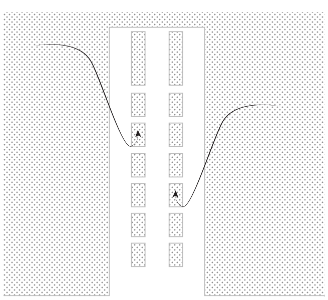
Ventilation



Wind catchers, instruments used to collect wind for ventilation purposes, can be found in deserts and other dry climates. Commonly, these tall, chimney-like structures divert cool, prevailing winds down into and across the dwellings they arise from. While these structures direct cool prevailing winds down, they typically reject the hot winds blowing from the opposite direction. This is a site and climate specific ventilation strategy.

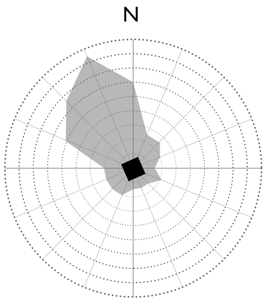


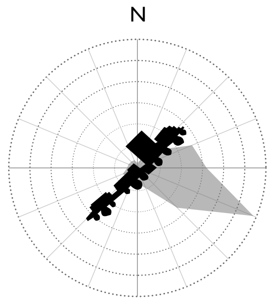
The Tjibaou Cultural Center utilizes form, program and technology to adapt to its changing weather conditions. The facade of each of these pods is an adaptable screen that encourages ventilation. This facade system can take in winds from two different directions as well as completely shut out and resist hurricane force winds.

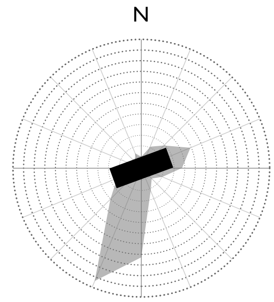


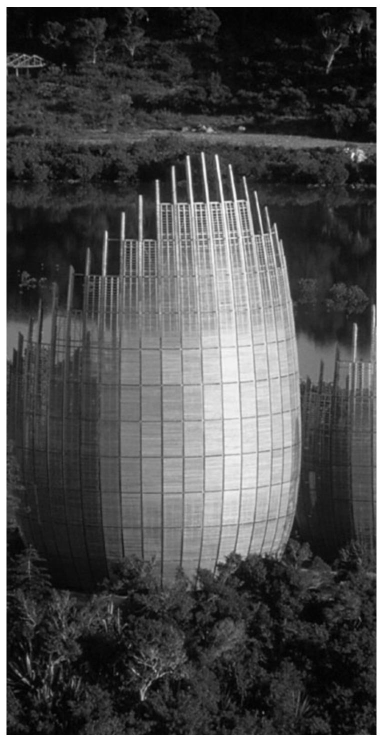
The MET tower was one of the first towers of its time to utilize its environment and use natural ventilation strategies instead of relying solely on mechanical systems. The three towers, connected at multiple floors, shelter the rooms from strong winds and the sun but allow breezes to enter the public spaces by means of channelling.

The utilization of wind for passive ventilation relies heavily on climate and tradition. To harness wind for ventilation purposes, parameters such as: future developments in the surrounding areas, structural costs, temperature and climate, pedestrian comfort, and overall form of the structure must be taken into account. For a building to provide comfortable conditions through passive ventilation, it must be able to adapt or respond to its local conditions.









WIND CATCHERS, "BADGIRS"

Location: Yazd, Iran
Constructed: Dates back to ancient Egypt
Designer: Persian-influenced

JEAN-MARIE TJIBAOU CULTURAL CENTRE

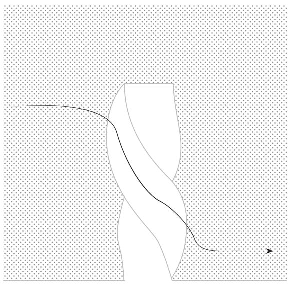
Location: Nouméa, New Caledonia
Constructed: 1998
Designer: Renzo Piano

THE MET

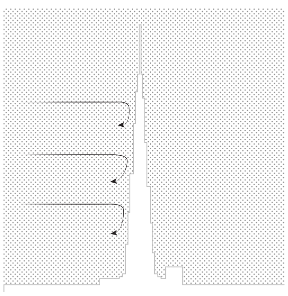
Location: Bangkok, Thailand
Constructed: 2009
Designer: WOHA

FIGURE 3.29. Buildings Designed to Utilize Natural Ventilation

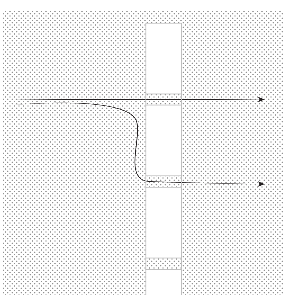
Build Taller



The tallest skyscraper in Sweden, the Turning Torso, twists 90 degrees from the top to the bottom of the tower. An exterior exoskeleton "provides wind resistance and dampens the buildings vibrations[12]". The helical form of the building actually redirects winds and gently guides them around the building to reduce the effects in the wake zone.



The Burj Khalifa, formerly known as the Burj Dubai, is considered to be the world's tallest building, reaching 823 metres. The form is strategically designed to "confuse the wind." This tapered form deflects, breaks-up and prevents winds from forming organized whirlpools of air currents, or vortices. If formed, these vortices would rock the tower from side to side and potentially damage the building[13]. A tuned mass damper (similar to a pendulum) is also used to counteract the swaying motion caused by winds.



Regarded as the tallest residential building in the western hemisphere, 432 Park Avenue utilizes several open floors scattered throughout the height to reduce wind loading by letting high speed winds pass through the building. The building also utilizes a tuned mass damper to reduce sway. Interesting to note was that marketable floor space was sacrificed to reach maximum heights, resulting in an increase in value.

While not required, wind engineers typically suggest that tuned mass dampers be incorporated into the design to ensure comfortable conditions within the skyscrapers. Without dampers to respond to the fluctuations and waves of wind, the individuals at higher levels would experience the sway of the building and feelings similar to sea sickness. In this way, the form of a building plays a significant role when dealing with stronger winds at higher elevations. An interesting article describing tuned mass dampers can be found at http://www.nytimes.com/2015/08/09/realestate/keeping-skyscrapers-from-blowing-in-the-wind.html.

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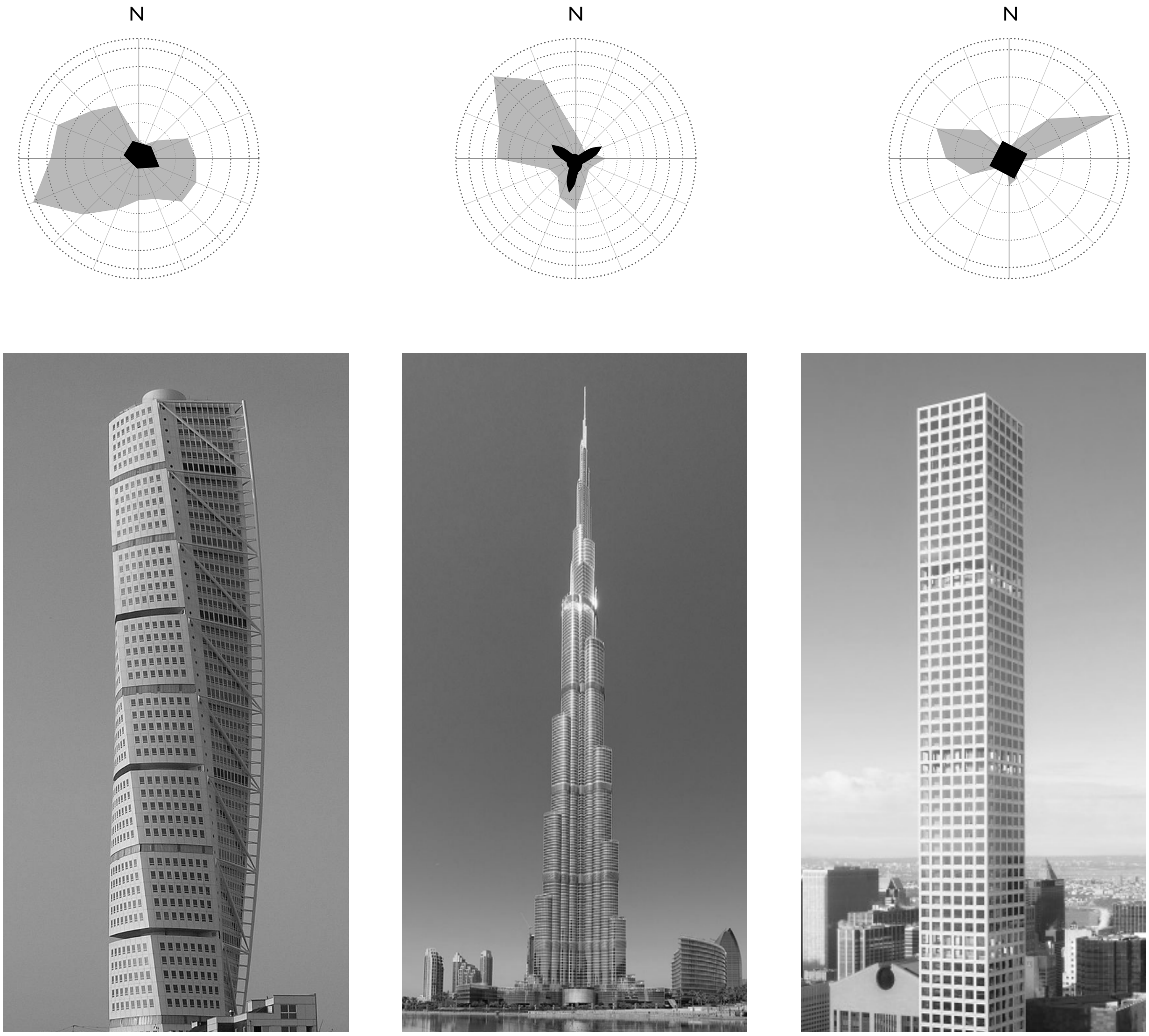
12. Feblowitz, *Confusing the Wind,* http://www.inquiriesjournal.com/articles/124/confusing-the-wind-the-burj-khalifa-mother-nature-and-the-modern-skyscraper.
13. Nyawara, *The Turning Torso*, http://www.archute.com/2016/01/23/the-turning-torso/.



TURNING TORSO

Location: Malmö, Sweden
Constructed: 2005
Designer: Santiago Calatrava

BURJ KHALIFA

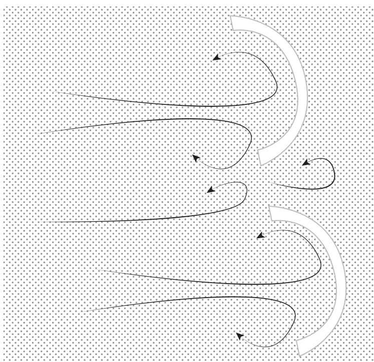
Location: Dubai, United Emirates
Constructed: 2009
Designer: SOM

432 PARK AVENUE

Location: Manhattan, New York, USA
Constructed: 2015
Designer: Rafael Viñoly

FIGURE 3.30. Towers Designed to Reduce Wind Impact

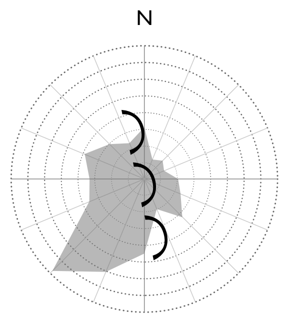
Protection

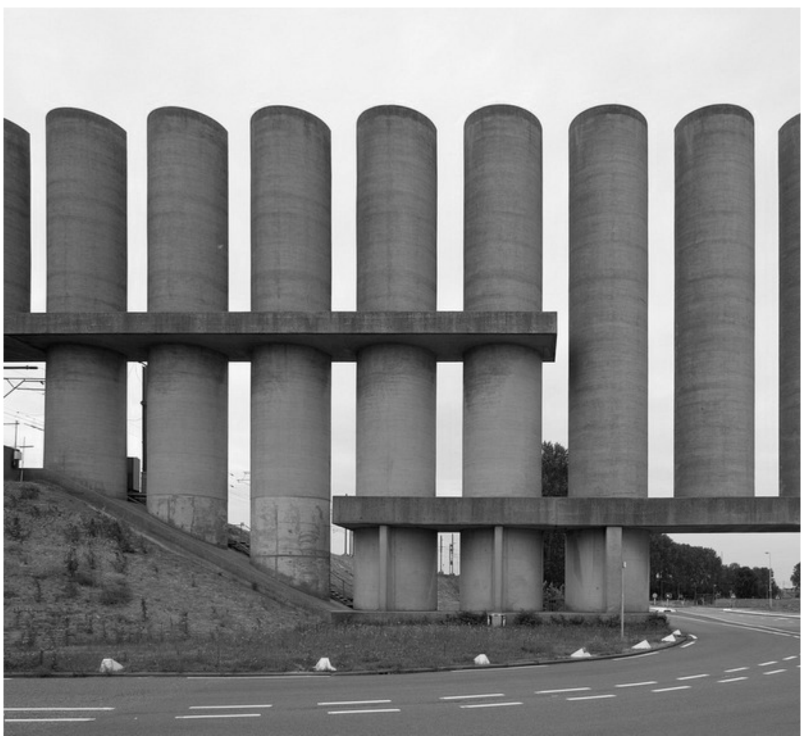


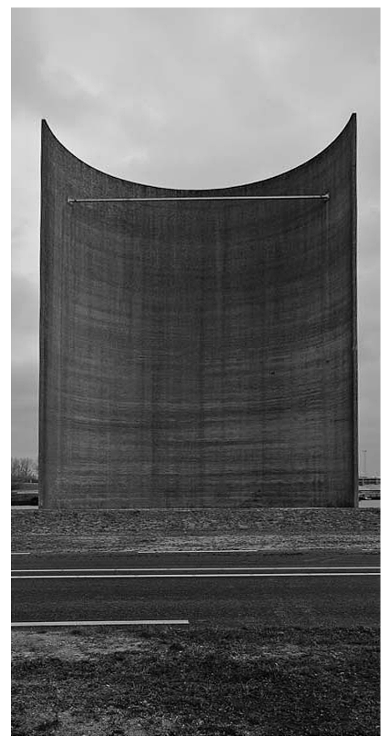
The Rozenburg Wind Wall, located alongside the Canal of Caland in the Netherlands, is often mistaken for a modern art installation. These massive concrete structures were installed to strategically break up winds that were slowing down shipping traffic in the canal. Prior to the wind wall, the passage had always been troubled by the incoming onslaught of wind.

The Wind Wall has been instrumental in restricting the wind interference by nearly 75%[14]. This reduction of wind was achieved by utilizing one-hundred and twenty-five individual concrete slabs that run along the edge of the western part of the canal for approximately 1.75 km. Beginning in the southern part of the canal, the slabs are shaped in semi-circles, 18 metres wide and 25 meters tall. Moving north, the semi-circles become more flat and the walls are packed closer together. Near the bridge of Calandbrug the walls are only 4 m wide and placed on top of a 15m embankment to attain the same 25 m height as the other sections. The barrier ends in the form of trees that provide similar protection to the water as the walls.

14. Kaushik, *Rozenburg Wind Wall*, amusingplanet.com/2013/06/rozenburg-wind-wall.html.







ROZENBURG WIND WALL

Location: The Netherlands (Port of Rotterdam)
Date of Construction: 1980's
Designer: Maarten Struijs and Frans de Wit

FIGURE 3.31. Working Against Wind to Protect - Wind Wall

"Part of the long struggle to understand and then to forecast weather was to accurately measure wind — and then to find some way of depicting it that others would readily understand."

- De Villiers, *Windswept*, 137.

PARAMETERS OF PREDICTION

FIGURE 4.1.

CASE STUDY

The trend of tall building construction or "Manhattanization" has rapidly increased over the past decade, making it crucial for more professions to understand how the resulting changes in wind affect people. When designing tall buildings many architectural offices use code-based wind-loading calculations to achieve structural stability. While being conscious of how wind affects a structure, how the form, its orientation and location alter exterior wind conditions at pedestrian level is commonly overlooked. Often, this leads to projects incurring mitigation costs as well as altering the original design intent. Considering that winds, along with other elements of weather, shape the habitability and health of cities, how the built environment changes the winds must be taken more seriously. A basic understanding of architectural aerodynamics would allow members of the architectural profession to contribute ideas to mitigate wind and potentially prevent redesigns and associated costs. Although it may be clear as to how a singular building interacts with wind, it is more difficult to predict the effect when multiple buildings are added and the city begins to densify. For these situations especially, it is necessary to work closely with wind engineers. For example, the Walkie Talkie Tower in London has received considerable attention for creating windy conditions that have been blowing people and signs over even though some form of wind testing had been done previously. Gwen Richards, the head of design at the City of London stated: "The wind outcome at street level experienced post-construction on a number of projects differs somewhat to the conditions [expected] from the one outlined in the planning application wind assessments[1]". This could be due to many possible reasons, including new or anticipated future construction in the surroundings not being included in the assessment.

Developments in outlining principles of aerodynamics have greatly contributed to communicating wind effects in clearer ways. The cultural, scientific and testing guidelines have been widely studied and reported by many engineers (Aynsley, 1977; Melaragno, 1982; Wu, 1996), science writers (Ball, 2009), story-tellers (Villiers, 2006) and by few architectural and planning professionals (Krautheim et al, 2014). However, while these documents describe wind effects within the urban environment, they mainly focus on describing singular buildings and their indivudal effects. This study aims to visually demonstrate how the form, orientation and proximity of the combination of buildings alters the winds.

1. Ward, *Walkie Talkie Skyscraper*, telegraph.co.uk/Walkie-Talkie-skyscraper-blamed-for-creating-wind-tunnel-on-the-street.html.

FIGURE 4.2. Discomfort Due to Windy Conditions

Wind Issues

The intersection of King Street West and Bay Street in Toronto, Ontario is the focus of this case study. The Financial District (as it is named), has received media attention in the recent years as pedestrians have complained of uncomfortable high speed winds. In 2014, Toronto chief planner Jennifer Keesmaat stated that "[The winds are] a result of the built form, that is absolutely true. This is a condition that we've created unfortunately[2]." In response, the city is taking steps to introduce specific development permit bylaws in specific areas within the city.

The high winds in the area have also sparked rage amongst business owners along King Street. Many claim to have lost business due to forceful winds created by tall tower development that created undesirable and uncomfortable environments. In another news report, the wind at the intersection of King and Bay was deemed "monstrous" in conjunction with cold weather[3].

In 1975 the Commerce Court, a public space at the heart of the Financial District, was deemed "so impassable on a windy day that rope lifelines were installed to assist pedestrians as they approached[4]" and a study was performed by Alan Davenport at the University of Western Ontario's Boundary Layer Wind tunnel. In an extreme case in 2012, when remnants of winds from Hurricane Sandy had made there way up to Toronto, a woman was struck and killed by a wind blown portion of a sign that broke loose.[5] Too easily, society blames architects and wind engineers for not properly taking wind into account while designing the city. However, the question that is most difficult to answer but must be asked is: which of these effects were predictable and how could they have been predicted?

2. Rhee, *City Planner wants to stop wind tunnels,* global news.ca
3. Westwood, *Toronto Fights Back Against Wind Tunnels,* metronews.ca
4. Roberts, *Wind Wizard,* 121-122.
5. CBC, *Flying Debris Kills Woman,* www.cbc.ca

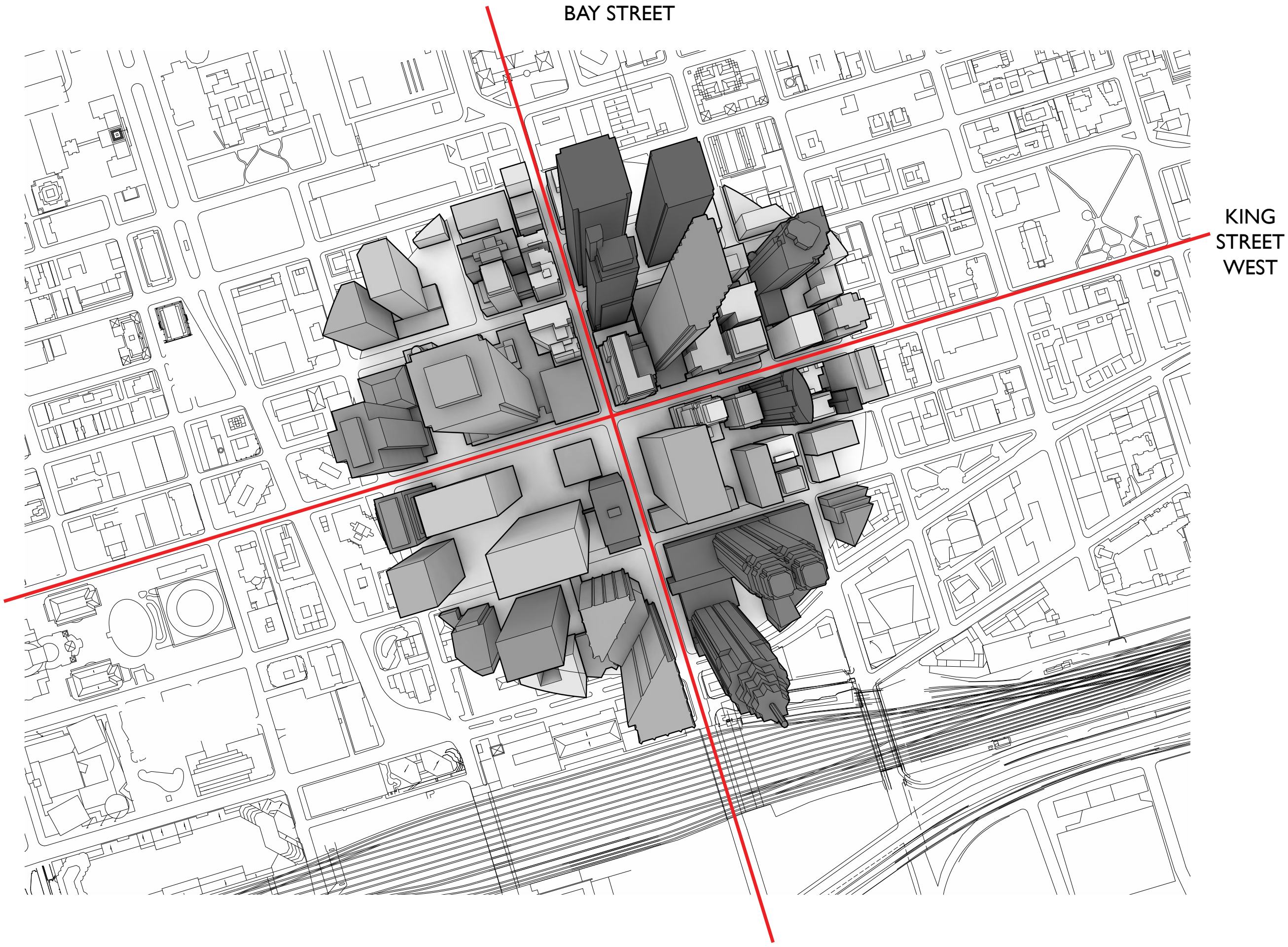


FIGURE 4.3. Intersection of King Street West and Bay Street

Development

The intersection of King Street West and Bay street, has been the site of the tallest towers at certain points in history and has undergone drastic development over the last seventy years. The six years selected: 1940, 1970, 1980, 1990, 2000 and 2015, are the years during which major tower development has occurred.

In 1931 the Commerce North Tower was the tallest building (at 28 storeys) in the Commonwealth until 1962[6]. In present day, the tallest tower in the area is the First Canadian Place tower (BMO) constructed in 1975, that has 72 floors and is 298m tall. The major developments appeared in order: 1970 the Mies Towers, in 1980 the BMO and Commerce Building, in 1990 the Scotia Tower, in 2000 the TD towers and in 2015 the Trump and the Bay Adelaide Towers.

6. Flack, *Toronto's most stately skyscraper,* blogto.com.

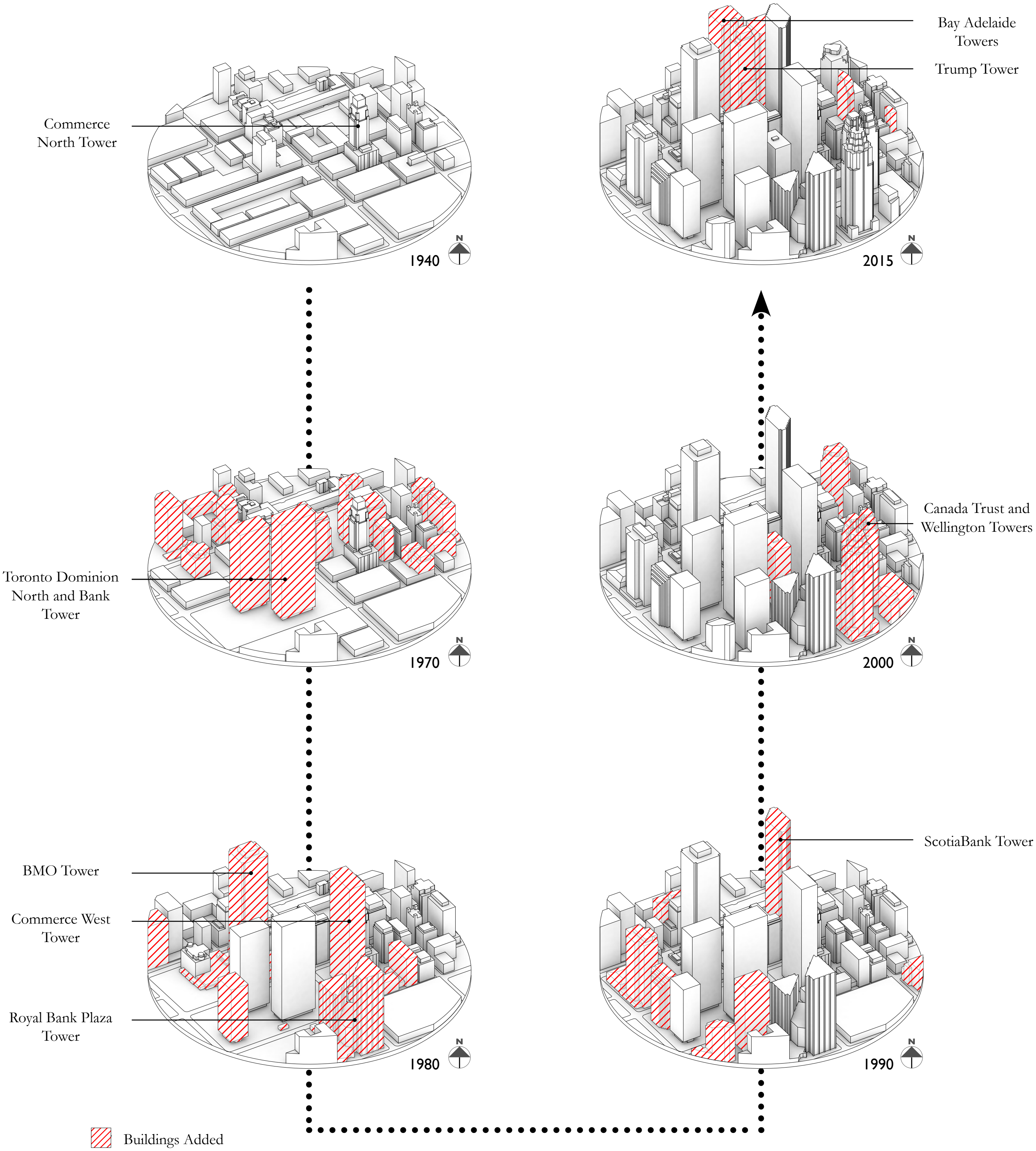
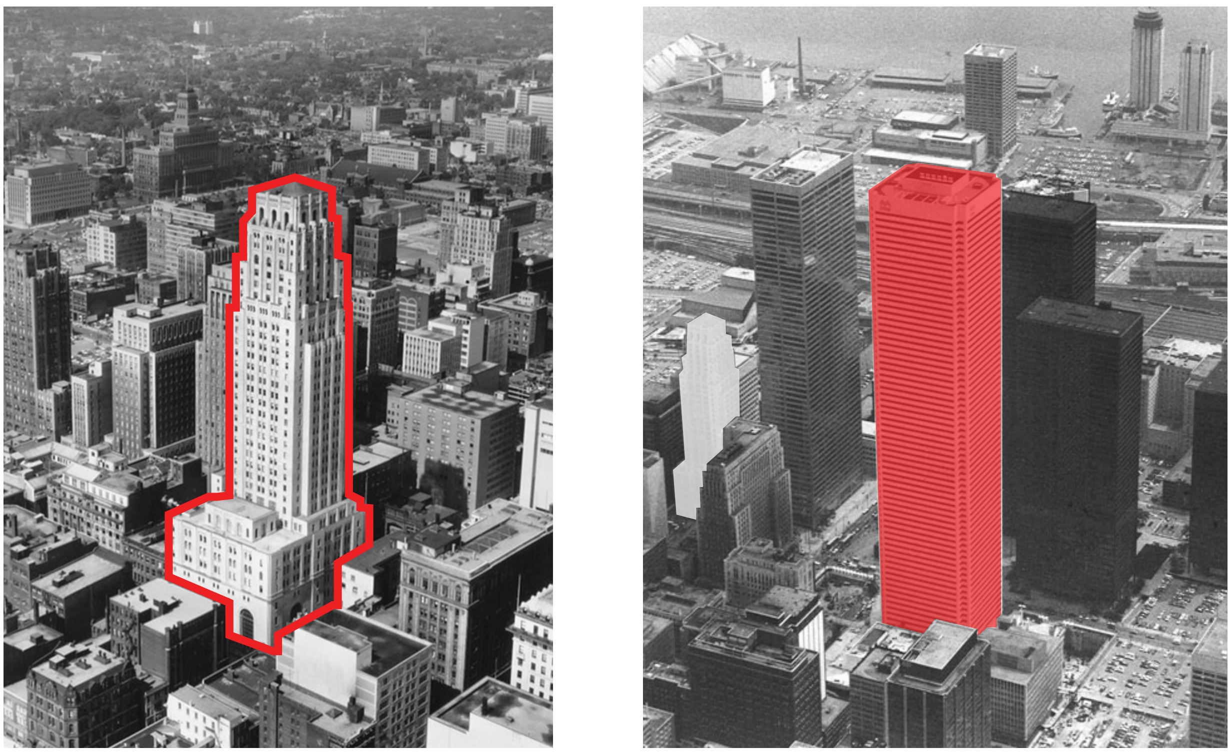


FIGURE 4.4. Development of the Financial District of Toronto

SKYLINE 1940

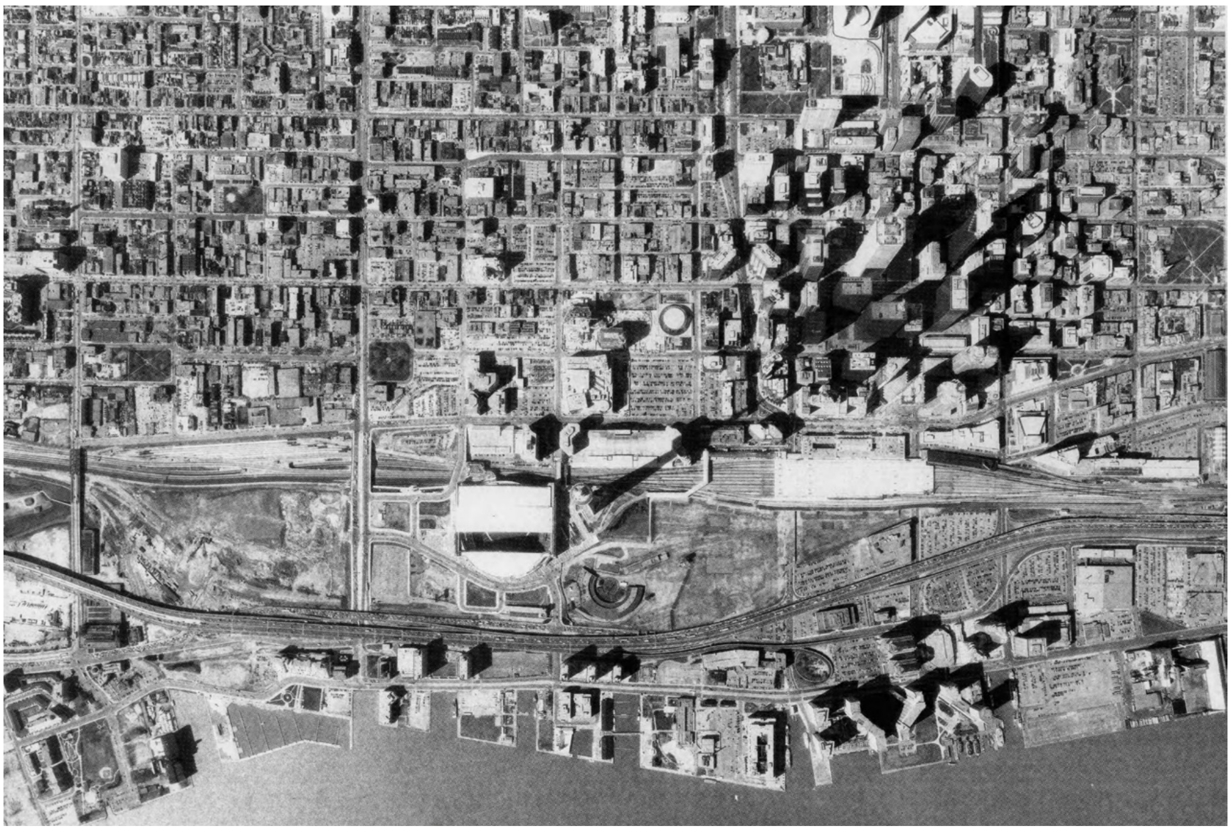
SKYLINE 2015



CANADIAN BANK OF COMMERCE

FIRST CANADIAN PLACE TOWER

FIGURE 4.5. Skyline Comparison



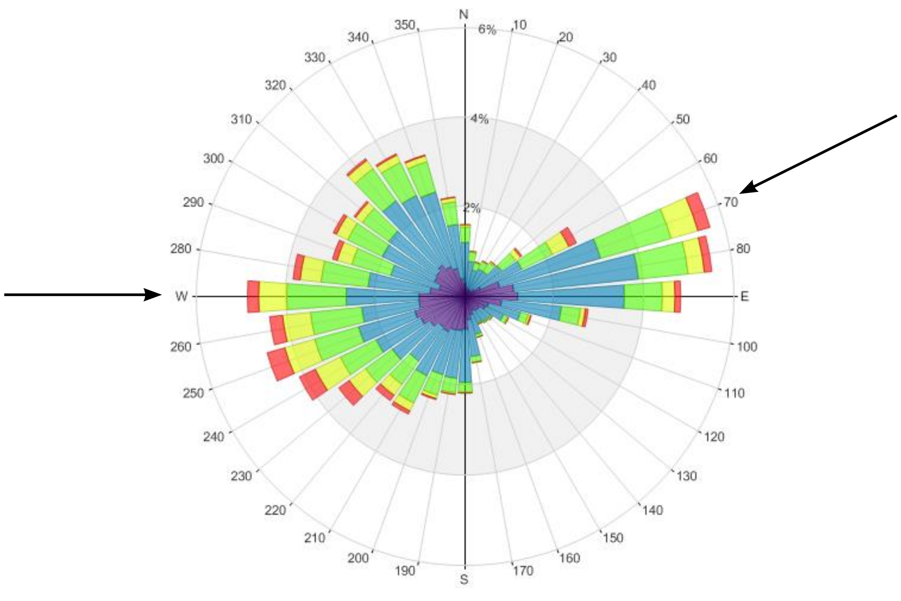
1940 AERIAL VIEW OF DOWNTOWN TORONTO

2015 AERIAL VIEW OF DOWNTOWN TORONTO

FIGURE 4.6. Skyline Comparison

Local Meteorology

The Financial District is located approximately 2 km (~1.3 miles) from the Billy Bishop Toronto City Airport. Meteorological data collected at the airport are representative of the conditions in the area of interest. Wind statistics recorded at the airport at a height of 10 m (33.3 ft) have been presented in the form of a wind rose. Each sector in the figure represents the frequency and speed of winds blowing from that direction. It can be seen that winds from the western half of the compass and the east and east-northeast directions are predominant in Toronto. Strong wind components (red and yellow bands) are more frequent from the west, west-southwest and east-northeast. These winds have the potential to create uncomfortable and potentially severe wind conditions at grade level upon interaction with buildings. Two wind directions West (270°) and East-North East (70°) have been used to investigate the six years of development. These directions affect the site for a high percentage of duration annually. The easterly wind runs in parallel with the streets while the western winds run 20° off alignment with the streets.



Annual Winds

	Wind Speed (km/h)	Probability (%)
	Calm	4.3
purple	1-10	23.5
blue	11-20	40.4
green	21-30	20.8
yellow	31-40	7.7
red	>40	3.3

RWDI WIND ROSE - TORONTO ISLAND AIRPORT
1971-2015

FIGURE 4.7. Wind Rose Provided by RWDI from Toronto Island Airport

Experimental Methods

Computational Fluid Dynamic Model (CFD)

Initially, the six years of development and two directions of wind were simulated in RWDI[1]'s proprietary computational fluid dynamics program developed for the qualitative assessment of pedestrian level winds. The computer model included all relevant surrounding buildings within a 300 m (1000 feet) radius centered on the intersection of King Street West and Bay Street. The prevailing winds from the west and east-northeast were simulated and results at a height of 1.5 m (~5 feet) above ground were analyzed. An in-house fluid dynamics program named Virtual Wind and created at RWDI was used that requires a triangulated mesh model, where each triangulation is given a point at its center, and the data from those points is retrieved to show the results. The simulation can run up to a maximum of 5000 times. The program runs a simulation using set parameters of aerodynamics input into the system and continues to run scenarios until every outcome has been performed. Each time the simulation runs, the wind can move a different way. The final image is a result of the accumulated effect of wind in that area and is manually calibrated to fit a legend that works with RWDI's comfort criteria, showing red as areas of high speeds.

Flow Visualization

Areas of interest determined from the computational model studies were further investigated and visualized using physical simulations including a water flume as well as a boundary layer wind tunnel. To visualize the flow, potassium permanganate dye was used in the water flume and smoke in the wind tunnel. The studies were performed using a model of a scale of 1:500 made out of high density foam. The use of the water flume and wind tunnel allowed greater control over the visualization medium and ease in switching from one area of interest to another.

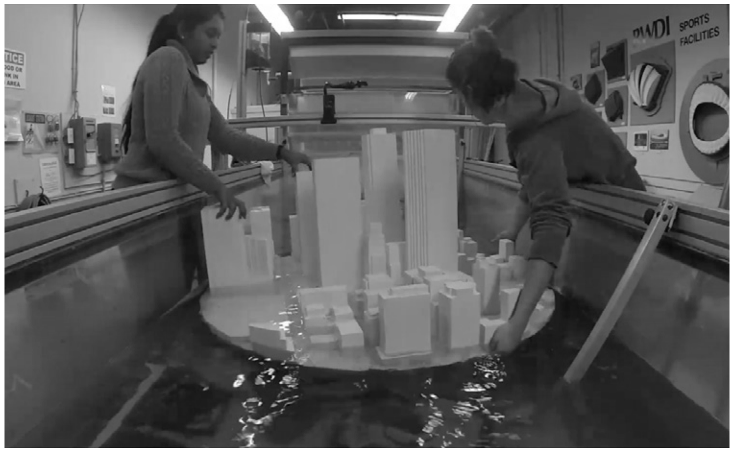
There were three methods of testing performed on the six configurations of the site. All were qualitative methods of testing, simply used to visualize and clarify the effects and areas of high speed winds outlined in the computational results.

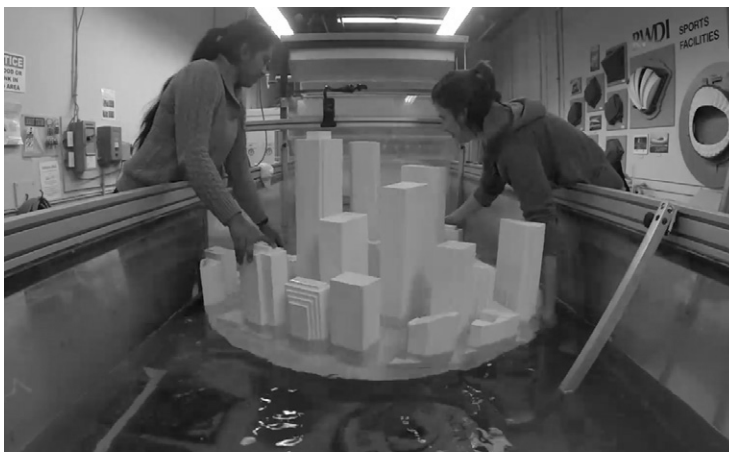
COMPUTATIONAL MODEL
FULL SCALE DIGITAL

WATER FLUME
1:500 PHYSICAL

WIND TUNNEL
1:500 PHYSICAL

FIGURE 4.8. Three Methods of Testing


SPORTS
FACILITIES


SPORTS
FACILITIES

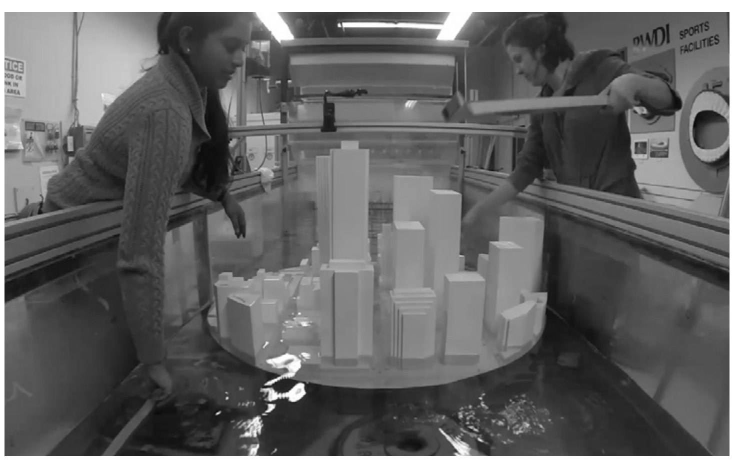

SPORTS
FACILITIES

FIGURE 4.9. Turning and Setting up the model in RWDI's Water Flume


RWDI
Rowan Williams
Davies & Irwin Inc.
Consulting Engineers


RWDI
Rowan Williams
Davies & Irwin Inc.
Consulting Engineers


RWDI
Rowan Williams
Davies & Irwin Inc.
Consulting Engineers

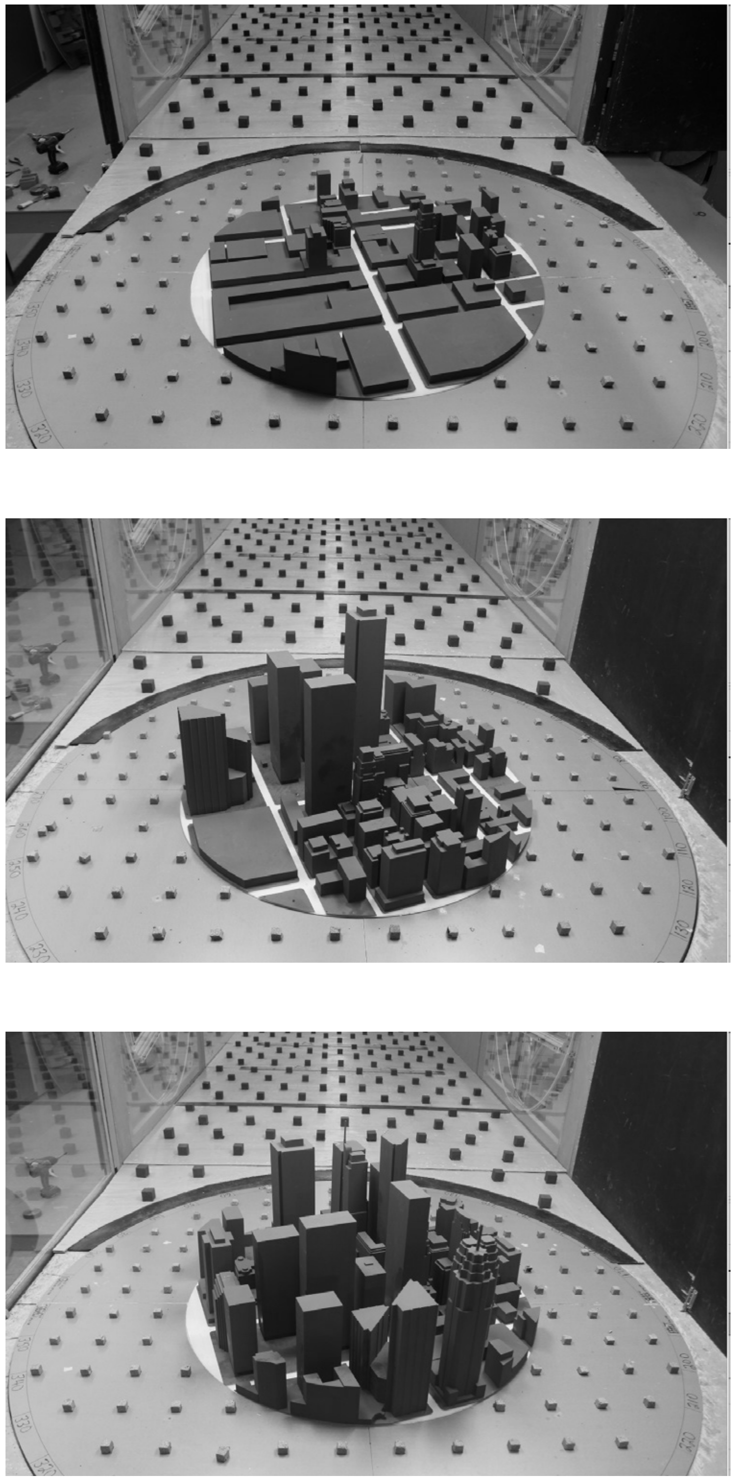


FIGURE 4.10. Turning and Setting up the model in RWDI's Wind Tunnel

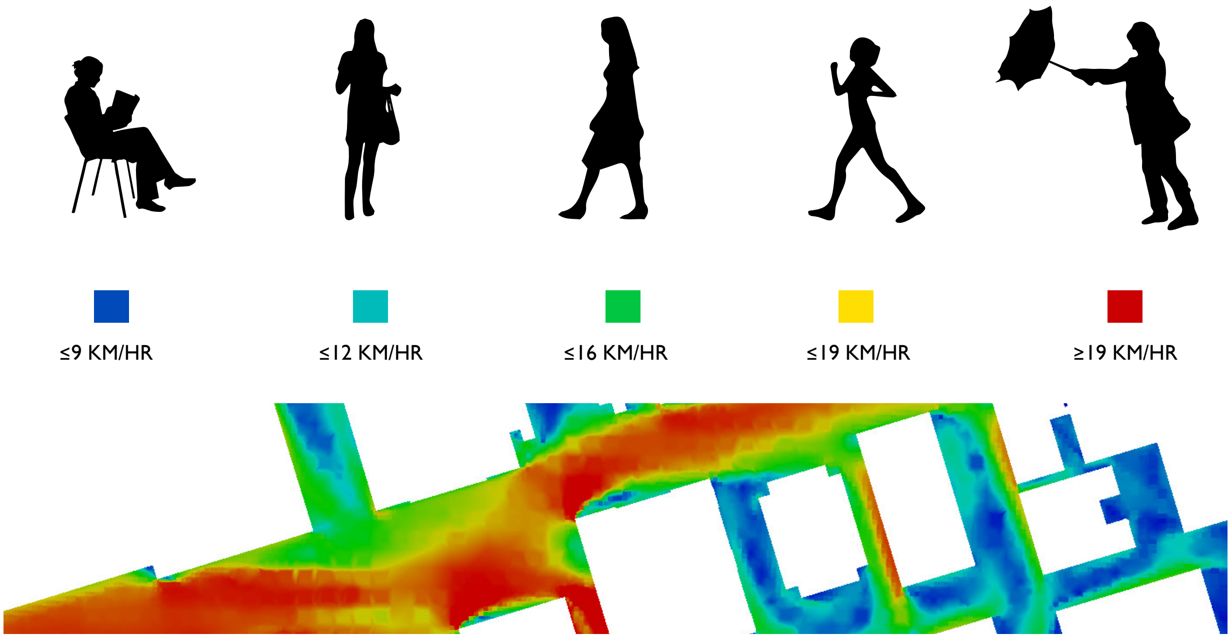
Details

The water flume used was 4 feet wide and is typically used to photograph sand deposits to determine snow and sand loading locations. The model was made out of a waterproof high density sign foam and each component was hollowed out to allow the water to seep in and keep the model submerged at the base of the tank. The height of the water reached only twenty inches so the taller buildings were not submerged. For a quantitative study, this would alter the results, but for a qualitative study of the pedestrian level, it was sufficient. A lighter coloured model produced clearer results with more contrast as the dye used to visualize the flow was a dark purple in color.

The final test was done within the wind tunnel using smoke from burning oil to visualize the flow. The length of the tunnel allowed the wind to gain the proper profile as it approached the test area. The same model used in the water flume was painted a dark color to allow the smoke to be visible. The wind tunnel was used to verify some areas that were unable to be seen in the flume. The videos collected from the tunnel were slowed down as the air in the tunnel moved much faster than the flow seen in the water flume.

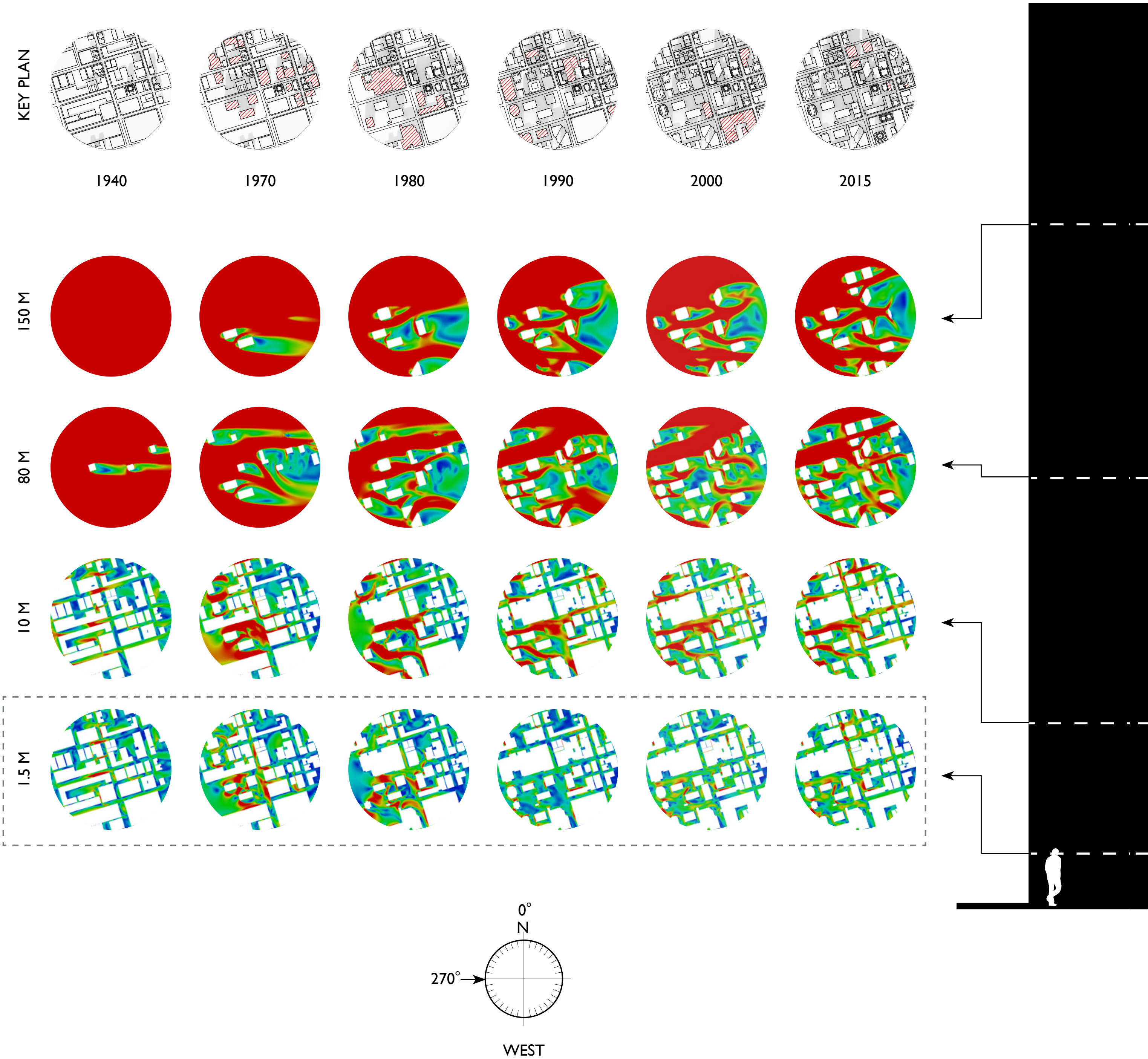
Calibration of Results

Initially, the computational wind simulations and analysis were conducted and then the results calibrated to demonstrate consistent color values. The results for the six development years and two wind directions simulated are presented in the form of contour plots with colors representing different ranges of speeds (FIGURE 4.11). The circular plots are centered on the intersection of King Street West and Bay Street. Areas of particular interest are discussed in the following sections. Where required for detailed inspection, images from the flow visualization experiments in the water flume and wind tunnel have been presented.



COMFORT CATEGORY	SPEED (KMH)	DESCRIPTION
SITTING	≤9	Calm or light breezes desired for outdoor restaurants and seating areas where one can read a paper without it blowing away
STANDING	≤12	Gentle breezes suitable for main building entrances and bus stops
STROLLING	≤ 16	Moderate winds that would be appropriate for window shopping and strolling along a downtown street, plaza or park
WALKING	≤19	Relatively high speeds that can be tolerated if one's objective is to walk, run or cycle without lingering
UNCOMFORTABLE	>19	Strong winds of this magnitude are considered a nuisance for most activities, and wind mitigation is typically recommended
SAFETY RISK	>90	Excessive gust speeds that can adversely affect a pedestrian's balance and footing. footing. Wind mitigation is typically required.

FIGURE 4.11. RWDI Comfort Criteria


KEY PLAN
1940
1970
1980
1990
2000
2015
150 M
80 M
10 M
1.5 M
0°
N
270°
WEST

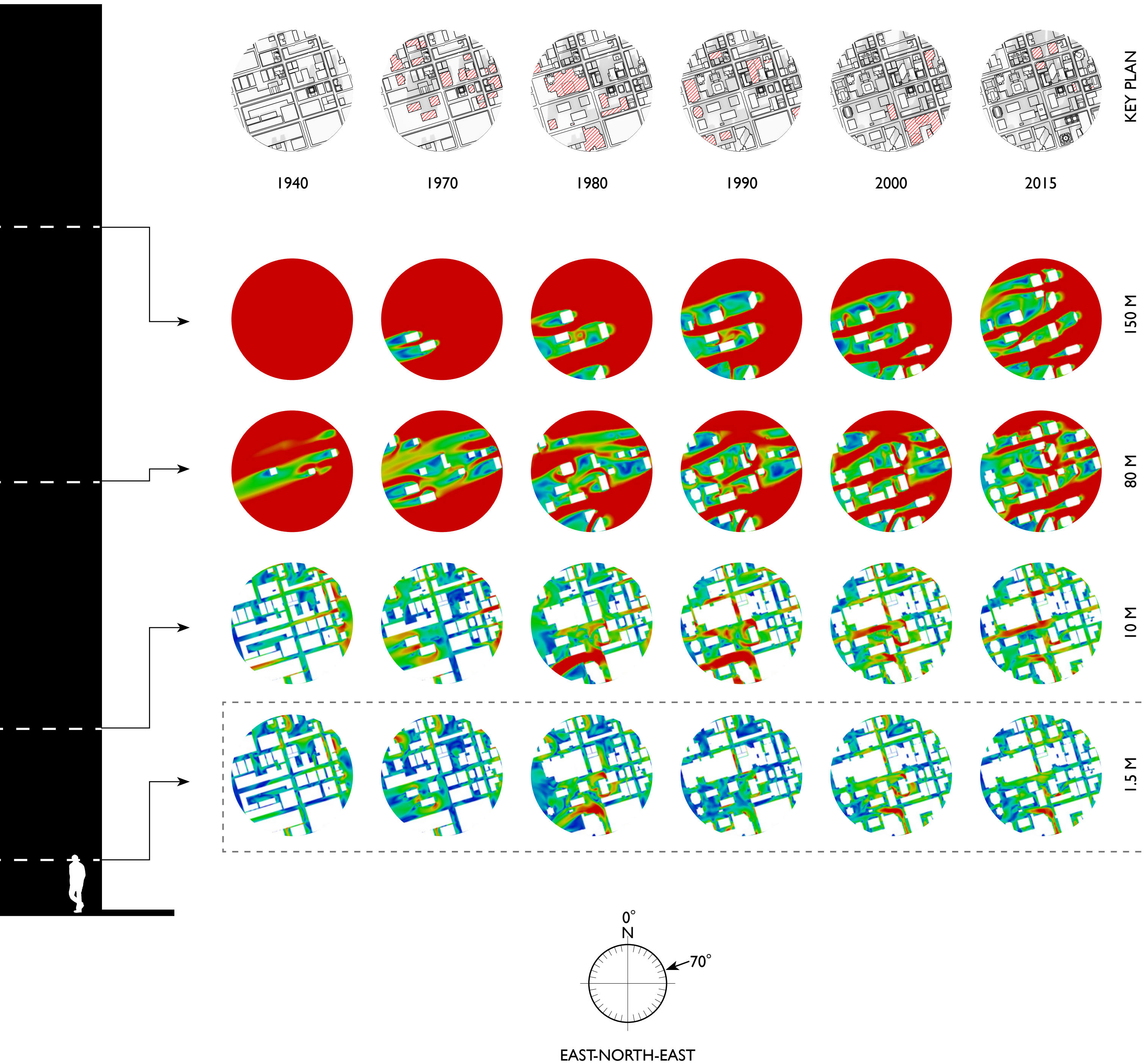
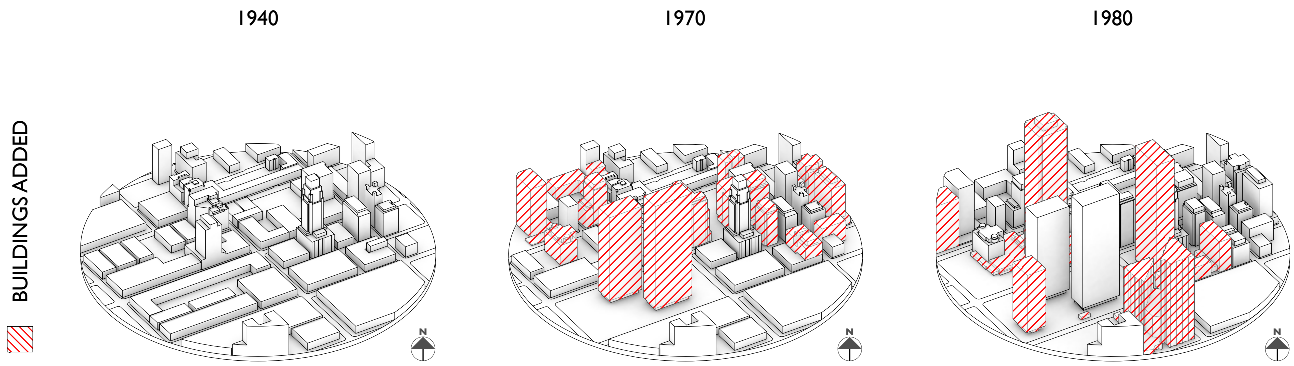


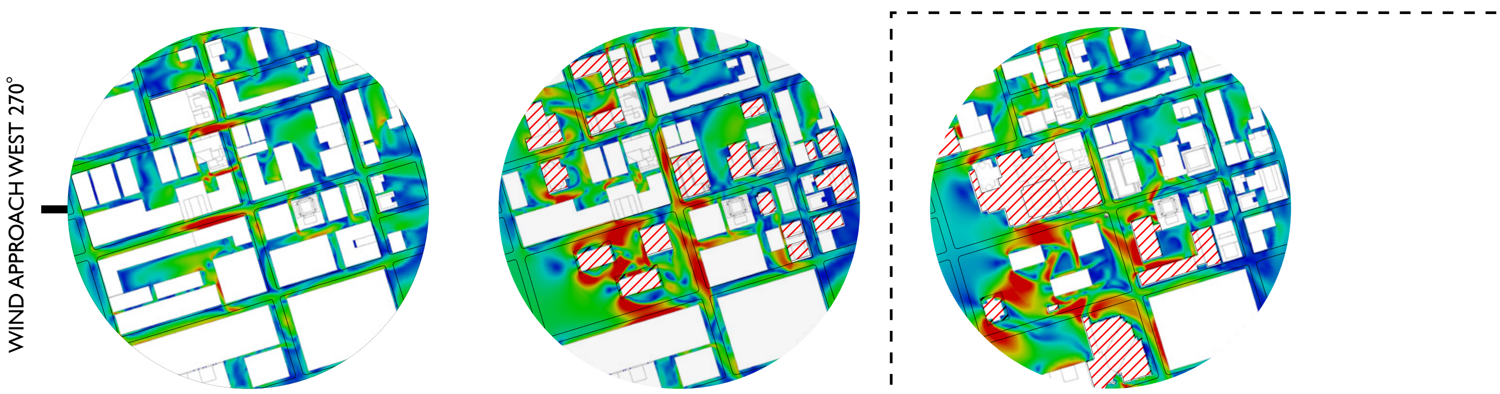
FIGURE 4.12. Computational Results Over the Years and at Different Elevations

RESULTS AND DISCUSSION

In a typical suburb, winds tend to flow over an even plateau of low-rise buildings. Winds seldom tend to be directed into the spaces between buildings because the areas are relatively evenly pressurized. When a tall building is added to relatively low surroundings, winds at high elevations that are stronger than speeds at lower elevations are intercepted by the tall buildings and redirected to ground level in a phenomenon called downwashing. Winds also tend to channel through the relatively narrow street canyons between tall buildings and accelerate around building corners, resulting in high wind activity in the area. Podiums are a common design feature of tall buildings; large setbacks at the base of towers on the podium are positive features in that they capture downwashed wind flows and protect ground level areas from strong wind activity. These are some of the common wind flow patterns resulting from building-wind interactions and are of importance in the following discussion.

FIGURE 4.13. Scotiabank Tower Canopy

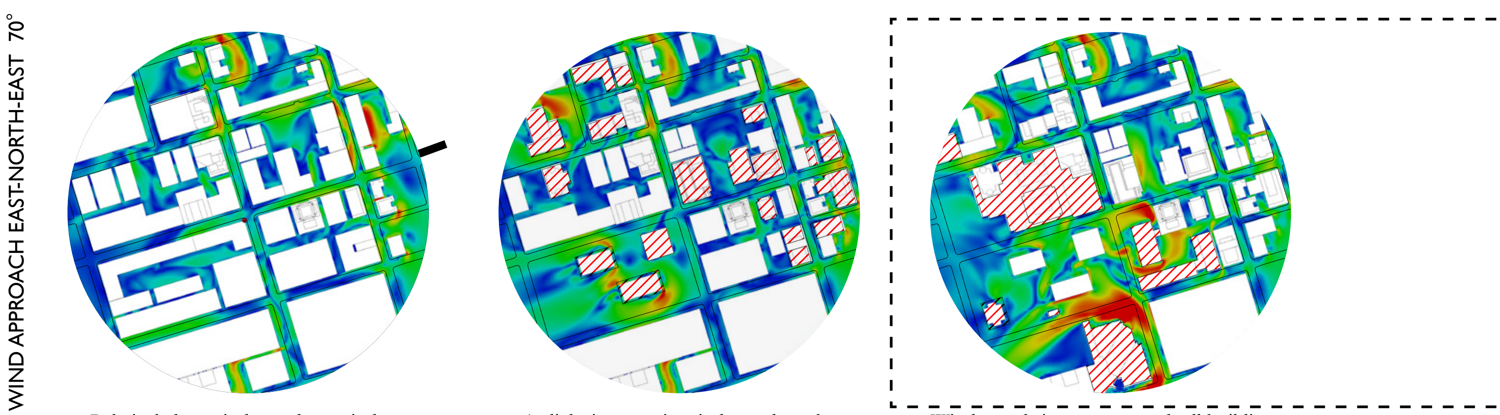




High wind speeds near taller buildings.

Wind speeds increase around tall buildings constructed.

Wind speeds continue to increase around tall buildings constructed.



Relatively low wind speeds as winds are travelling parallel to street orientation.

A slight increase in wind speed can be found around the edges of the tall buildings constructed.

Wind speeds increase around tall buildings added.

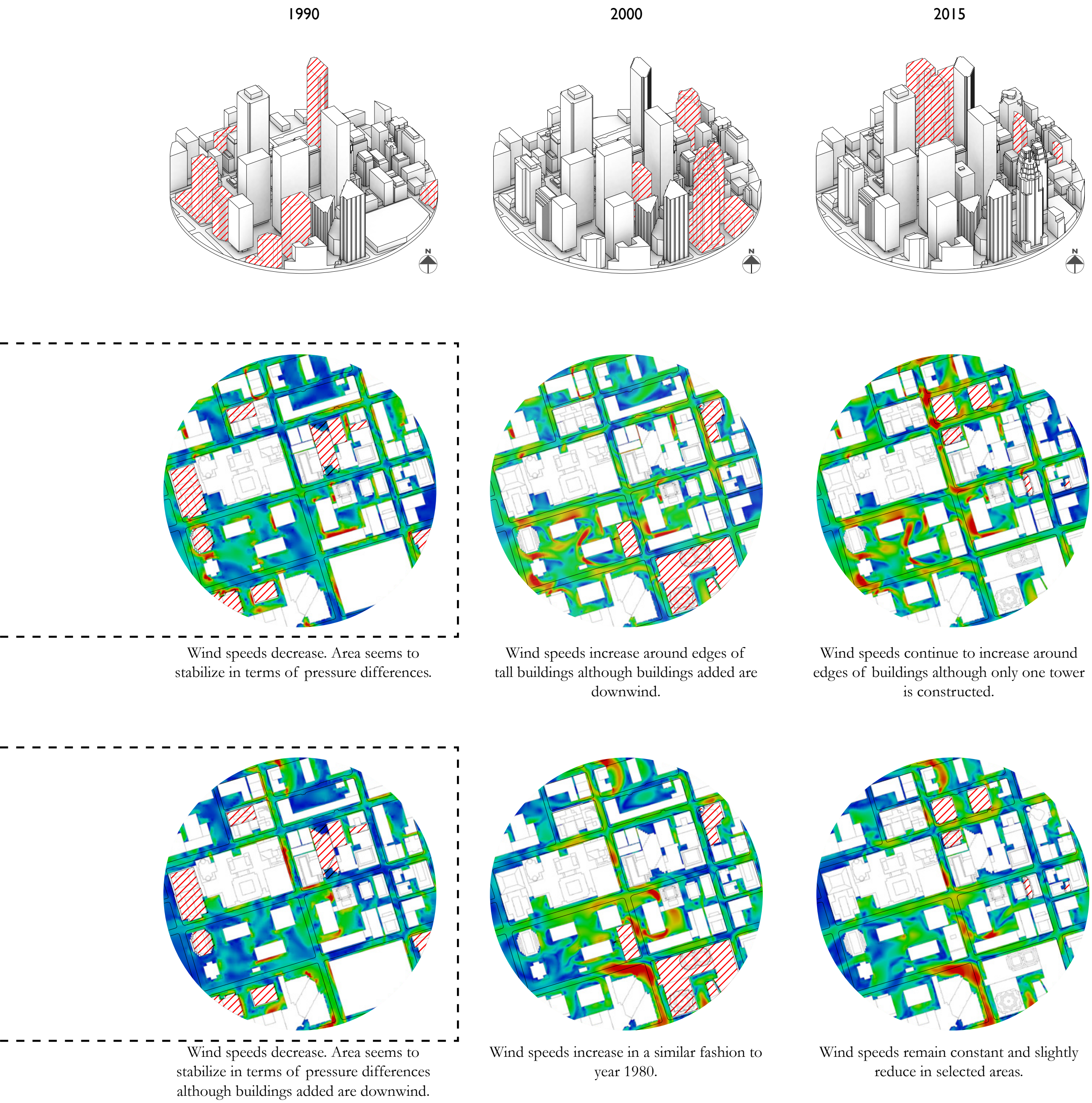
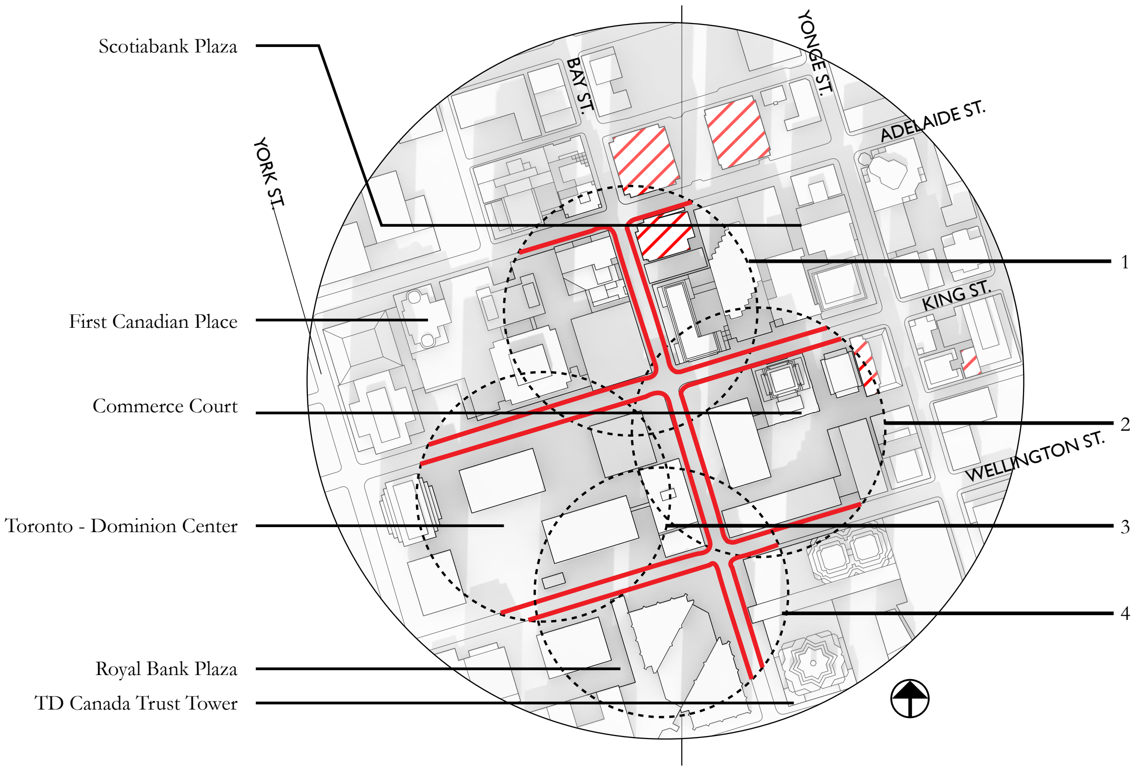


FIGURE 4.14. Pedestrian Level Winds Flows Shown through Virtual Wind Simulation (East and West Directions)

Focus Areas

Before the major high-rise development began in the study area, wind speeds were low in the majority of the area around the King and Bay intersection (blue and green zones in FIGURE 4.14, 1940). As taller buildings were added in subsequent years, as expected, wind activity at pedestrian level began to increase, as indicated by the growing red zones in FIGURE 4.14. Based on the evolution of wind flow patterns, four main areas of the study region were investigated further – the Northern corridor between First Canadian Place and Scotia Plaza; the Eastern and Southern corridor and the adjacent Commerce Complex; the West corridor housing the Dominion Center towers; and the lower South corridor of the Royal Bank Plaza.

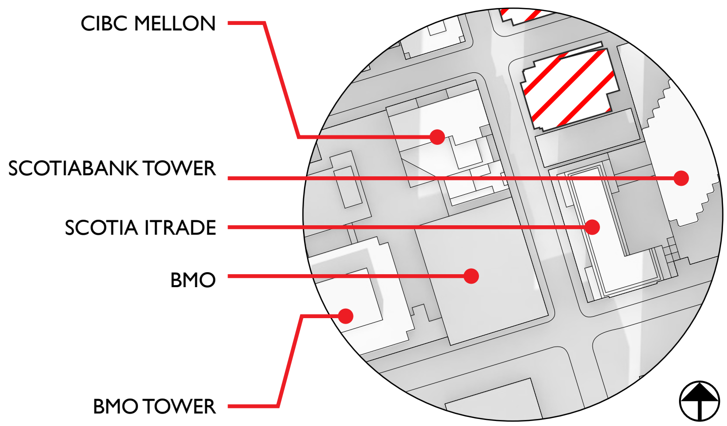
The focus areas will describe a particular effect evident in the area during a selected number of years for only one direction of wind. Following the specific exploration will be an overview of the effects over all study years in both West and East-North-East directions.



FOCUS AREAS
1. NORTH CORRIDOR - FIRST CANADIAN PLACE AND SCOTIA PLAZA
2. EAST AND SOUTH CORRIDOR - COMMERCE COMPLEX
3. WEST CORRIDOR - DOMINION CENTER
4. LOWER SOUTH CORRIDOR - ROYAL BANK PLAZA

FIGURE 4.15. Focus Areas

1. North Corridor



As seen in the overall results (FIGURE 4.14, 1940) the majority of the buildings around the intersection are low-rise, with one mid-rise tower to the west of the intersection and a few about a block away to the north and east. While wind speeds appear generally low (blue and green zones in FIGURE 4.14, 1940), higher wind activity can be observed near the mid-rise towers (red and yellow zones). Winds from the west approach and wash down and accelerate around CIBC Mellon and flow into the southern alleyway (red streak seen in the CFD results in FIGURE 4.16, 1940). In 1970 the newly added Scotia iTRADE building intercepts and redirects west winds down to street level. Prior to the addition of the building, winds would flow through the site. However, in 1970, the pressure differential created by the Scotia iTRADE building re-routes the downwashed winds around the building, creating high wind zones on Bay Street (red zones in FIGURE 4.16, 1970). The flow splits and increases in speed in both North and South directions on Bay street as seen in the stills from the tests in the water flume in FIGURE 4.16. (In 1980, the BMO complex is added and the wind speeds on Bay Street reduce significantly because the west winds are deflected to the roof of the BMO podium, upwind of the Scotia iTRADE building. These flows can be seen in FIGURE 4.16, 1980. This area continues to improve in 1990, however in 2000 and 2015 some corner acceleration occurs once again as tall towers constructed north of the area divert winds down as seen in FIGURE 4.14. FIGURE 4.17 and FIGURE 4.18 on the following pages include the overall development of winds in these areas in both directions of wind approach.

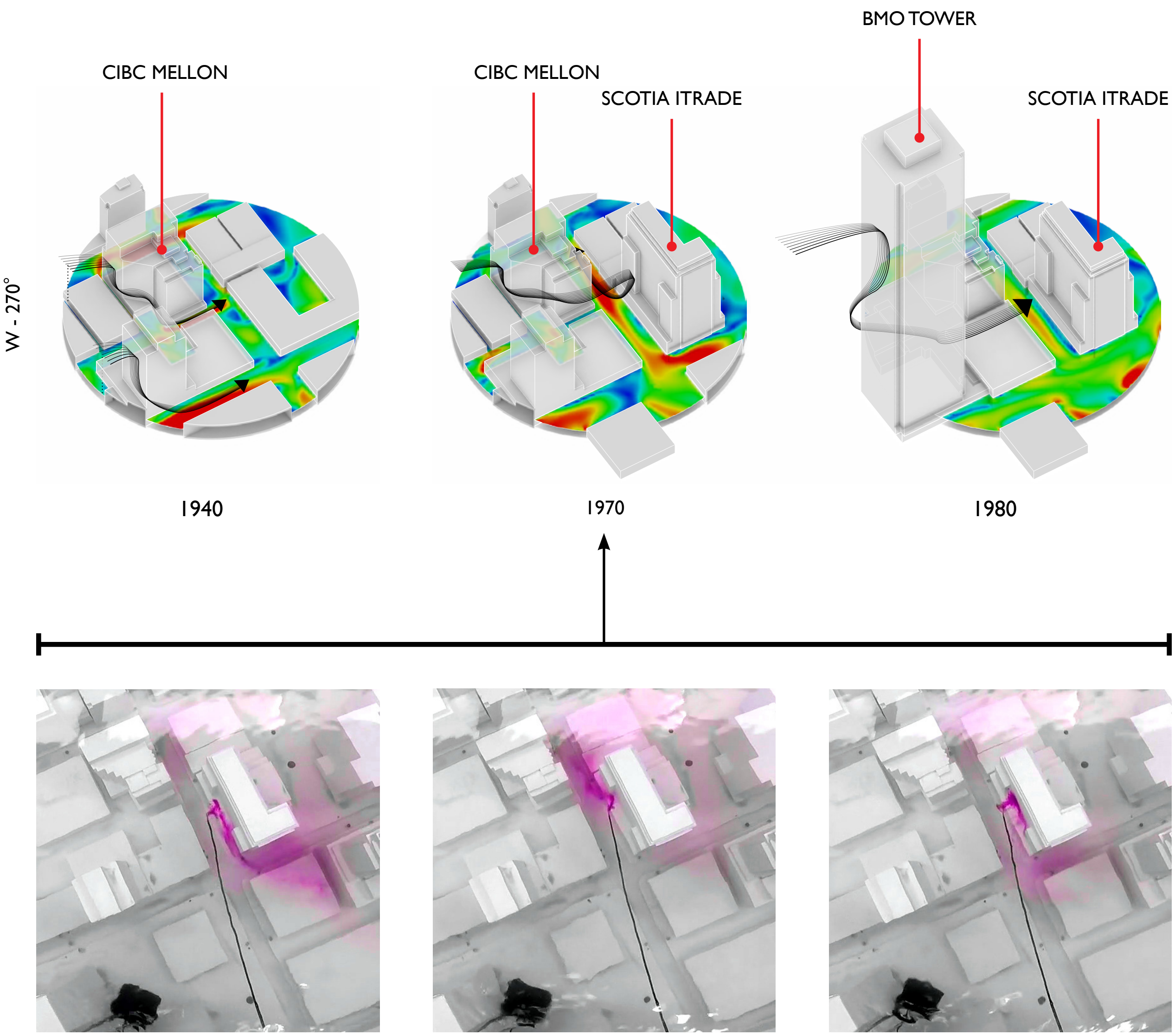
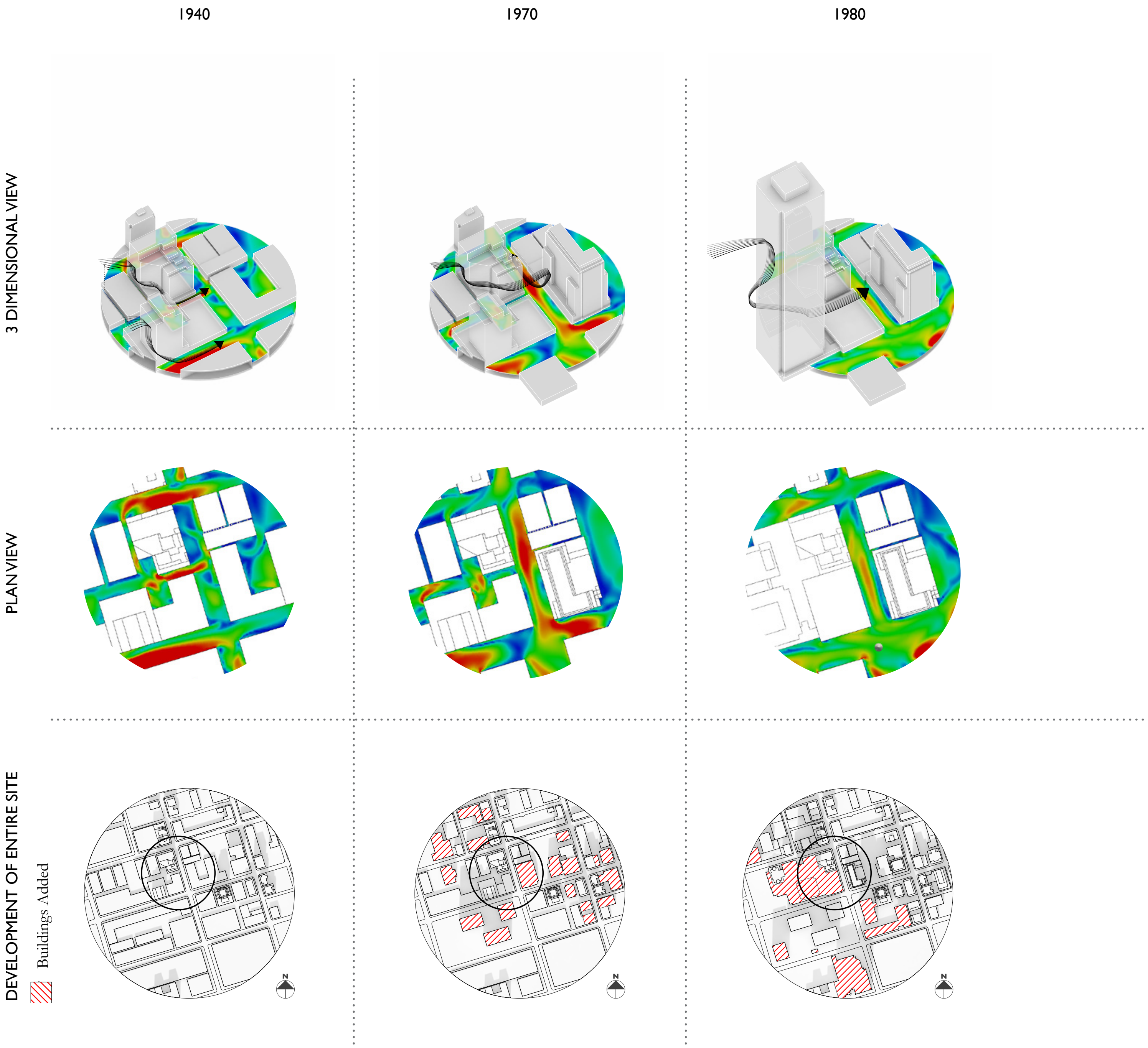
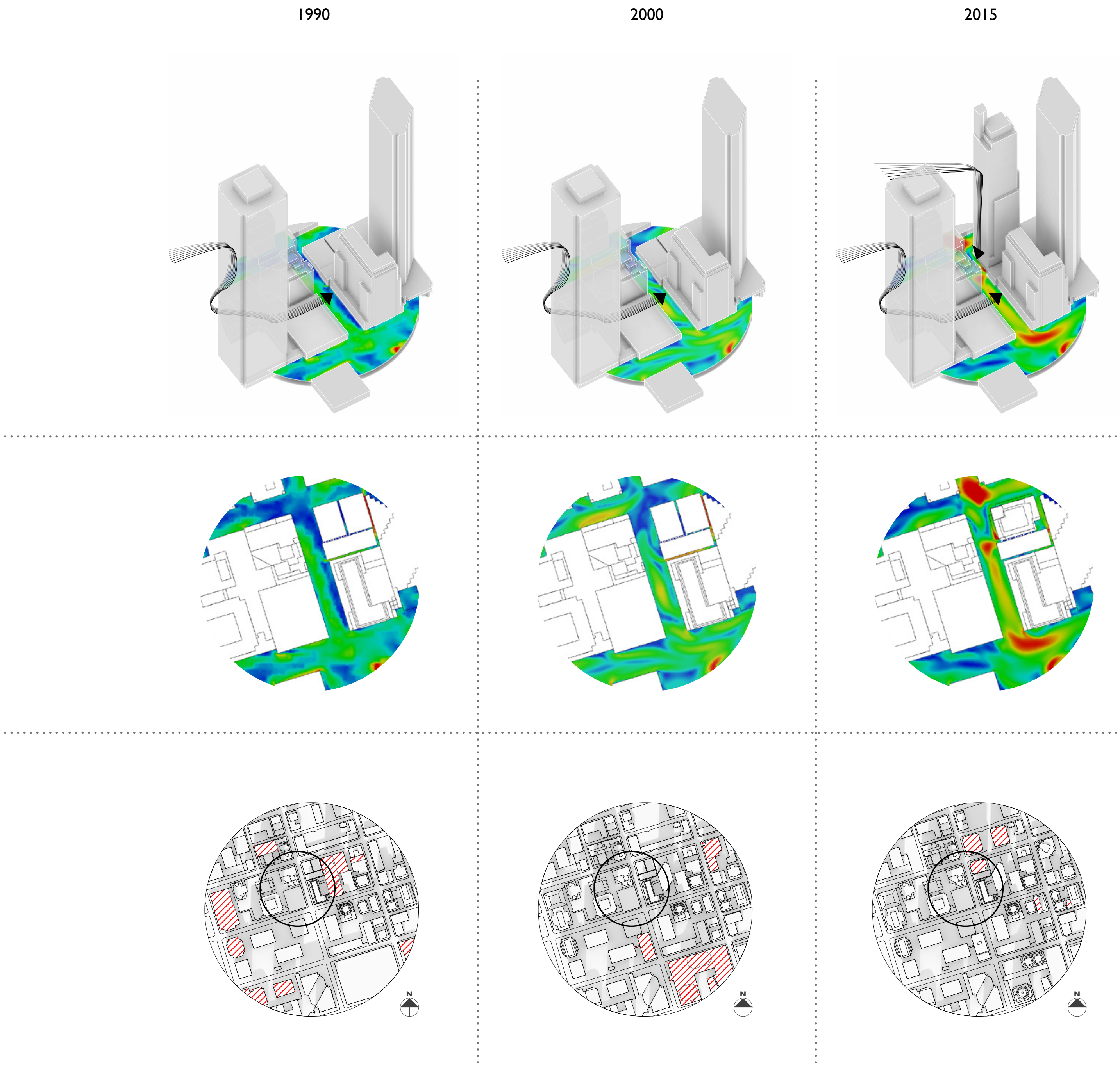


FIGURE 4.16. Downwashing and Channeling, Images from Water Flume


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N
N
N



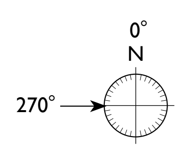
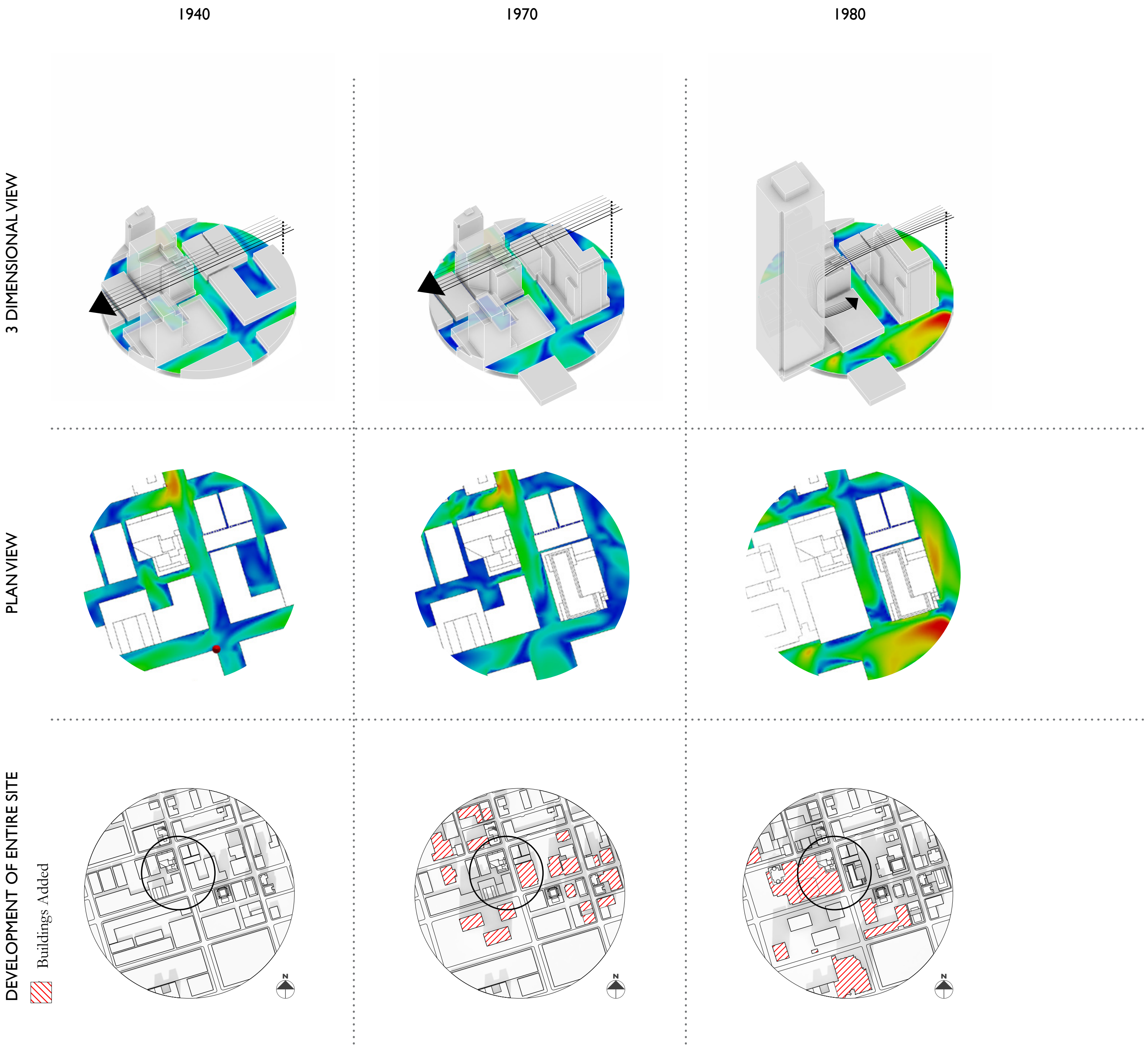


FIGURE 4.17. Study Area 01 - West Wind Approach


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N
N
N

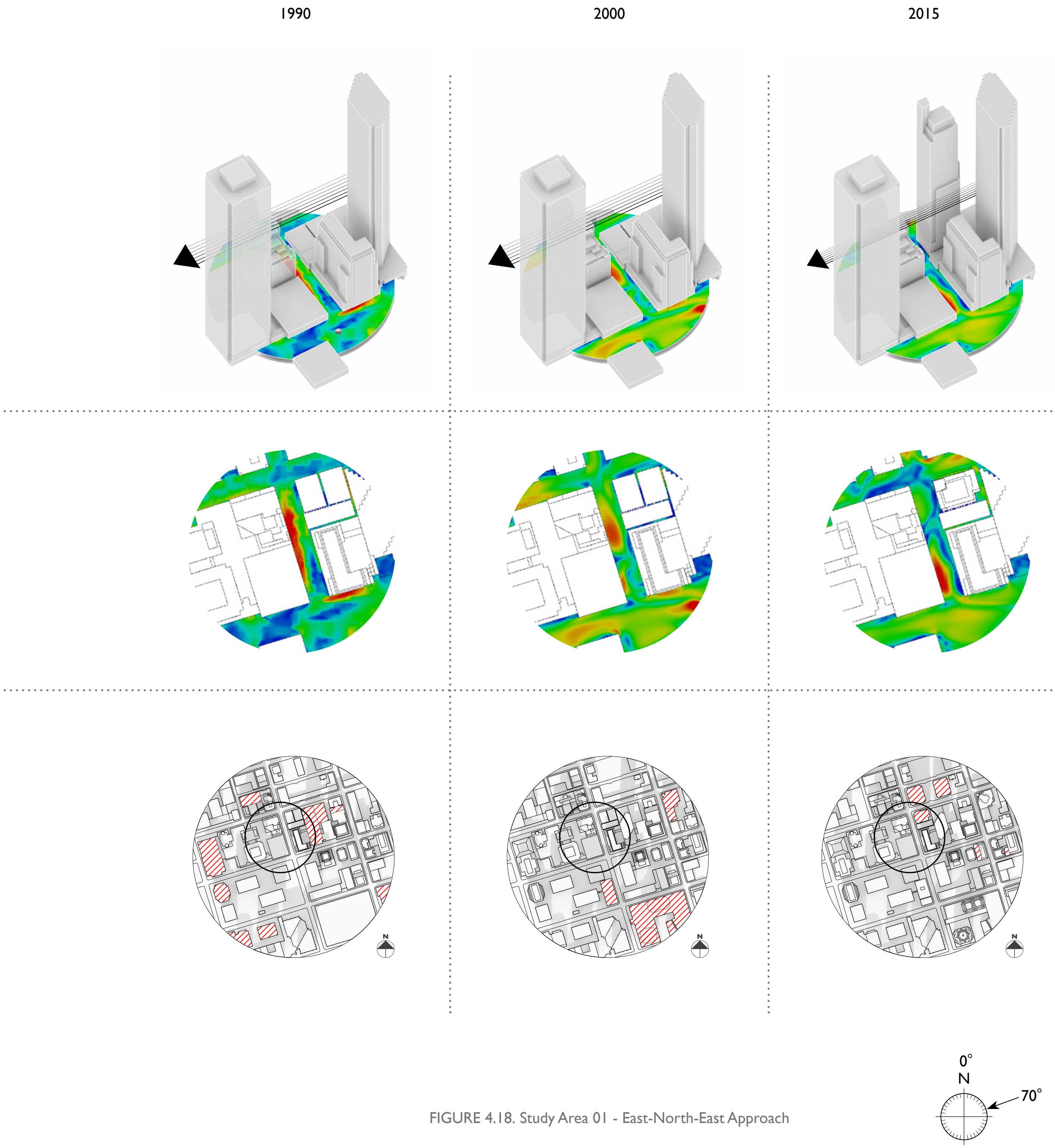
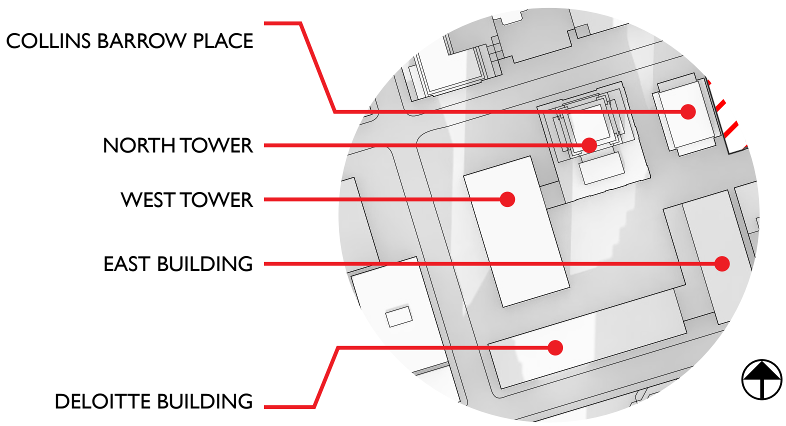


FIGURE 4.18. Study Area 01 - East-North-East Approach

2. East and South Corridor



In 1940, when the buildings in the area are all low-rise with the exception of the north tower, wind speeds appear low (blue and green zones in FIGURE 4.14). In 1980 the west tower is constructed and is exposed to east-northeasterly winds. First these winds accelerate and wash down the exposed eastern façade and then accelerate into the alley between the West Tower and Deloitte building, resulting in a large area of high wind activity that potentially disrupted the comfort of the southern corridor and adjacent alleyway (red zones in the CFD results in FIGURE 4.19, 1980). After the alley, these winds rush into the wake on the leeward side of the building. This results in a vortex system in the wake zone (red area in wake seen in FIGURE 4.19, 1980). This vortex effect can be seen in more detail in the stills from the water flume test in FIGURE 4.19. In 1990 this vortex system is reduced, although only buildings outside of the selected east-south boundary are added. As more towers are added in the following years and the city densifies, the high wind accelerations in this area seem to increase once again (see red zones in FIGURE 4.14, 2000 and 2015). In FIGURE 4.14 it can be seen that downwashing and corner acceleration also are generated from the addition of the West tower in relation to the westerly winds. Similar to the east-northeasterly winds, the west winds also improve in 1990 and worsen in 2000 and 2015. FIGURE 4.20 and FIGURE 4.21 on the following pages include the overall development of winds in these areas in both directions of wind approach.

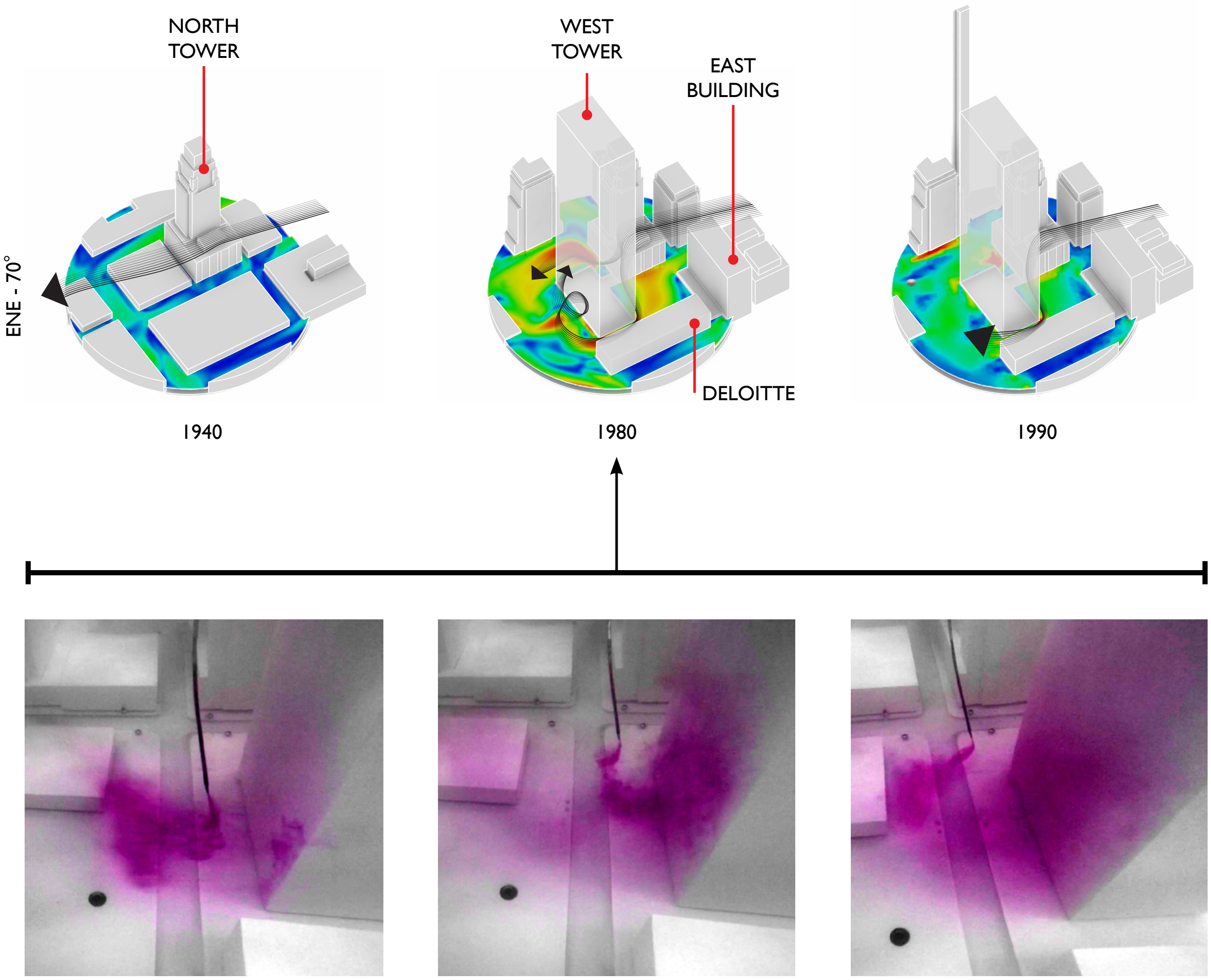
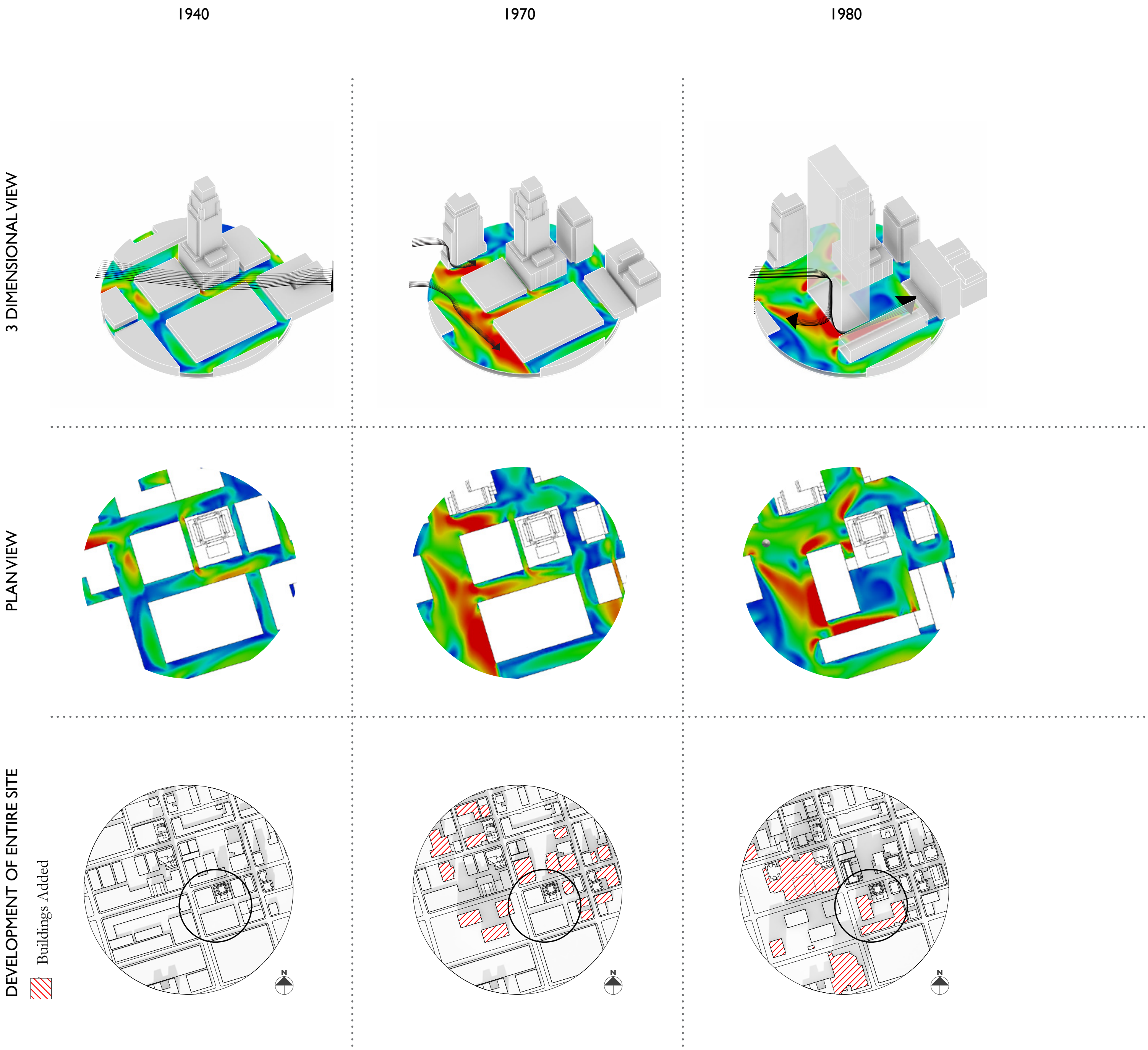


FIGURE 4.19. Corner Acceleration and Vortex System, Images from Water Flume


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N
N
N

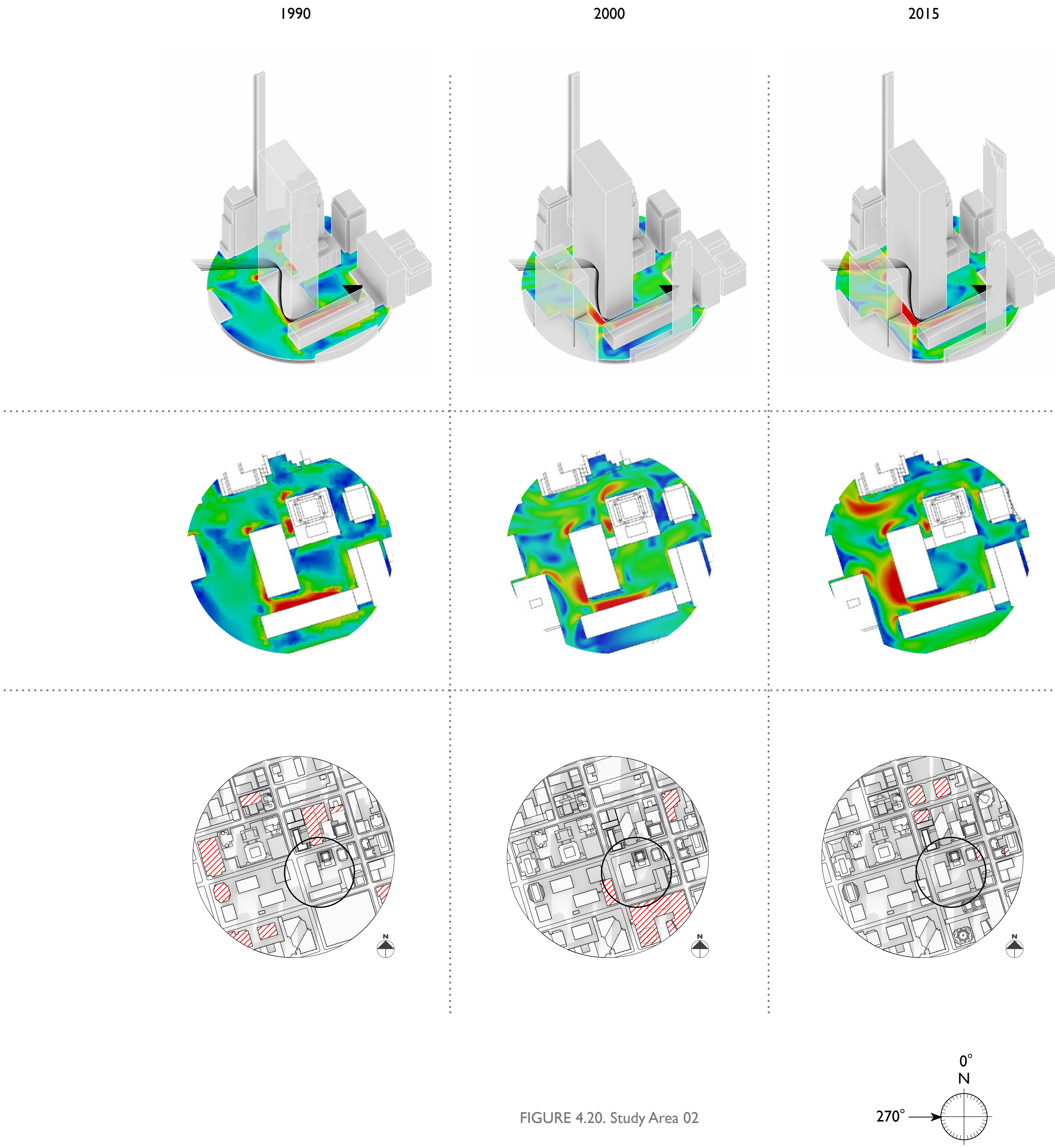
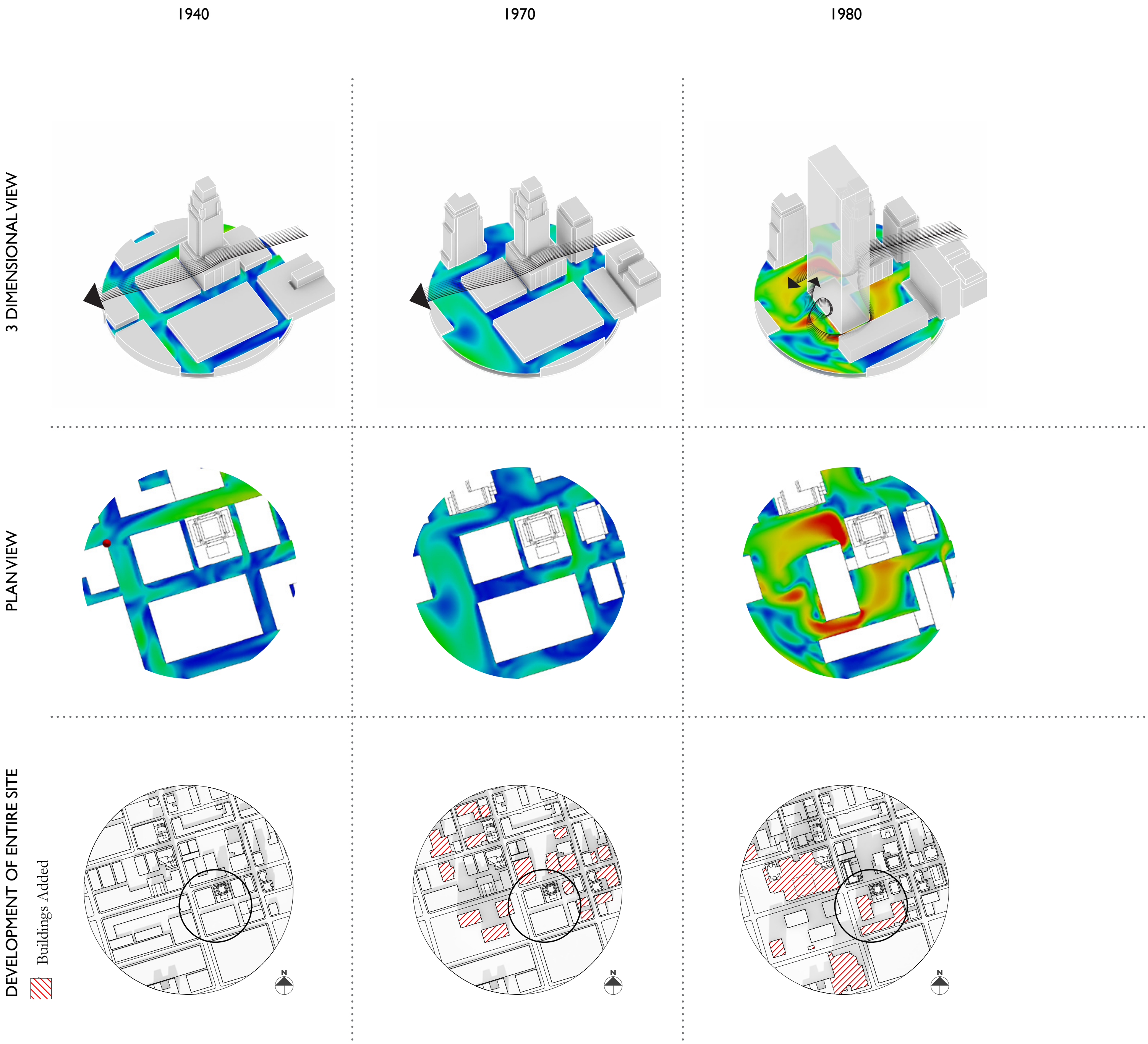


FIGURE 4.20. Study Area 02


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N

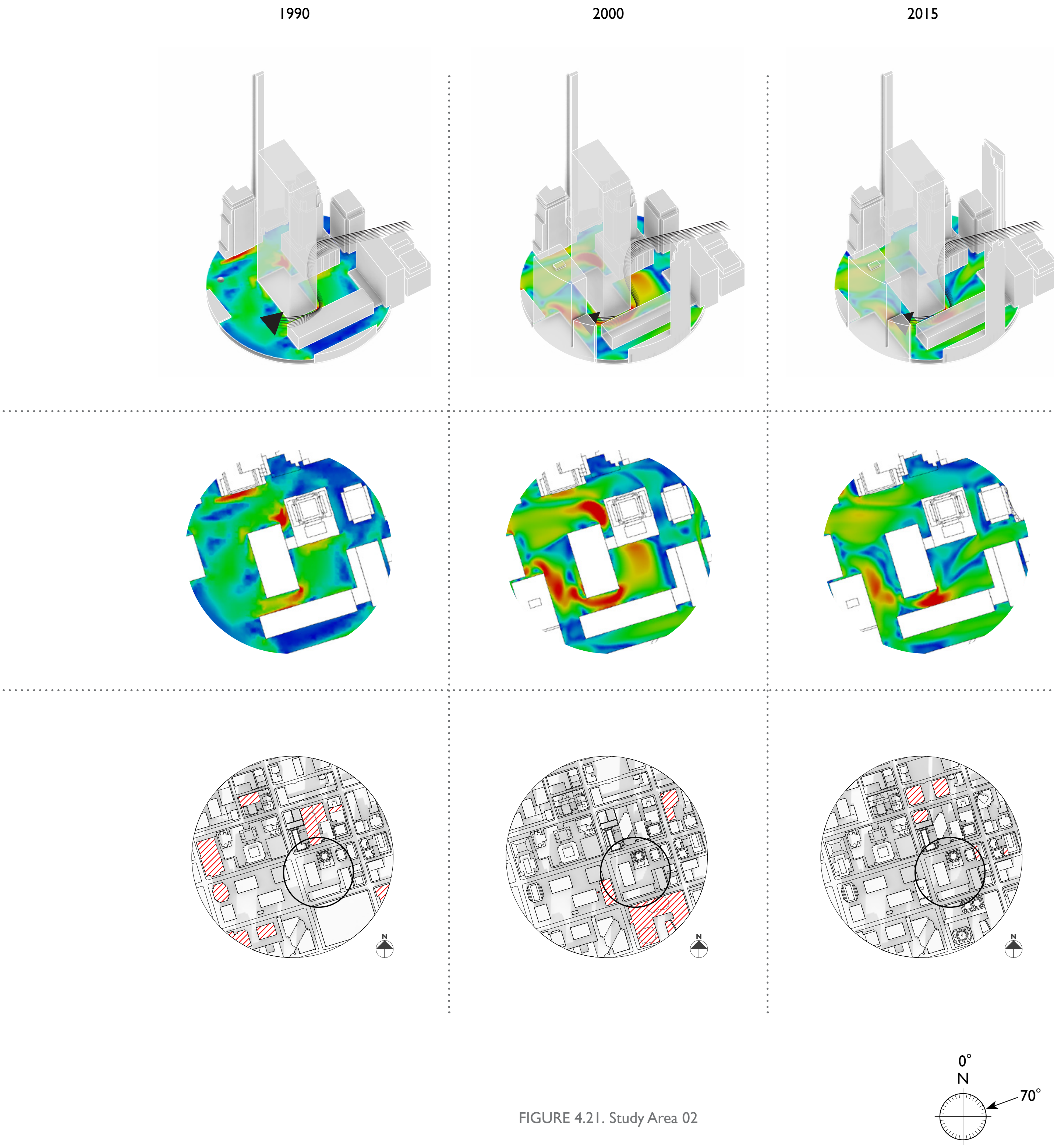
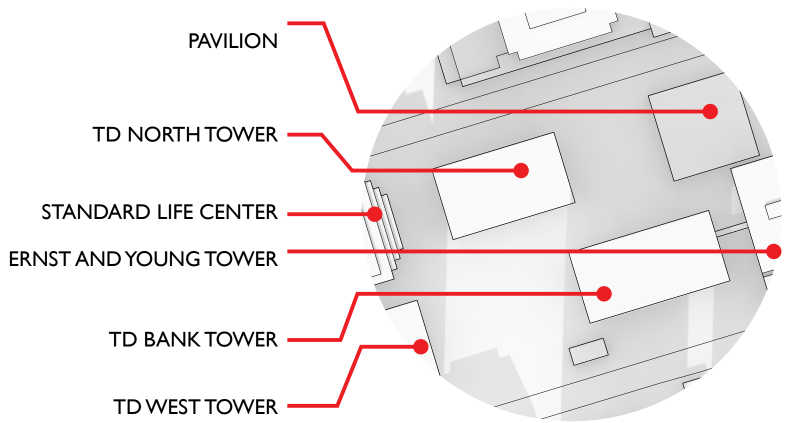


FIGURE 4.21. Study Area 02

3. West Corridor



In 1940, when the buildings in the area are all low-rise, wind speeds are low (blue and green zones in FIGURE 4.14). Between 1940 and 1970 buildings are demolished and a large area in the West Corridor was opened up for new construction. In 1970, while three tall towers – TD North, TD Bank and Ernst and Young Tower, collectively known as the Dominion Centre Towers – are added in the area, without many buildings nearby to the west, the towers are exposed to the strong westerly winds. However, winds accelerate around the exposed western façade and corners and channel in between the closely spaced towers, resulting in a large area of high wind activity that potentially disrupted the comfort of the public square (red zones in the CFD results in FIGURE 4.22, 1970). The stills from the wind tunnel in FIGURE 4.22 show how in 1970 the flows are channelled between the two buildings as they accelerate around the corners of the buildings. This remains constant until 1990 when the TD West Tower is constructed upwind of the area, in addition to other buildings outside of the selected West Corridor boundary. The newer buildings upwind slow westerly winds approaching the study area and thereby, wind conditions are seen to improve in 1990. As more towers are added in the following years and the city densifies, newer areas of high wind accelerations can be observed, but they remain localized around the tower bases (see red zones in FIGURE 4.14, 2000 and 2015). FIGURE 4.23 and FIGURE 4.24 on the following pages include the overall development of winds in these areas in both directions of wind approach.

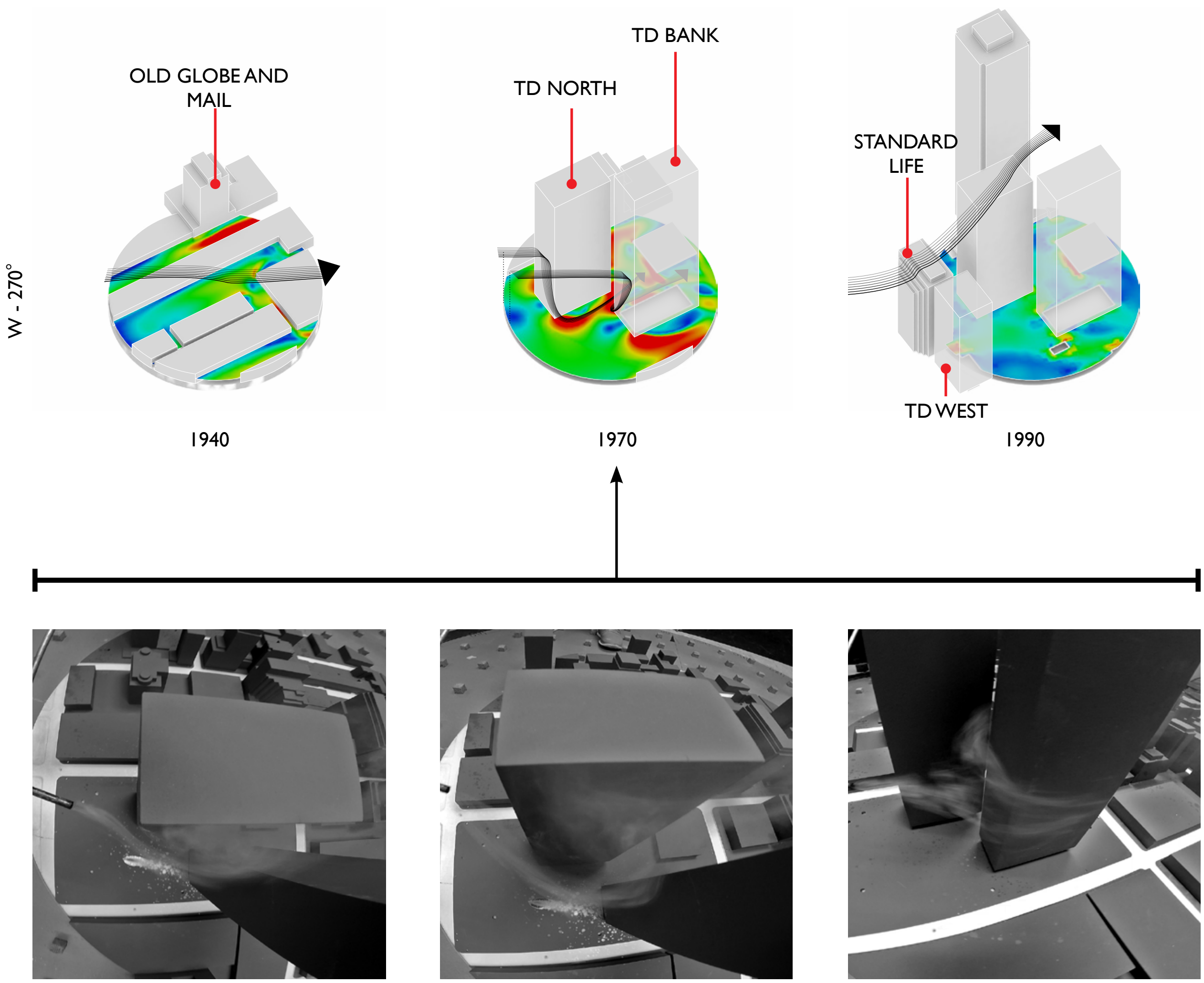
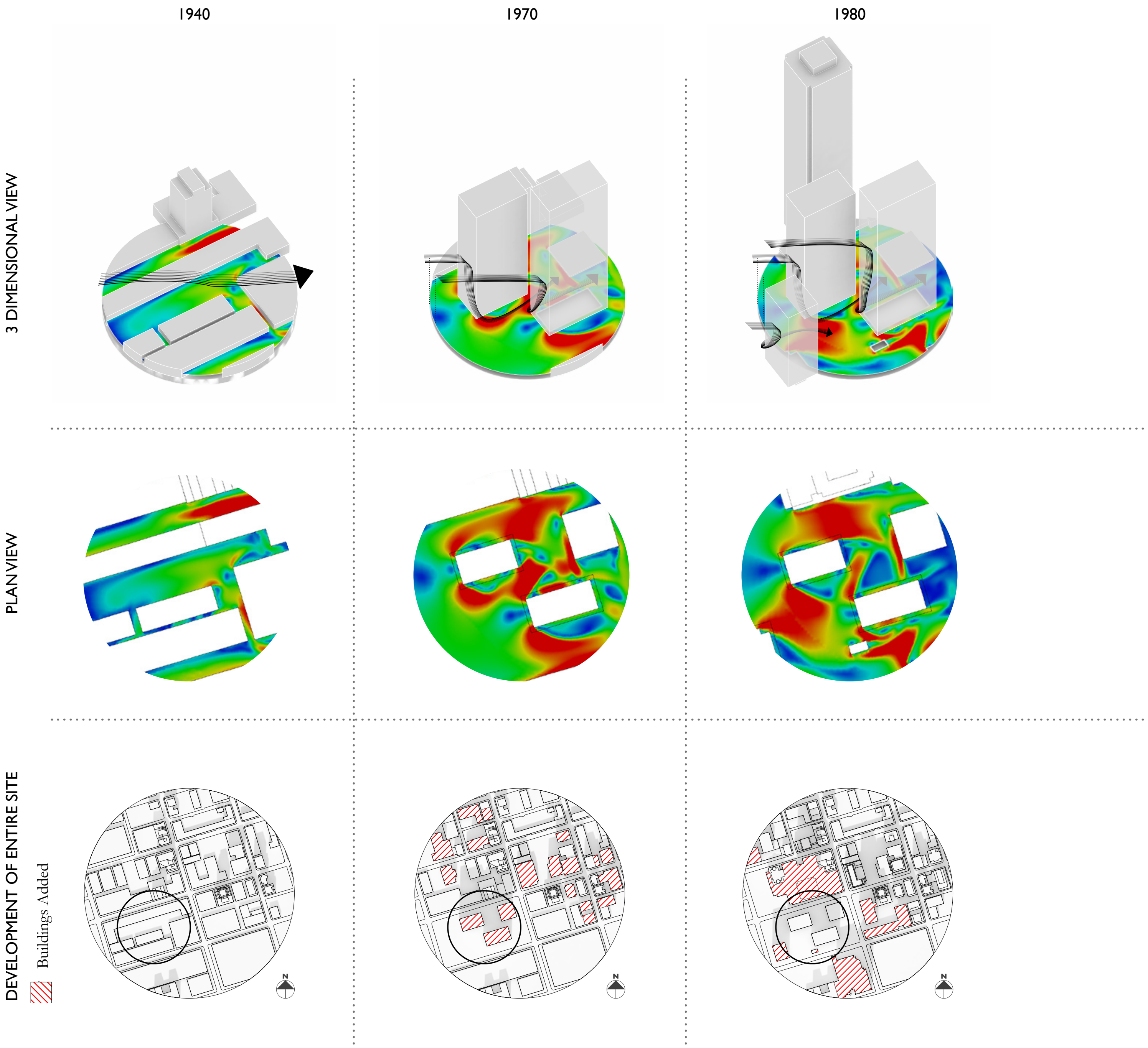


FIGURE 4.22. Channeling and Corner Acceleration, Images from Wind Tunnel


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N

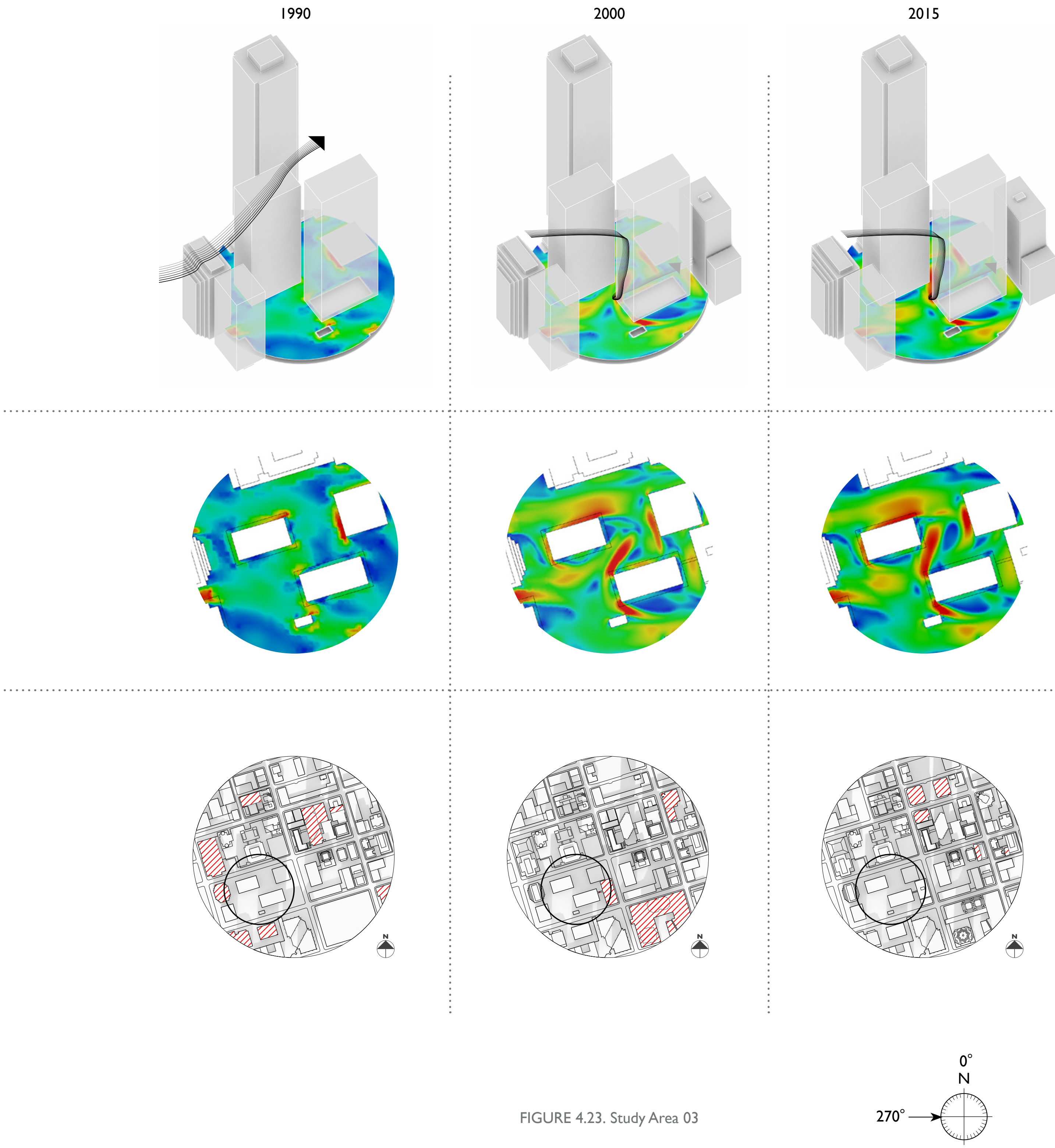
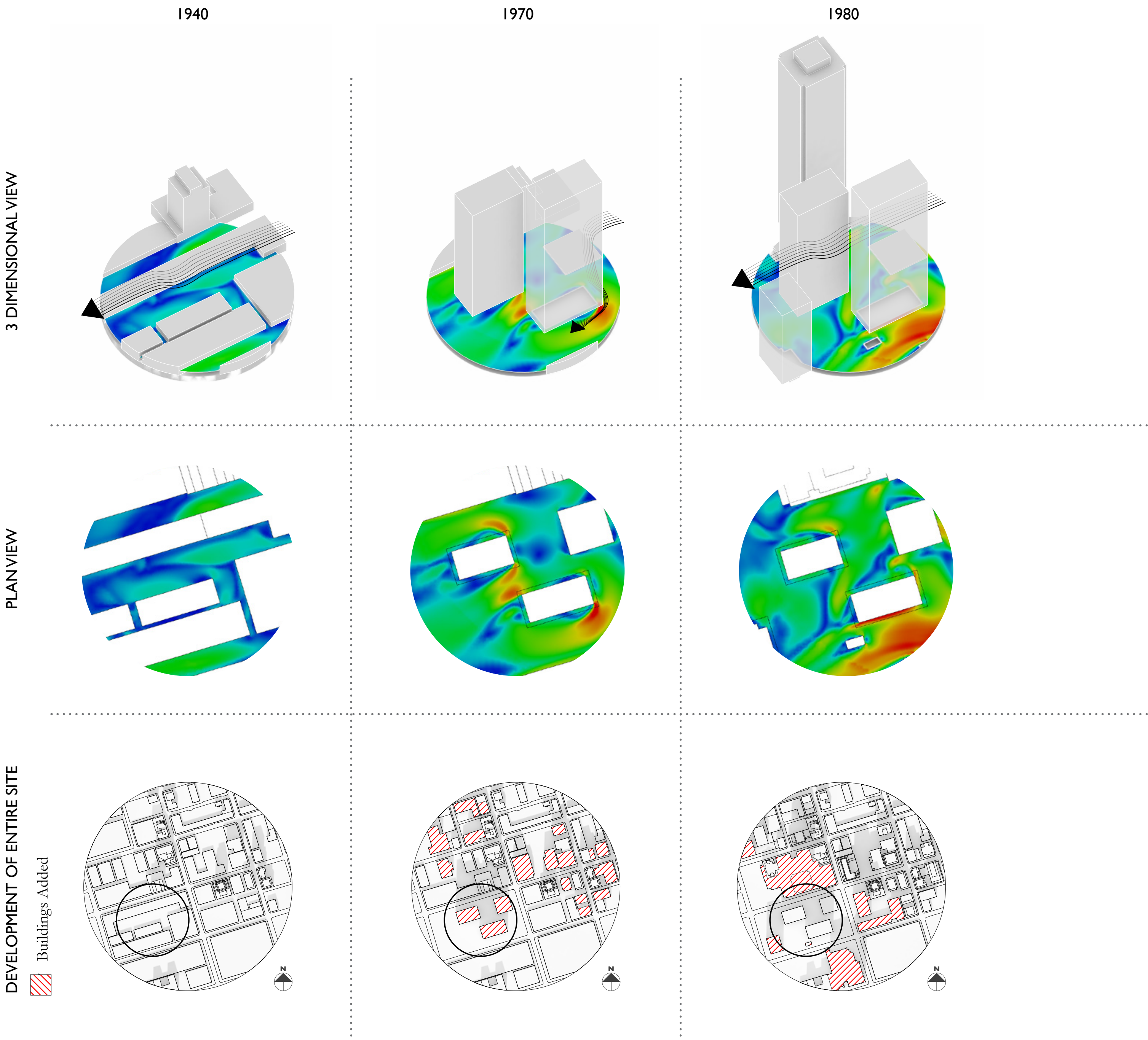


FIGURE 4.23. Study Area 03


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N
N
N

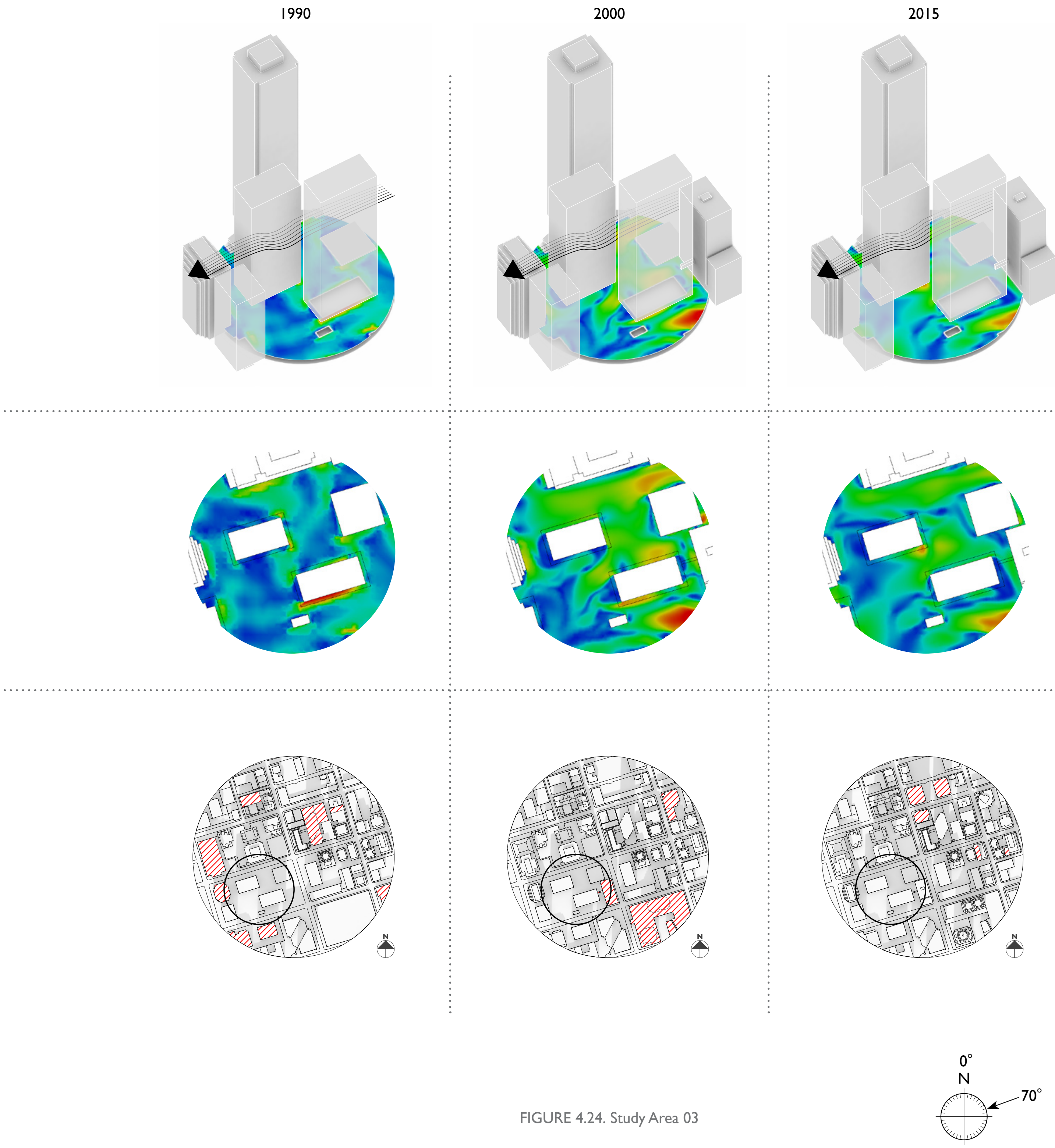
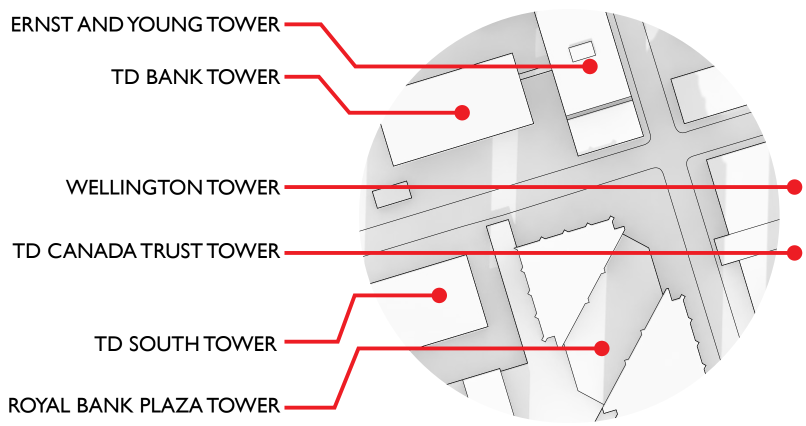


FIGURE 4.24. Study Area 03

4. Lower South Corridor



In 1970, when the buildings in the area were all low-rise, wind speeds were low (blue and green zones in FIGURE 4.14, ENE). In 1980, when the TD Bank tower was constructed, the winds with no obstruction prior to this, wash down and accelerate with great speed into the street corridor (red zone FIGURE 4.25, 1980). In 1990, the TD South Tower is constructed, reducing negative pressures downwind of the Royal Bank Plaza Tower caused by the east-north-easterly winds in 1980. This addition, significantly reduces the suction occurring, therefore wind speeds are reduced (as seen in the CFD results of FIGURE 4.25, 1990). However, in 2000 the Ernst and Young Tower is constructed across the street and the Wellington Tower and Canada Trust Tower are constructed upwind. This construction encourages high speed winds to wash down into the street corridor once again, creating seemingly uncomfortable conditions (FIGURE 4.25, 2000). In the stills from the water flume in FIGURE 4.25, the flows coming from the ENE can be seen to strongly accelerate and channel into the street around the Royal Bank Plaza Tower. The area of high speed winds coverage remains consistent well into 2015 (FIGURE 4.14, ENE, 2015). FIGURE 4.26 and FIGURE 4.27 on the following pages include the overall development of winds in these areas in both directions of wind approach.

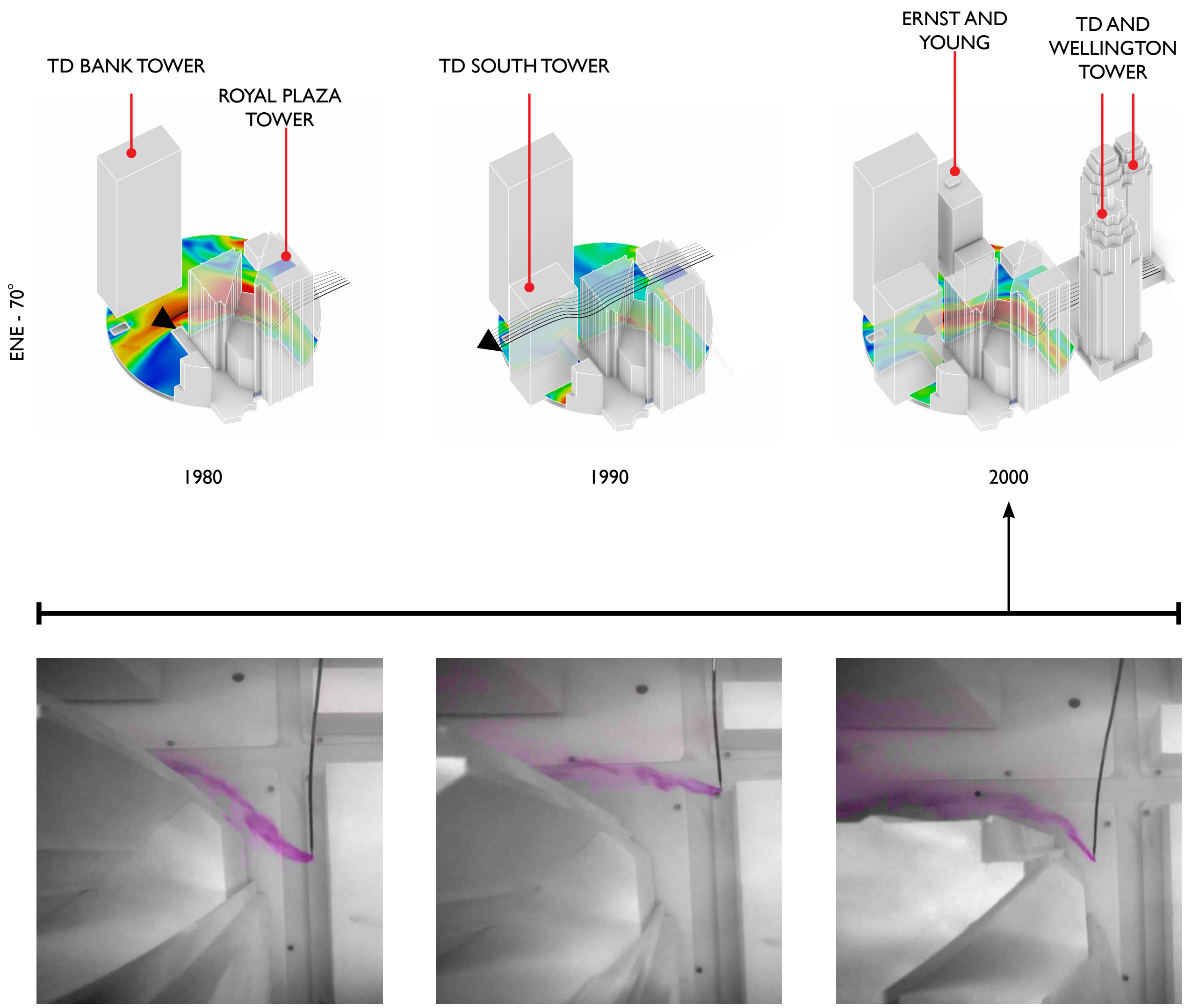
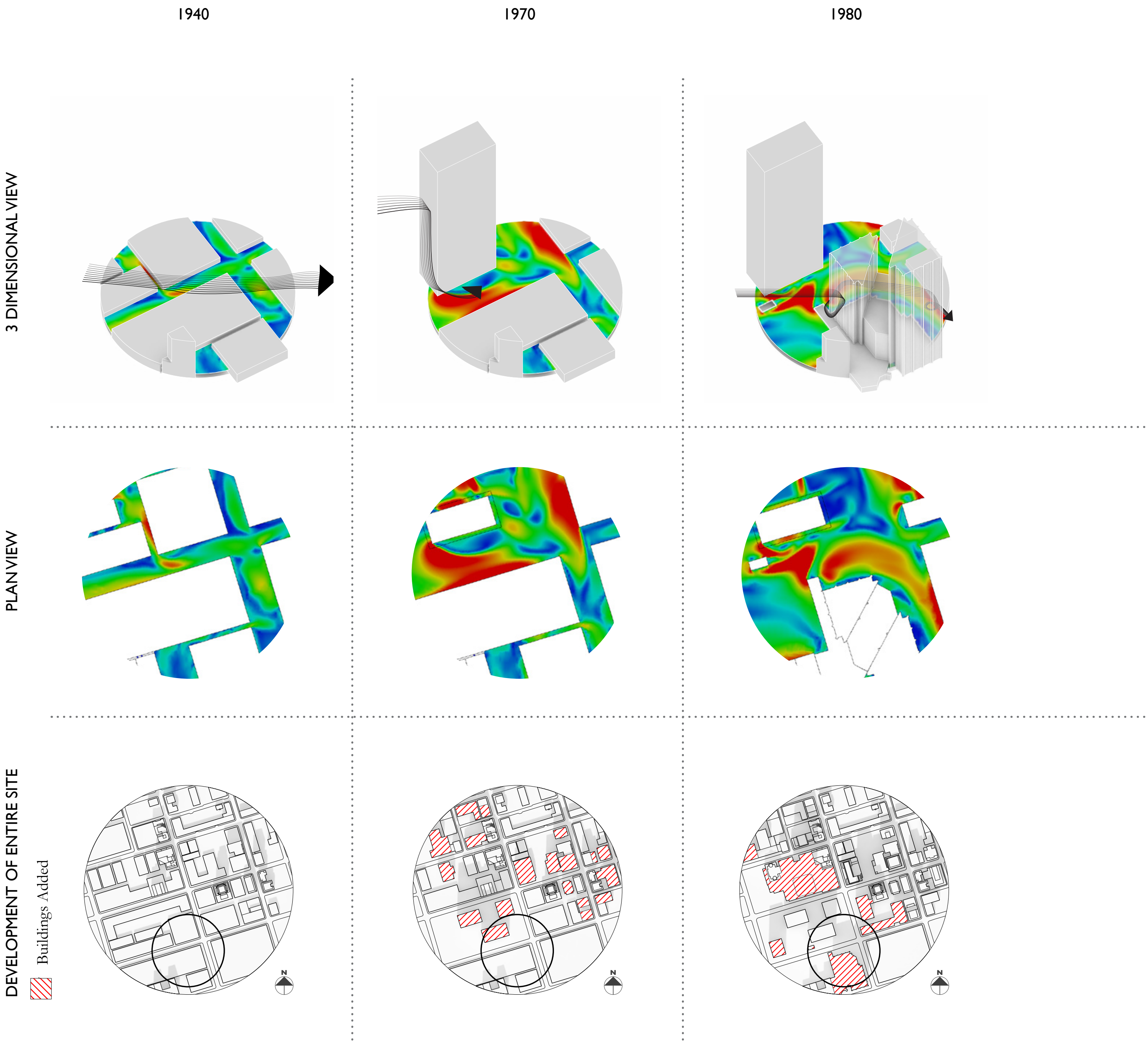


FIGURE 4.25. Corner Acceleration and Channeling, Images from Water Flume


1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N

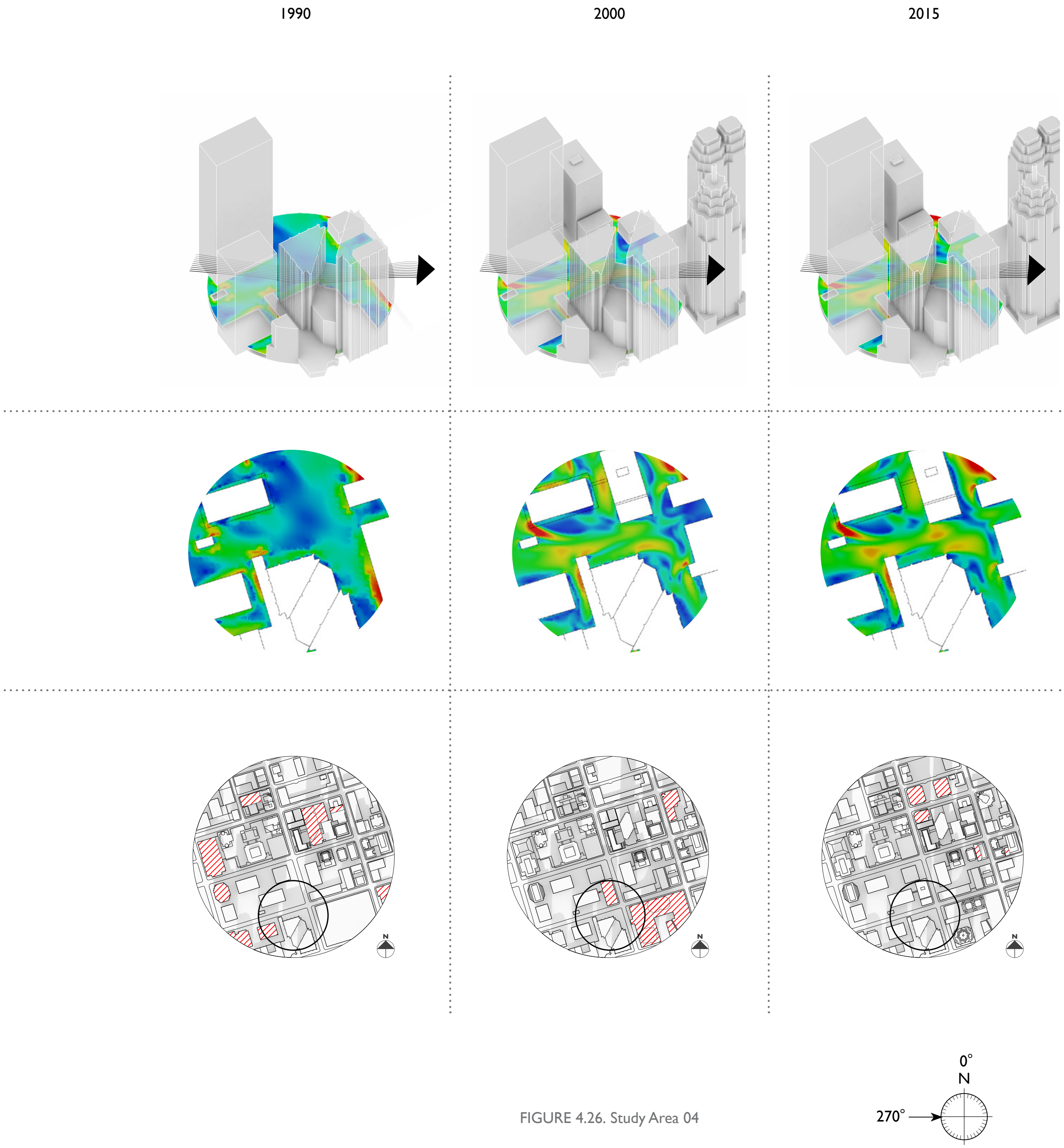
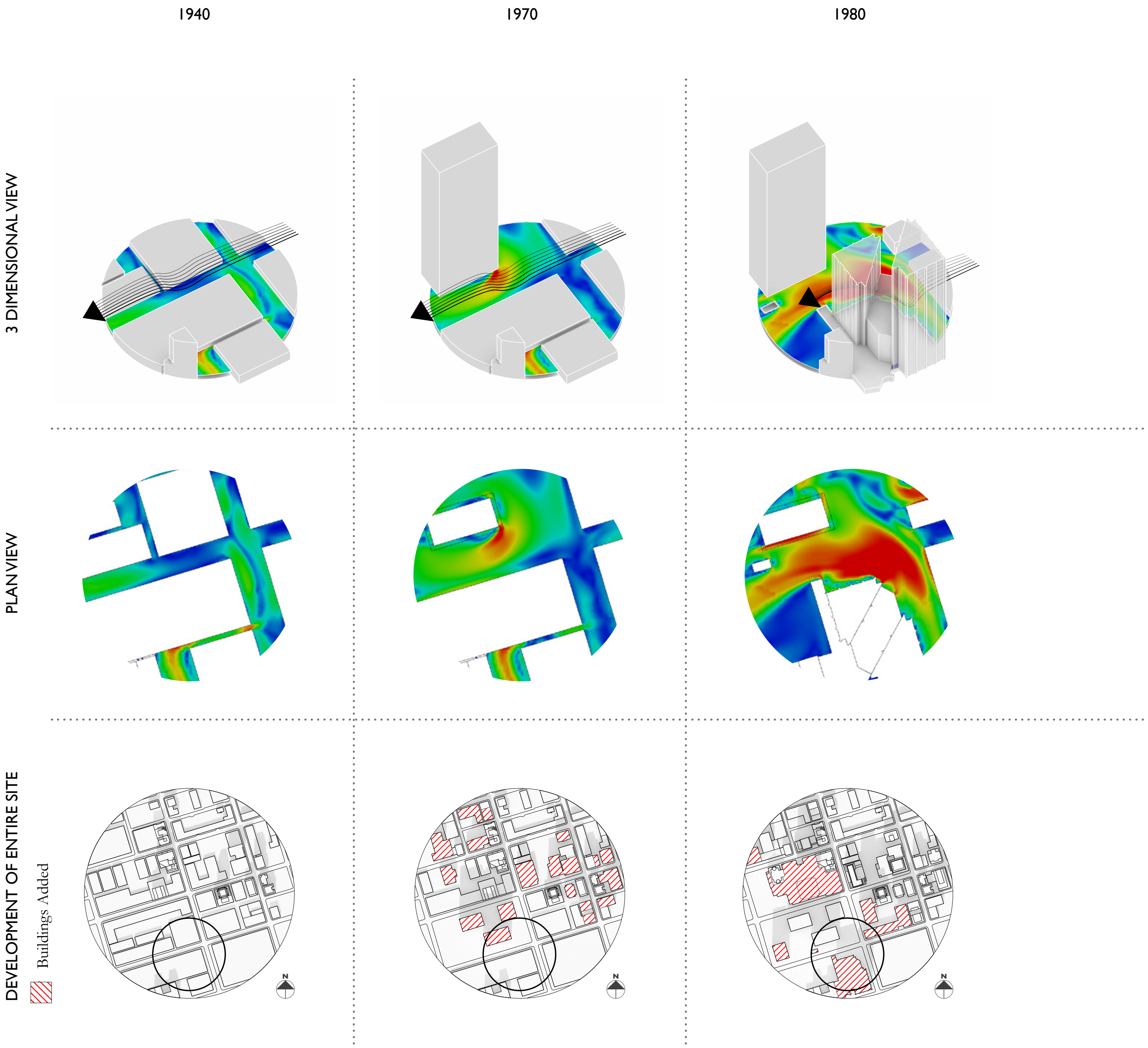
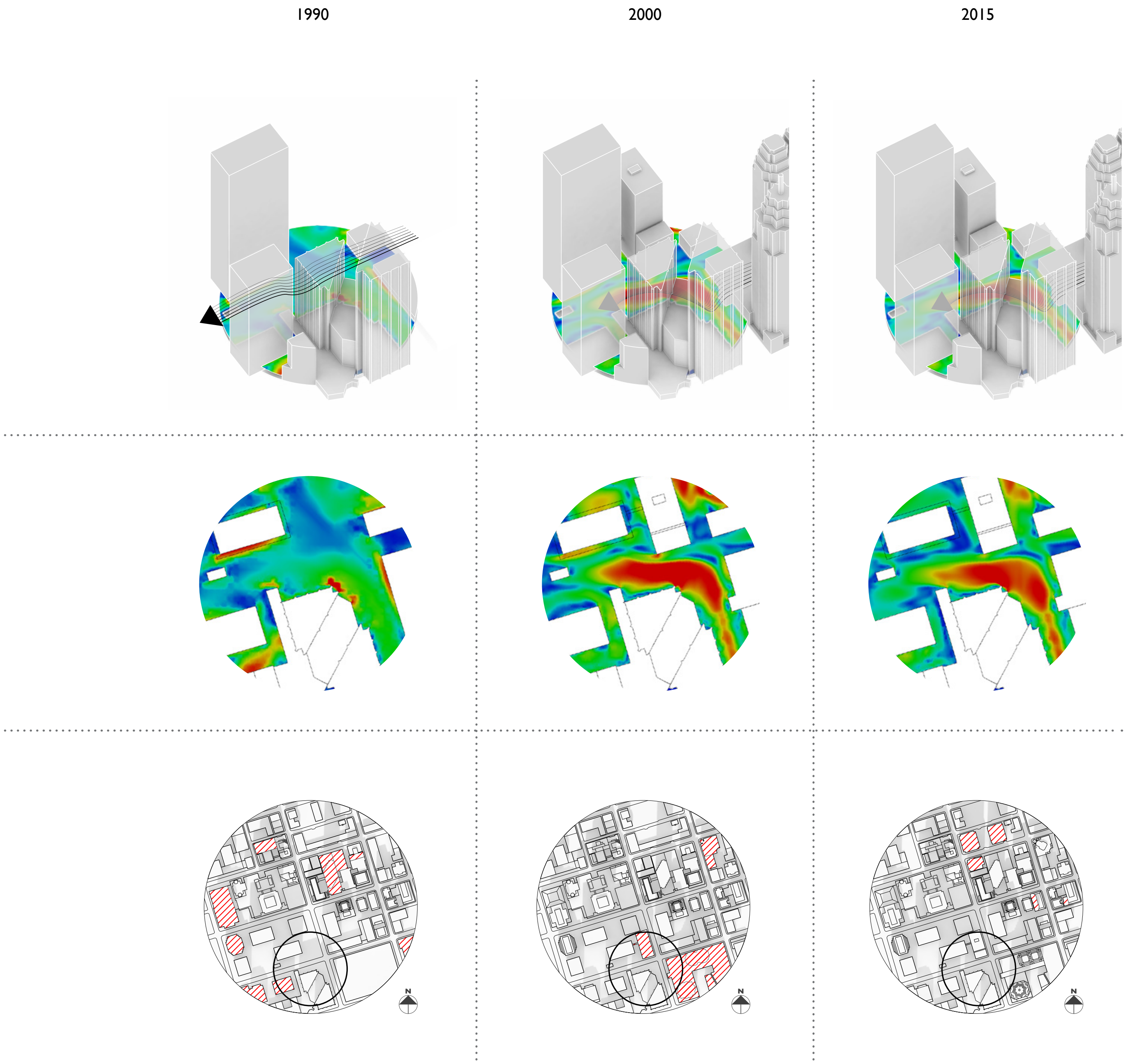


FIGURE 4.26. Study Area 04



1940
1970
1980
3 DIMENSIONAL VIEW
PLAN VIEW
DEVELOPMENT OF ENTIRE SITE
Buildings Added
N



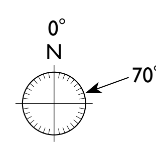
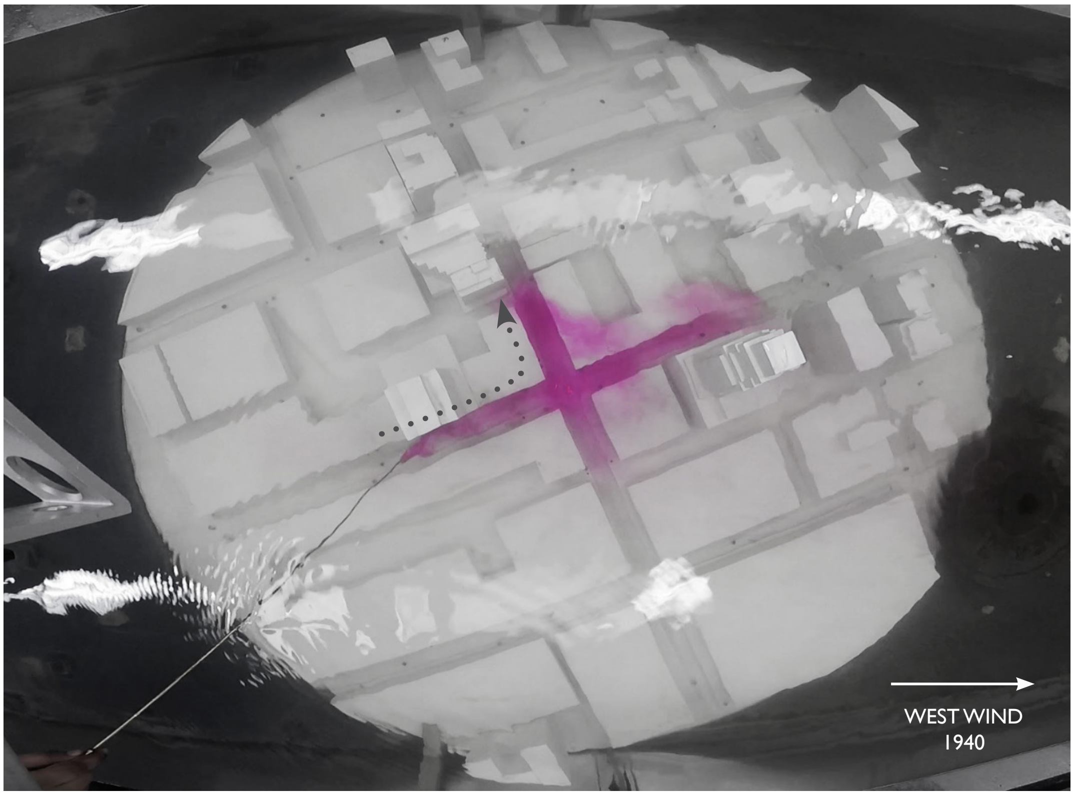
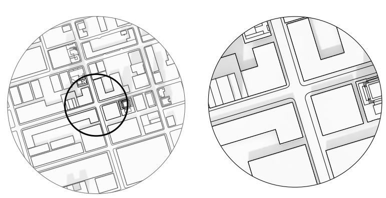


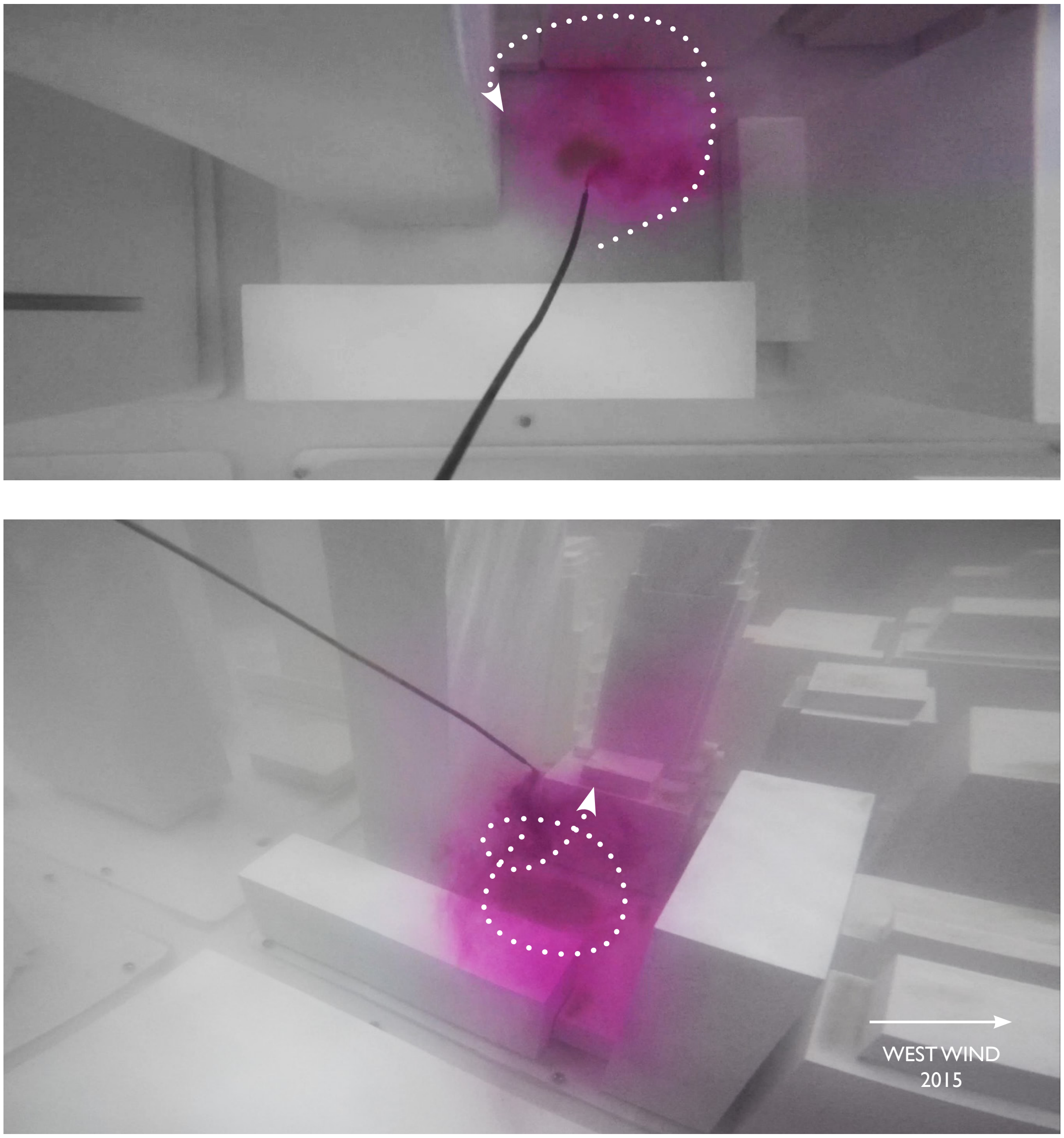
FIGURE 4.27. Study Area 04

Other Effects



CIBC MELON AND SCOTIA ITRADE BUILDING
REVERSE FLOW AND CORNER ACCELERATION





COMMERCE COURT PUBLIC SPACE
VORTEX EFFECT

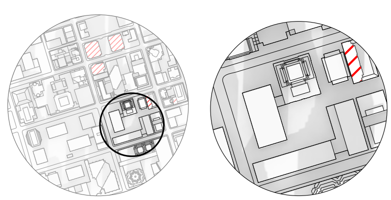
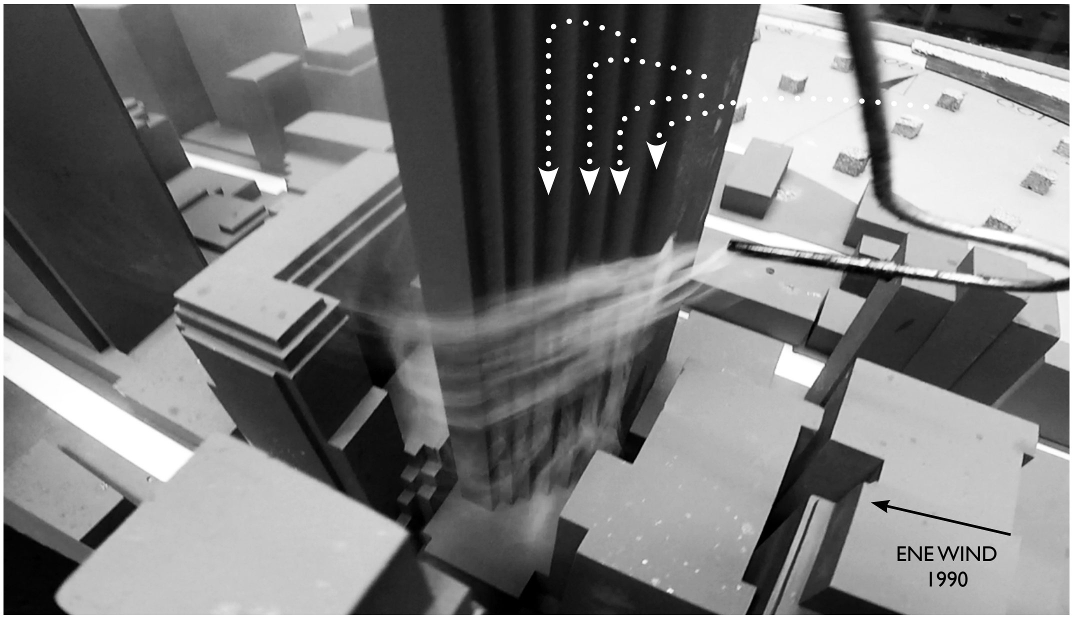
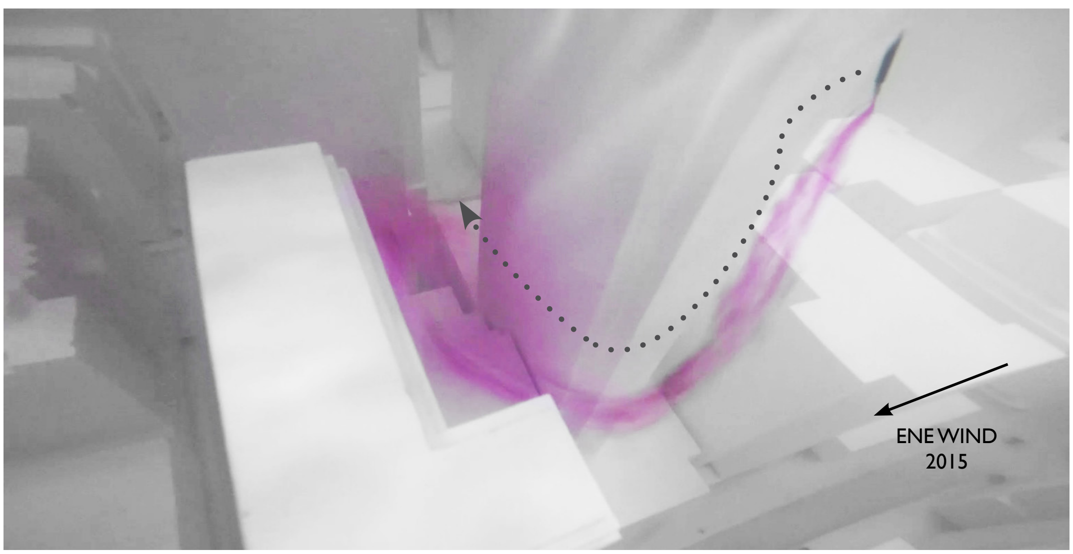
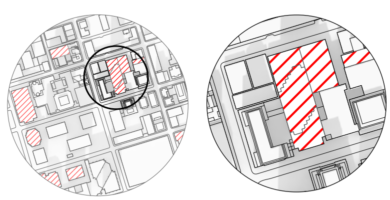


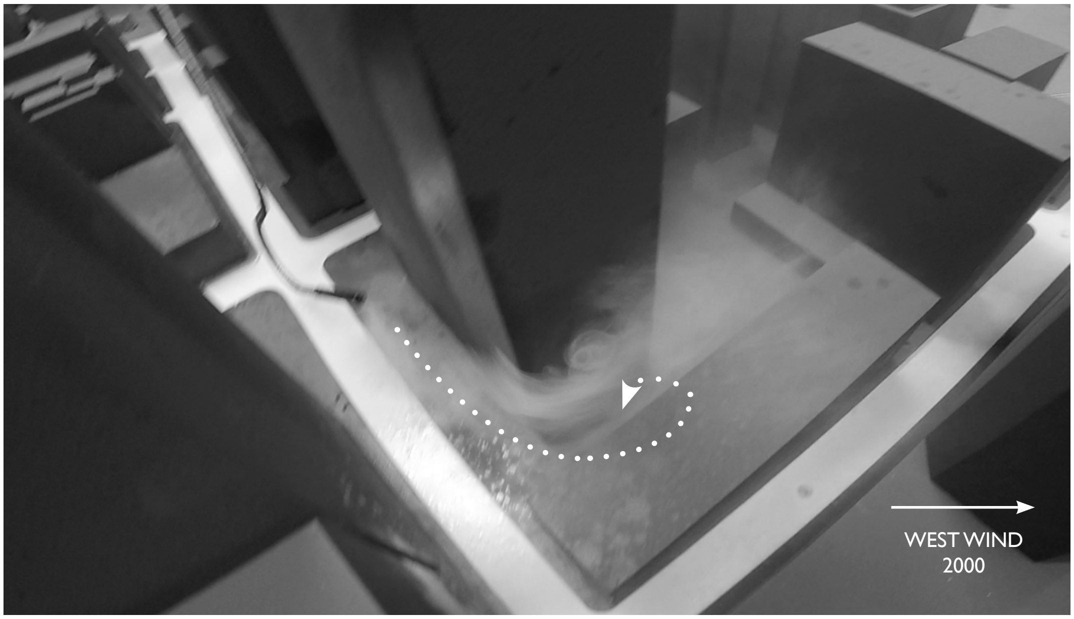
FIGURE 4.28. Effects Uncovered in the Water Flume and Wind Tunnel

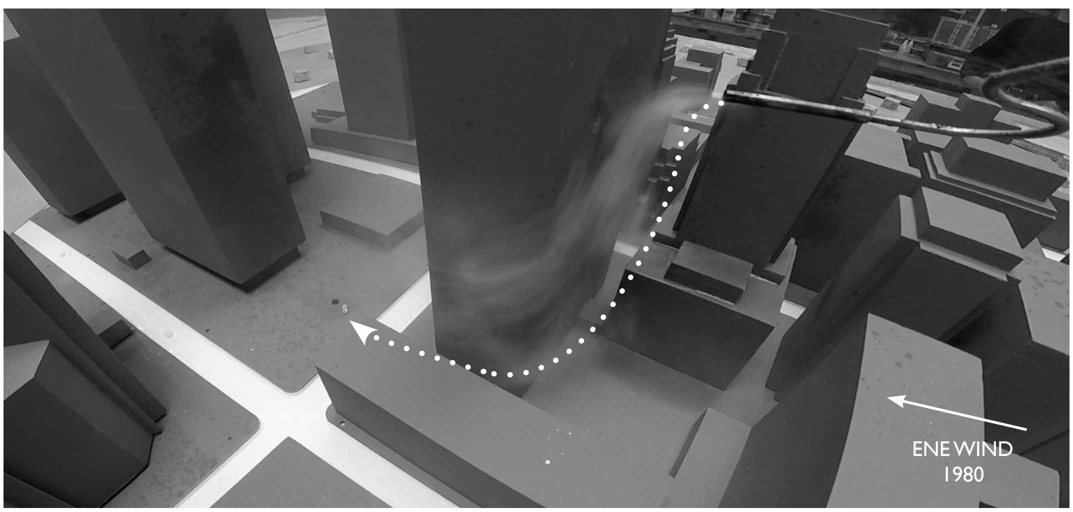




SCOTIABANK TOWER
FORM SLOWING DOWN WINDS AND WAKE EFFECT







COMMERCE PLACE WEST TOWER
DOWNWASHING AND CORNER ACCELERATION

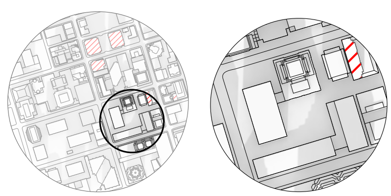
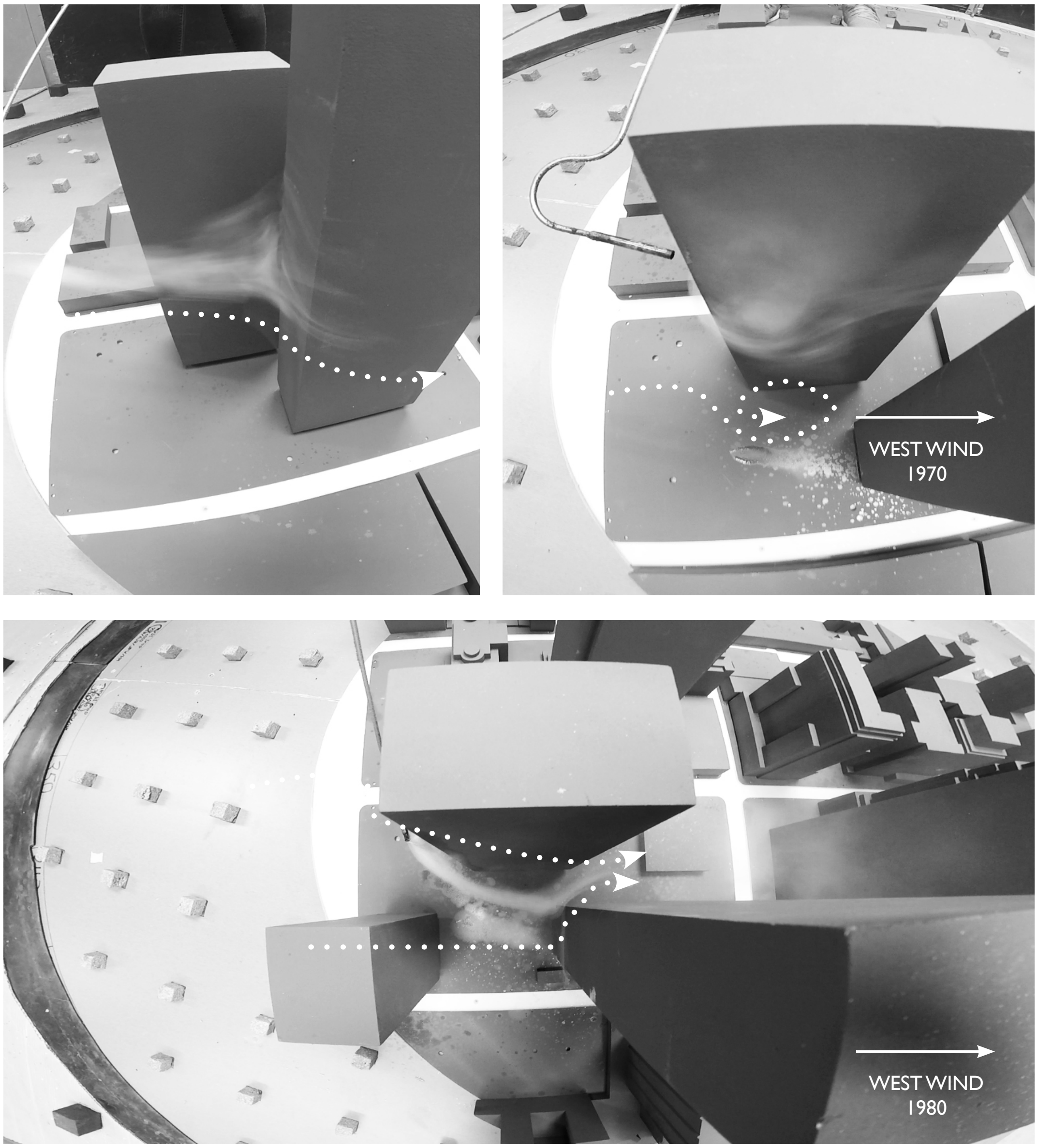
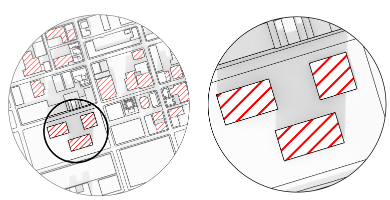
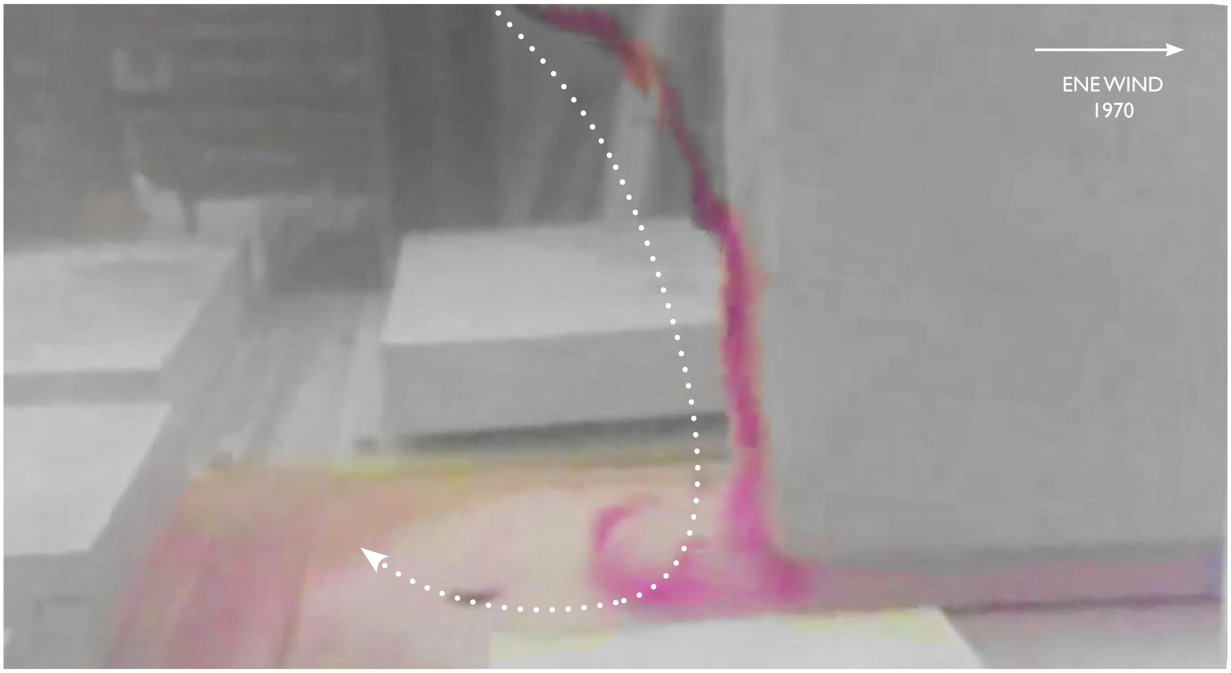


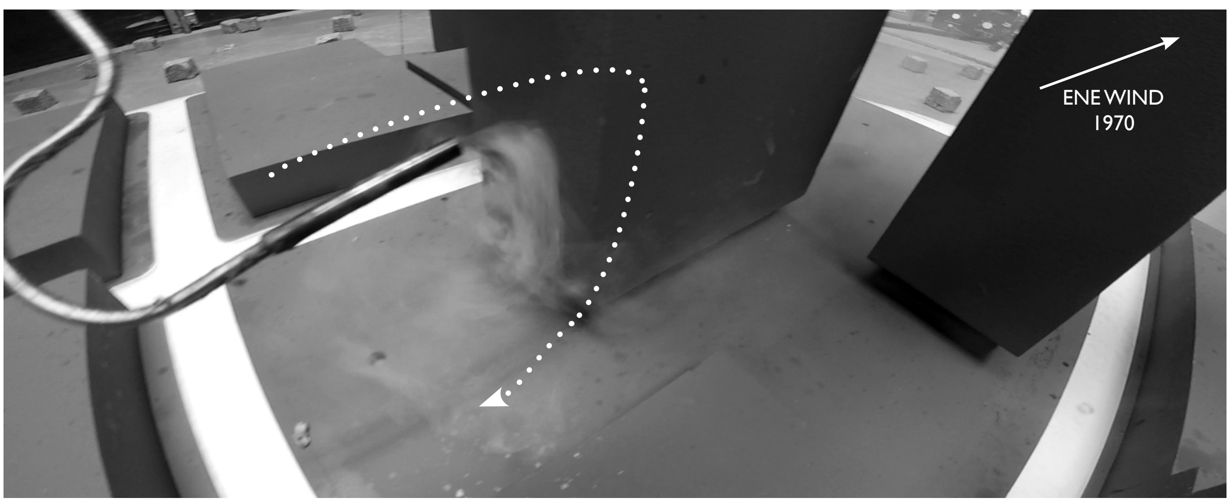
FIGURE 4.29. Effects Uncovered in the Water Flume and Wind Tunnel



DOMINION CENTER TOWERS
CORNER ACCELERATION AND CHANNELING







TD BANK TOWER
DOWNWASHING / SPILLING EFFECT

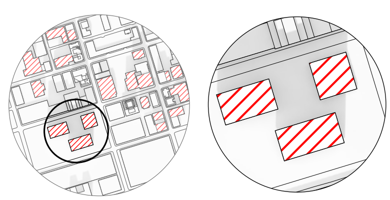
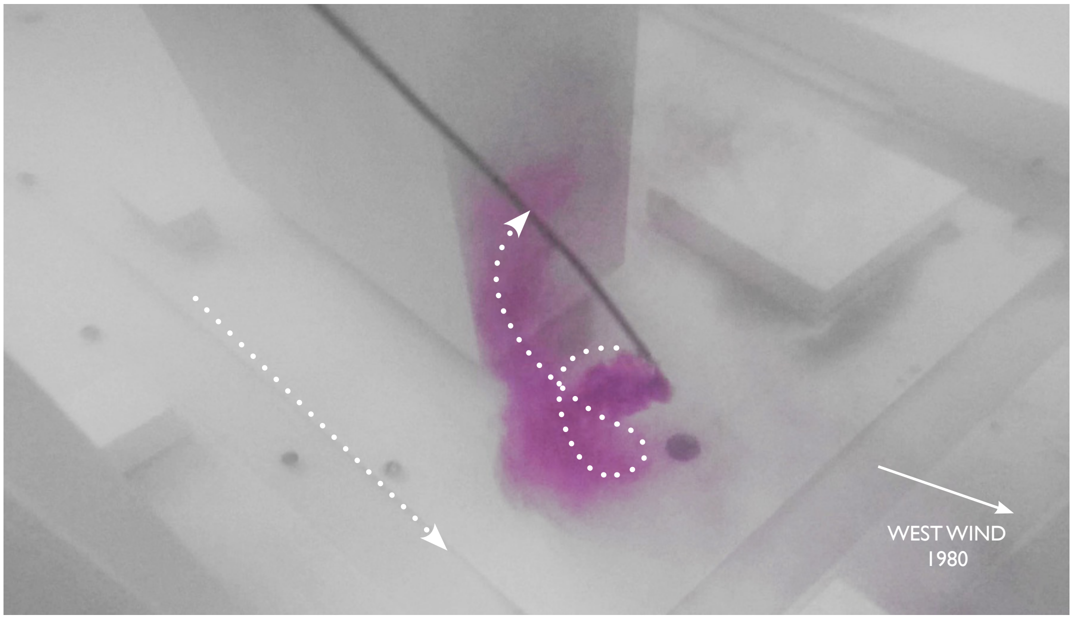
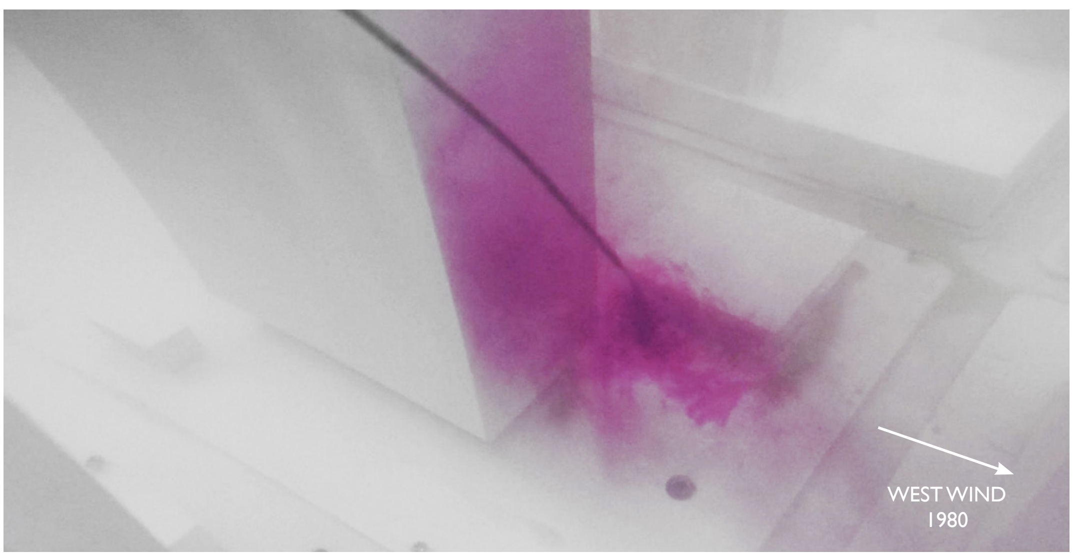
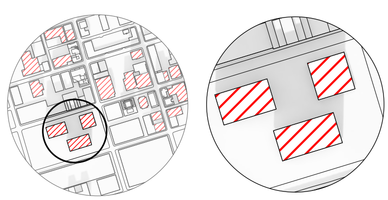


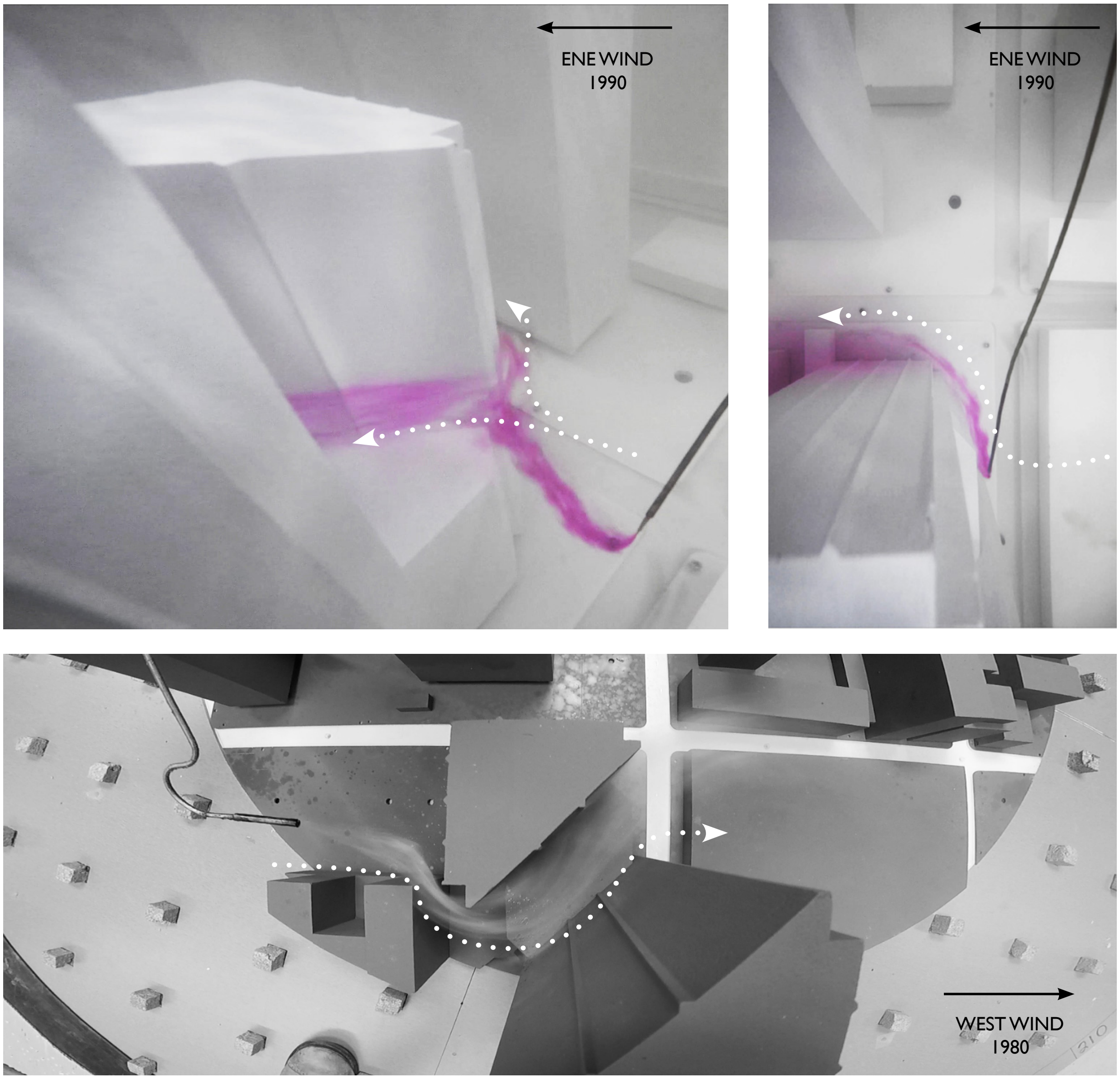
FIGURE 4.30. Effects Uncovered in the Water Flume and Wind Tunnel





TD BANK TOWER
WAKE ZONE





ROYAL BANK PLAZA
CORNER ACCELERATION AND CHANNELING

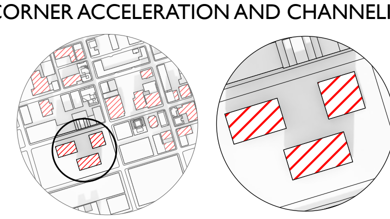


FIGURE 4.31. Effects Uncovered in the Water Flume and Wind Tunnel

MOVING FORWARD

Many of the effects uncovered within the study could have been prevented with knowledge of architectural aerodynamics prior to construction. Many of the problematic areas were solved post-construction by the City of Toronto with large installations and art work to break up winds. However, some effects, such as the reduction of wind speeds between 1980 to 1990, would have been harder to predict. In both west and east-north-east directions, the high speed winds completely avoided the pedestrian level. The studies within the water flume and wind tunnel demonstrated a reduced suction effect at grade that generally causes these areas of high speeds. In 1990, the exact accumulation and height of the constructed towers in conjunction with the wind speeds and direction, created a pressurized area that no designer could have predicted on their own. While this effect was unexpected, many of the other effects could have been anticipated. Due to this, planning departments such as the City of Toronto have begun to create documents outlining wind effects to be aware of in regards to pedestrian comfort and safety within tall building design. It is clear that designers must not only work together to solve these issues but also work closer with wind engineers.

Although these results clearly show the building and wind interaction, not all designers have access to this software or tools to perform the testing. While the computational software was useful (easy to set up and produced visual material) it was only able to provide qualitative data. The wind tunnel and water flume were helpful in ruling out issues with the CFD results and provided a more personal and tangible method of investigating the wind effects. While the CFD produced results, the wind tunnel and water flume allowed investigation into the cause and effect.

This collaboration with RWDI and the ability to not only utilize their facilities, but also their experience, contributed to the overall reliability of these tests. Even with access to the tools, the ability to know what to look for and decipher the information was a task that required an experienced wind engineer. However, once experience is gained, the designer can have a better grasp on what building components to consider in relation to wind so that when wind engineers are brought in, the project can move forward.

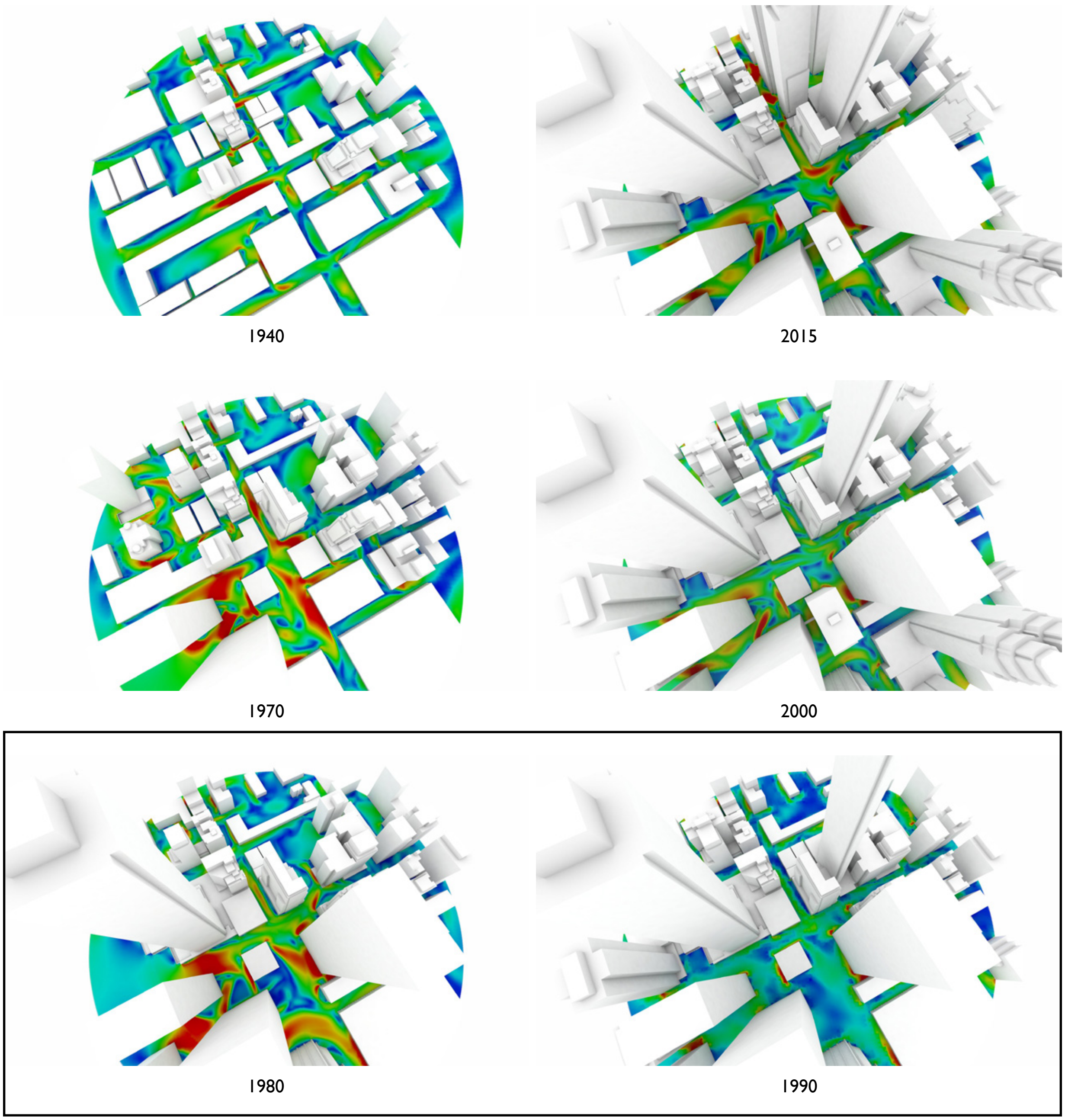


FIGURE 4.32. Development of Winds

Changing Winds vs. Changing Infrastructure

Visually understanding the relationship between the change in winds and the changing infrastructure is easier in two dimensions and more difficult in three dimensions. Following the testing of the project in Toronto, an exercise where high speed winds were isolated and stacked into a three dimensional form was performed. The goal was to clearly demonstrate how, over time as the city initially developed, large areas of high speed winds could be found at pedestrian level (black areas in 1970). As the towers grew, suddenly in 1990 the high speed winds slowed down (reduced dark areas in 1990). As time continued, the dark areas returned once again. Through these images, it is evident how the high speed winds that begin unified in 1940, break up and spread out as taller towers pierce the sky.

HIGH SPEED WIND DEVELOPMENT

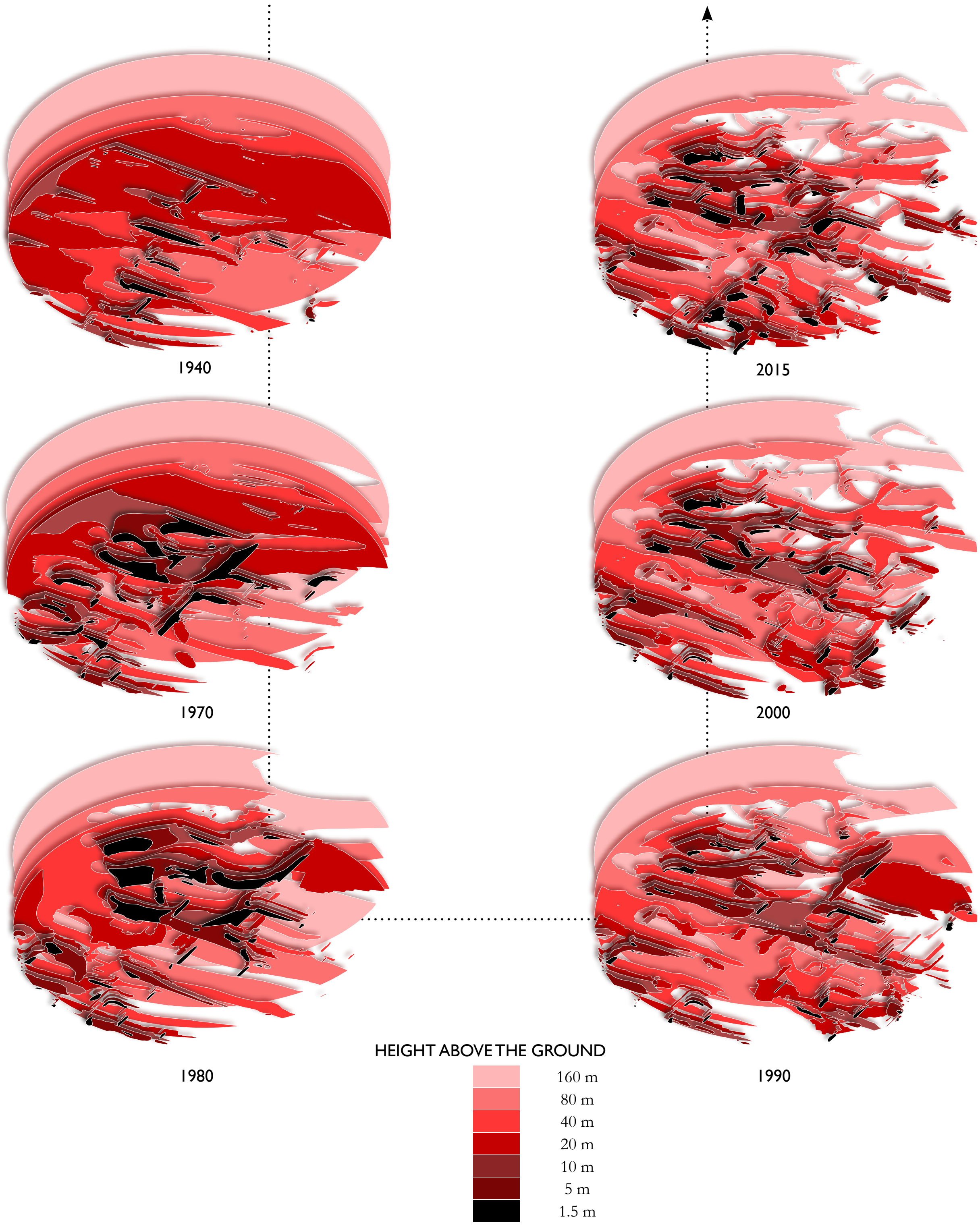
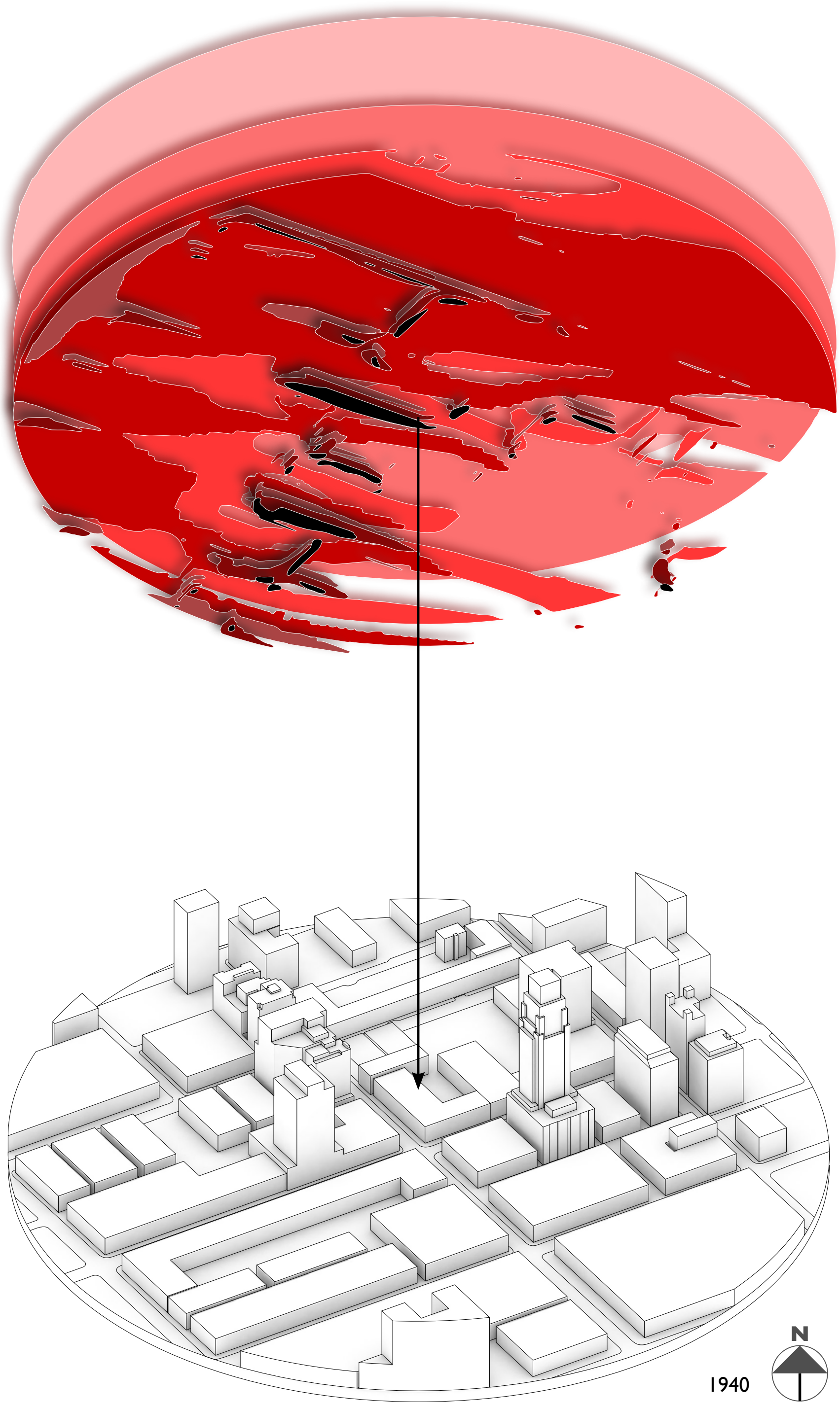


FIGURE 4.33. Worms Eye View Visualizing High Speed Wind Development (West Winds)


1940
N

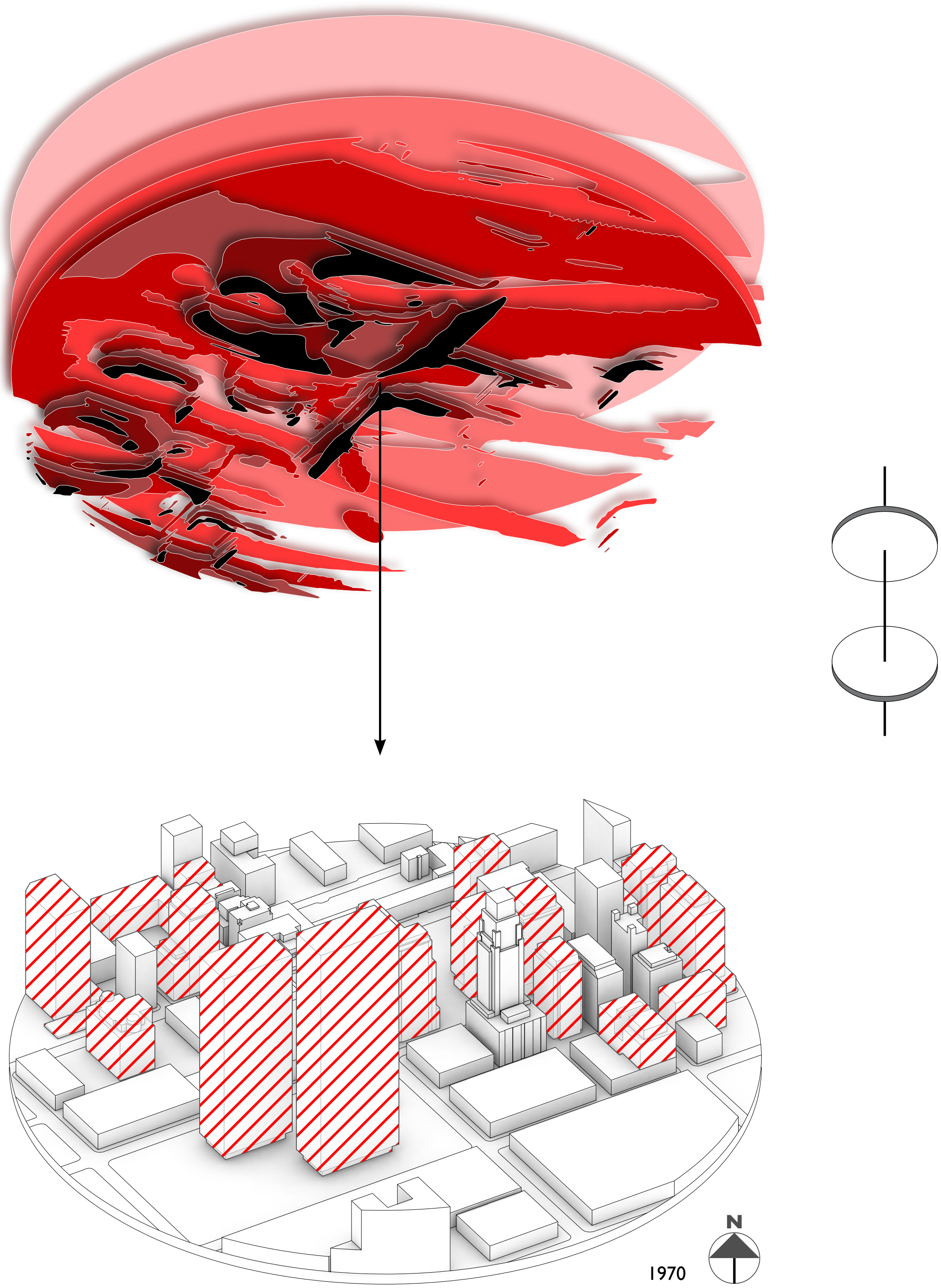
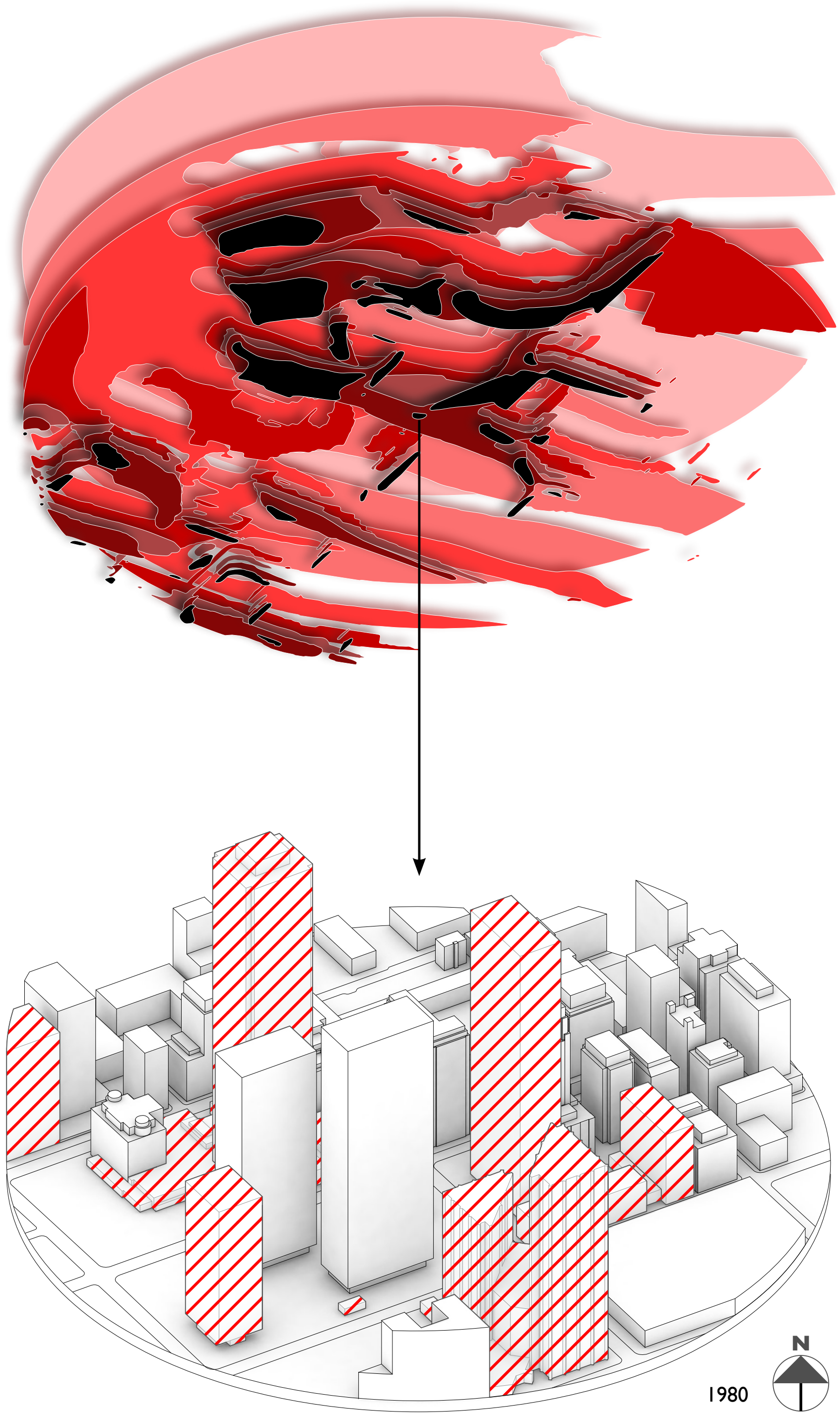


FIGURE 4.34. Visualization of Wind and Tower Development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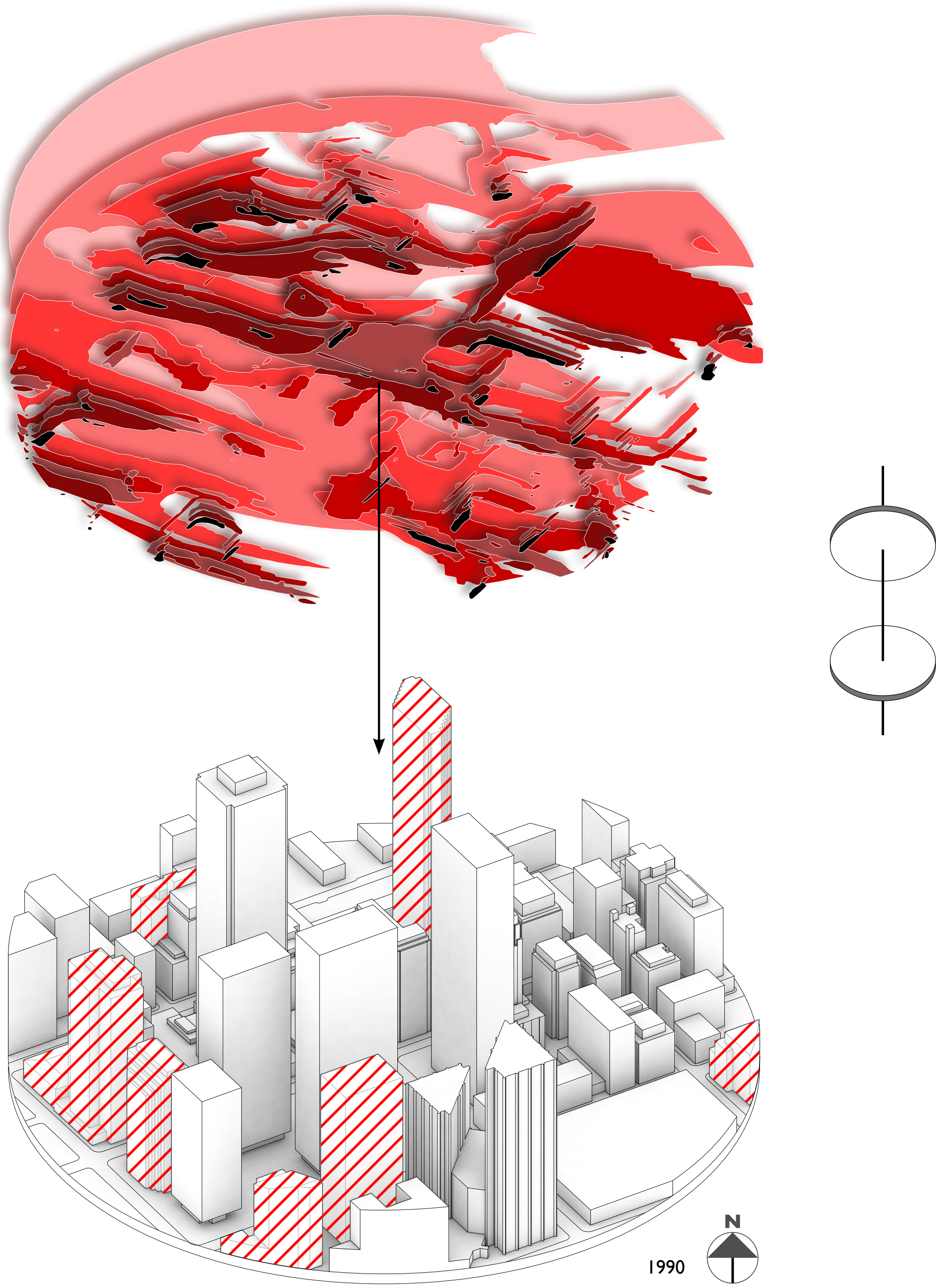
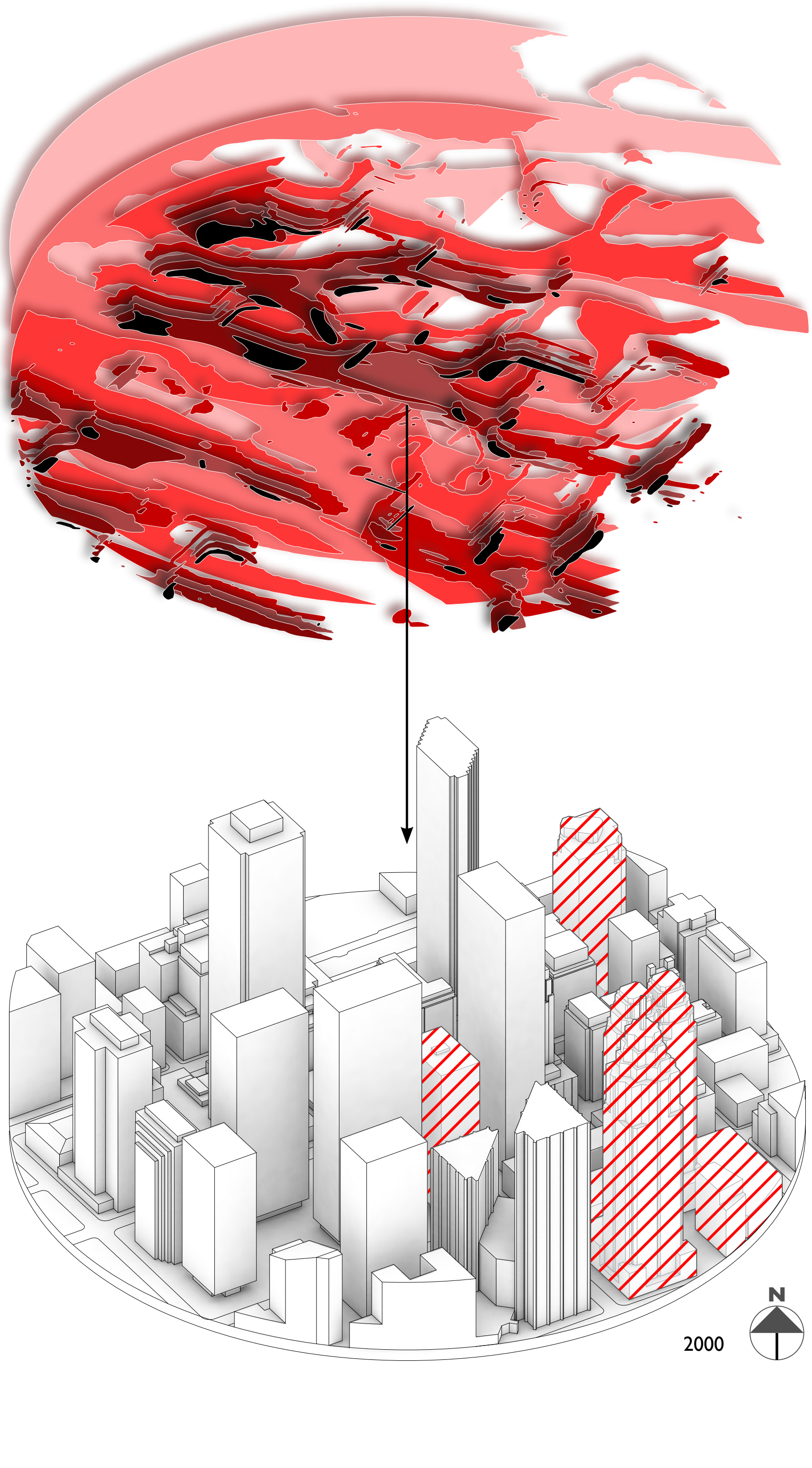


FIGURE 4.35. Visualization of Wind and Tower Development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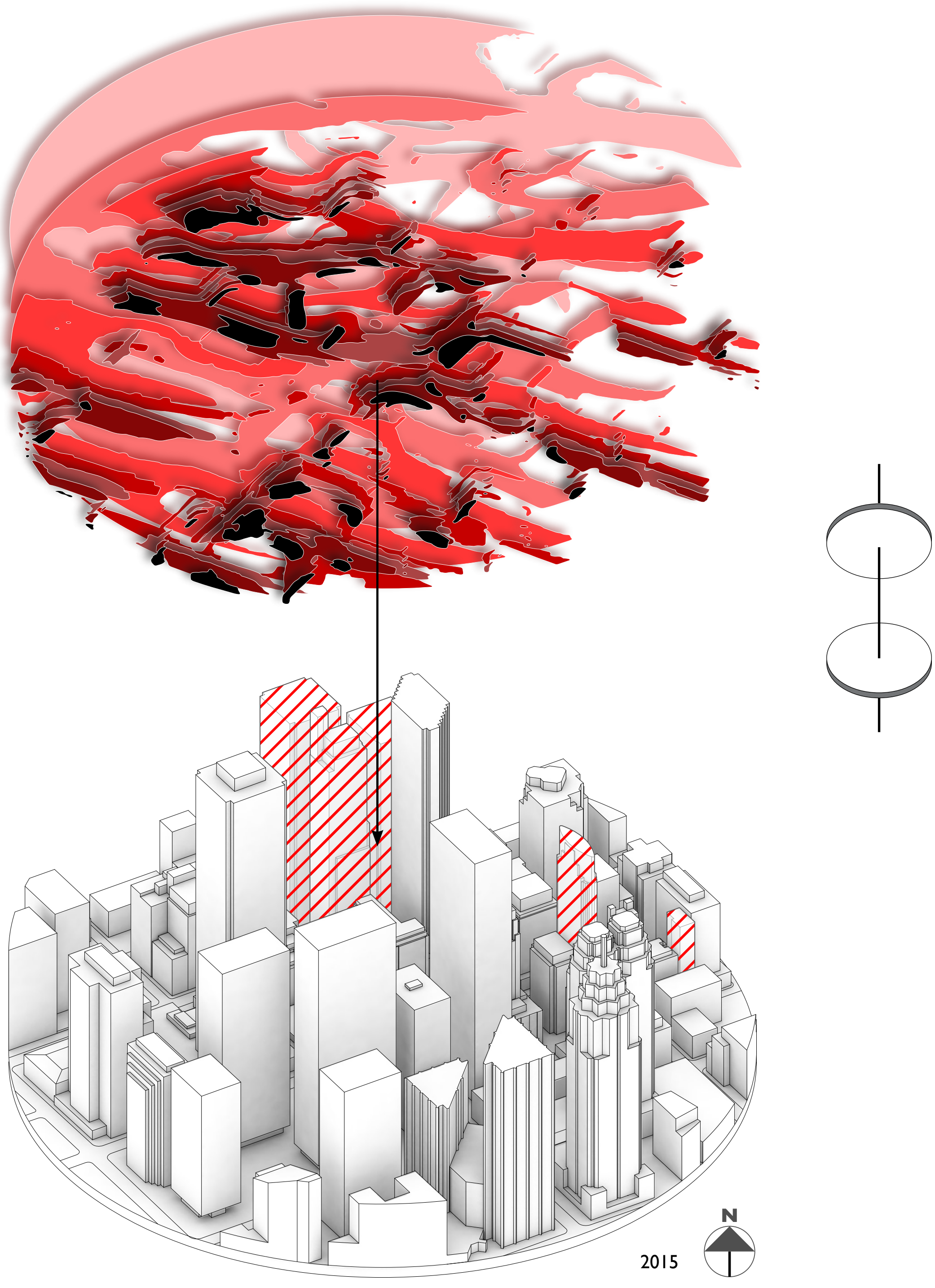


FIGURE 4.36. Visualization of Wind and Tower Development

"The wind, coming to the city from far away, brings its unusual gifts, noticed by only a few sensitive souls, such as hay-fever victims, who sneeze at the pollen from flowers of other lands."

- Calvino, *Marcovaldo: ovvero Le stagioni in città*, 1963.

CONCLUSION

FIGURE 5.1.

Wind in Design Today

Although invisible, wind significantly impacts the world. It simultaneously ensures and threatens human survival by equalizing the environment. The affect and impact of wind can be found in many parameters of design including issues of ventilation, structural strength, comfort parameters, energy generation, and even mobility. However, common speculation labels wind as an unpredictable force that can only be withstood, instead of worked with. In many cases, windy conditions are considered simply out of human control, when in fact, buildings and cities alter winds a great deal. This is mainly because visualizing and seeing the wind is a task on its own, necessary to even consider utilizing it in any other way than in a structural calculation.

The densification of cities in the present and coming years signifies a shift in the tools of design. The rapidly transforming urban landscape creates obstacles that provide opportunities for high speed winds from higher elevations to be brought down to pedestrian levels. With the increase in tall building construction, it is not enough to simply work against the wind, but to instead become aware of its interactions with buildings and people. Although designers — specifically architects — learn basic principles of mechanical, structural, and electrical engineering, little is discussed regarding aerodynamics other than conceptual notions of energy production and ventilation.

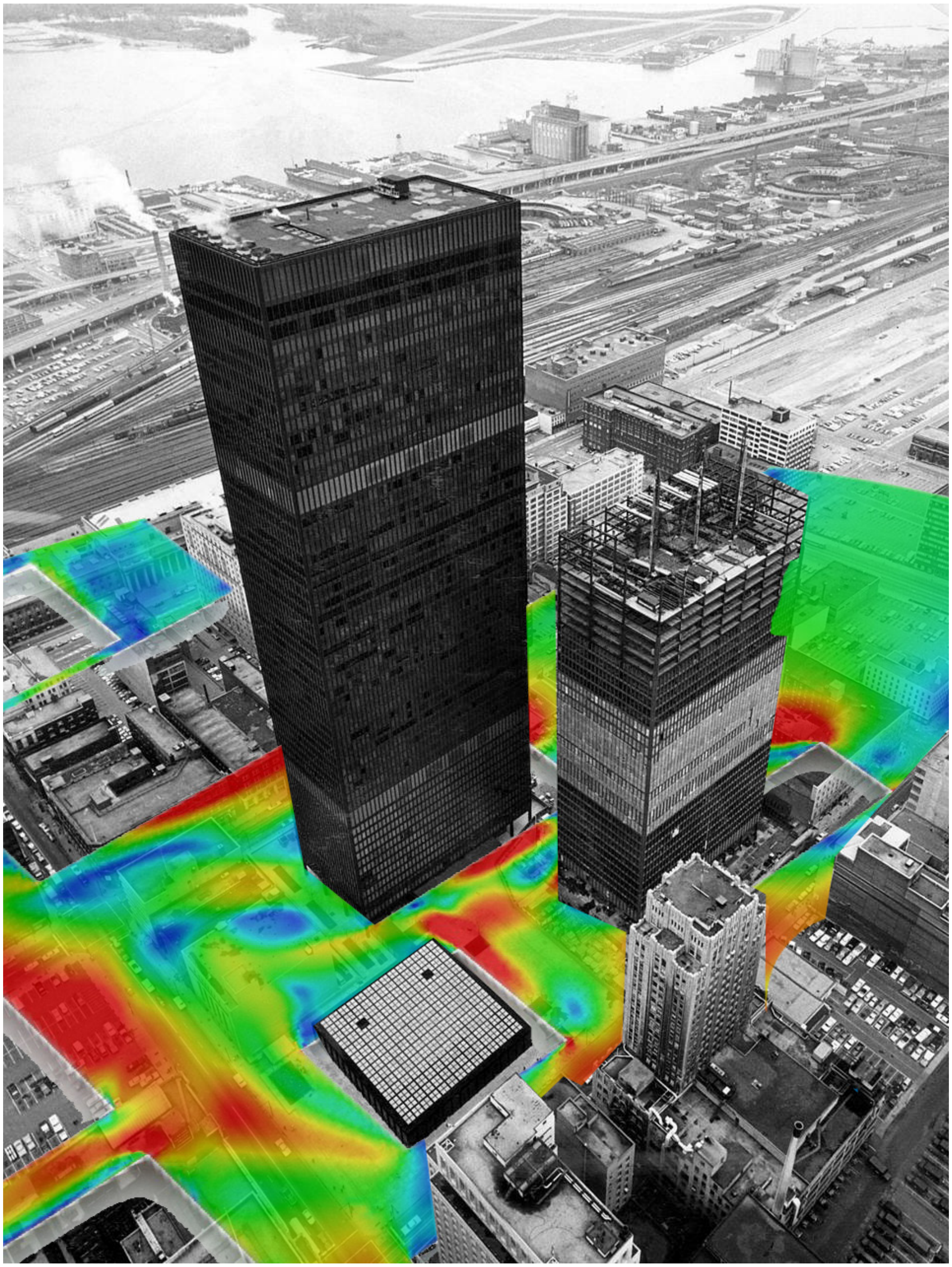


FIGURE 5.2. Collage, Visualizing Wind During Construction, Dominion Center Towers

While many designers are aware of wind's presence, being aware and predicting issues, such as the downwashing condition of the Walkie Talkie tower that turned dangerous, is a different matter. Although wind is commonly referenced and depicted as a simple arrow that follows a straight line from point A to B, there is a complexity that is overlooked. Within architectural practice, the fact that a building does not interact with wind in isolation, but as part of a larger, complex net of buildings connected by pressure differences is not commonly taken into account. This of course is not easily incorporated and requires a collaborative effort to carefully design the master plan that considers individual designs within the collective. As more buildings are constructed and comfort and safety of people put to the test, codes and regulations will be increasingly applied to evaluate a building's impact on its surroundings through its interactions with wind. Although there are guidebooks describing architectural aerodynamics, many describe wind's interaction with form using formulas and charts, or images of specific projects that cannot be linked to any other site, all of which are inaccessible to architects. Lists of diagrams that illustrate specific interactions between forms and wind can be found, but these do not assist in the future of developing strategies for architects to consider wind when creating form. Although increasing in number, only a few building codes in the world require wind experts or wind tunnel testing. However, wind engineers are working toward more useful methods of working with architects. These methods include working meetings in the wind tunnel or water flume to provide the designer with a visual understanding of how their iterations are altering the wind. This could be the next step in increasing collaboration between designers and wind engineers. However, the designers must first be aware of these facilities, understand the benefit of wind testing, and be aware of the steps to take within the design prior to approaching these experts.

FIGURE 5.3. Photograph by Eamonn and James Clarke.
Resulting Effects Winds Amplified by the Down Draft from The Beetham Tower in Manchester, England.

An Approach to Wind

Rather than waiting for issues to arise after the completion of a project, this thesis recommends an earlier understanding of architectural aerodynamics. While architects are limited by the means to explore winds in a visual sense, small bits of information are available through computational programs, meteorological data, as well as full-scale observations, all of which can assist in establishing a useful baseline. Each project will interact with wind in a unique way.

There are three moments within the design and construction of a building during which different approaches to wind at pedestrian level can be taken. These include: during the masterplan of the area, the design development of a building or group of buildings, and either during or post construction. Ideally, the properties of form (texture, edges, surfaces, sizes), and space (proximity and orientation) must be considered early within stages of design in order to maximize available benefits. In the initial stages of master planning, the proximity and orientation of buildings in relation to the prevailing wind direction is the most important. Questions to consider include: from where and how fast are the winds approaching, and in addition where is wind wanted or unwanted? Having an overall picture of the development can aid in avoiding costs. Within design development of a singular or group of buildings, edge and surface conditions as well as proximity and orientation to other buildings must be considered in relation to dominant wind direction. Parameters that alter the entire form such as an aerodynamic shape, or the addition of a podium are best considered at this stage.

Wind engineers and tall building guidelines (such as the 2013 Toronto guidelines) suggest that designs with buildings significantly taller than their surroundings, with two or more buildings, located in areas of high wind speeds or a design with a large site area should obtain qualitative or quantitative wind tunnel studies depending on the context.

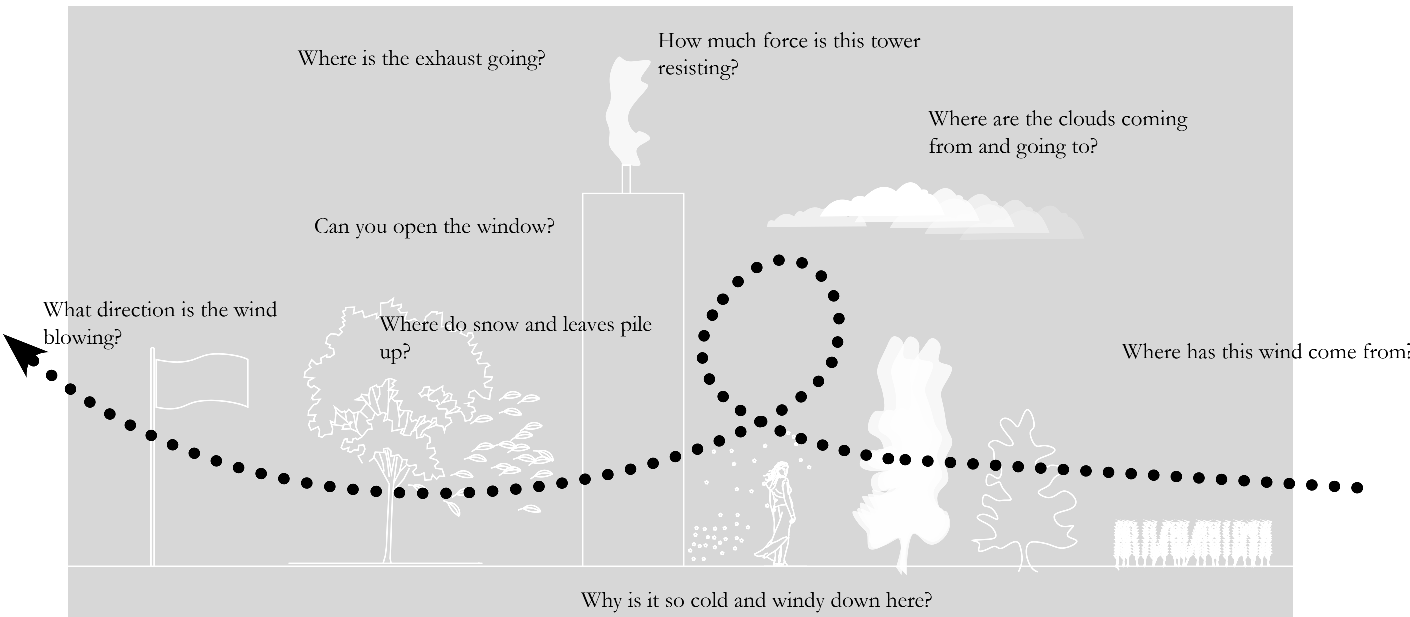


FIGURE 5.4. Searching for Wind in Unexpected Places

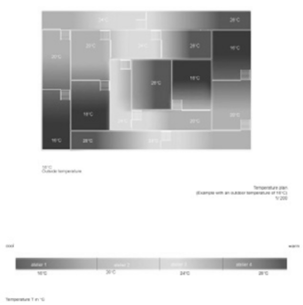
Once the basics of aerodynamics are incorporated into design, it is possible to consciously estimate where snow might deposit, where programs should be located around a building, where exhausts should be located, and the overall form and orientation of a building. During these stages, computational programs can be referenced to give a general idea of the kinds of effects to expect as well as data from surrounding projects that have previously been tested in wind tunnels. This data is electronically published by the city after a few years. However, principles must be kept in mind when utilizing computational programs in order to clearly understand the nature of the information that can be used. The complexity of the natural environment and the winds that exist within it can never full be solved by a computational model. Wind resists the urge to be digitized and encourages individuals to physically sense the atmosphere instead of simply thinking about it. Although there are unpredictable elements of wind that require intensive studies with more complex tools, the designer can be aware of the basic principles and relationship of the building to the site through wind. By acquiring this knowledge, designers can work with wind engineers to progress and improve upon a design. Instead of viewing wind effects as negative, urban development can be viewed as an opportunity for winds to be managed and applied to design in the city.

FIGURE 5.5. Forms Sculpted by Winds on the Shore of Lake Michigan - Joshua Nowicki

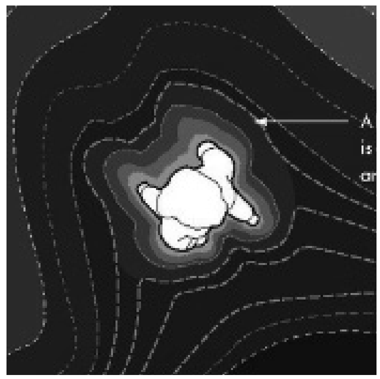
City of Wind: Exposing the Invisible

The goal of this document is to enable designers to "see", and have an understanding of wind effects, how to uncover them, and how to work within the boundaries of available information. This "awareness" in design can be traced back to vernacular design and haptic architecture that utilizes the senses and intuition based on full-scale interaction and first-hand experience with conditions. While this document intended to use wind in the design of a building, the very nature of "seeing" and understanding wind became a task in its own right. Due to its invisibility, it is not difficult to assume and stretch ways in which wind can be manipulated theoretically, but it is more difficult in full scale application. It is necessary to become aware of accuracy in testing for wind due to the threat on the safety and comfort of pedestrians.

The possibilities for wind in design are far from being common in practice, however there are designers testing and utilizing intangible elements as architectural materials. Philippe Ram and Sean Lally focus on the movement of heat within a space as a building material in architecture; Diller Scofidio and Renfro used wind and water to create the fog of the Blurr Building; Junya Ishigami questions the possibilities of changing atmospheres as people inhabit taller and taller towers; Renzo Piano employs simple techniques to create an adaptive design of the Tijbaou Center; architect/engineer David Menicovich proposes blowing air around a facade to alter the pressure that winds put on buildings. These types of designers are pioneers in considering not only how physical tools control interior space, but the ways interior and exterior space relate. There is great potential in the unknown of wind. Just as nomadic tribes learned to live around the changing "threshold" of a campfire, society must learn around buildings. Stepping into the world with a new awareness of wind will better inform the design process, and is the key to the future.

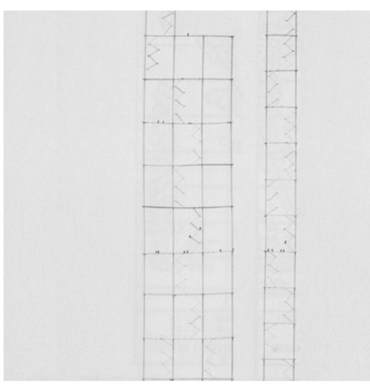


PHILIPPE RAHM



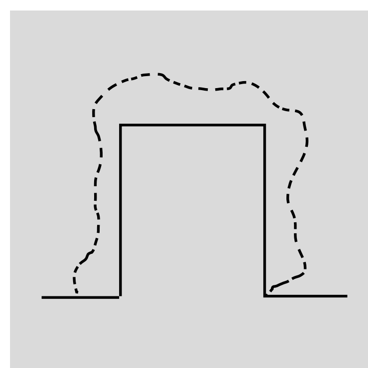
SEAN LALLY

DILLER SCOFIDIO + RENFRO



JUNYA ISHIGAMI

RENZO PIANO



DAVID MENICOVICH

FIGURE 5.6. Properties of Climate as Tools in Design

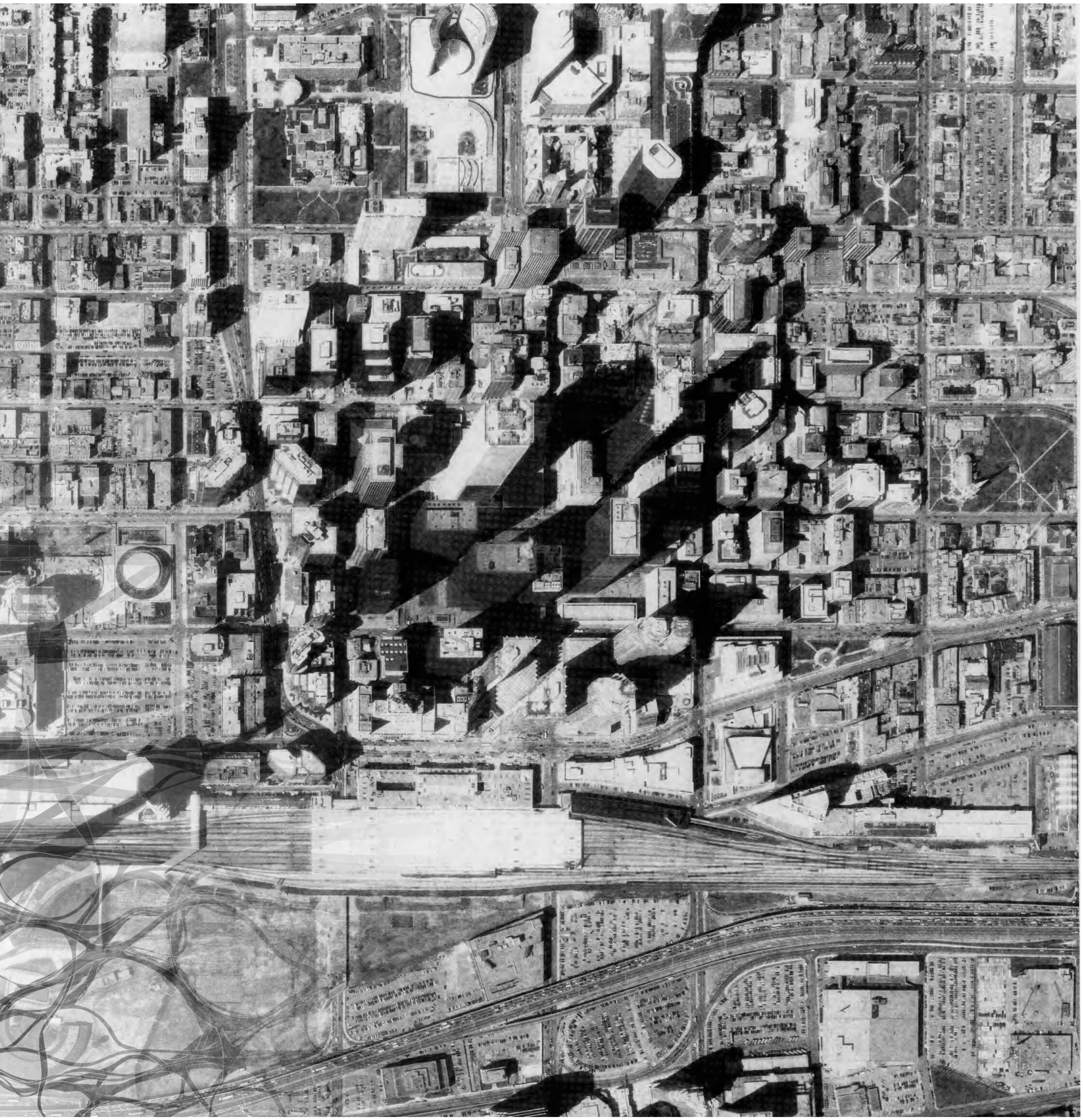


FIGURE 5.7. Collage. Visualizing Wind Over the City

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