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Urban Form, Wind, Comfort, and Sustainability: The San Francisco Experience

By

Hyungkyoo Kim

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

City and Regional Planning

in the

Graduate Division

of the

University of California, Berkeley

Committee in Charge:

Professor Elizabeth Macdonald, Chair
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Professor Peter Bosselmann
Professor Edward Arens

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Urban Form, Wind, Comfort, and Sustainability:
The San Francisco Experience

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ABSTRACT

Urban Form, Wind, Comfort, and Sustainability:
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by

Hyungkyoo Kim

Doctor of Philosophy in City and Regional Planning

University of California, Berkeley

Professor Elizabeth Macdonald, Chair

In 1985, spurred by the residents' strong interest in the quality of the built environment and in securing comfort in public open spaces, San Francisco became the first city in North America to adopt a downtown plan, supplemented by a planning code, on ground-level wind currents to mitigate the effects of adverse wind. Since then, the plan has mandated that new developments in the downtown and four additional areas in the Rincon Hill, South of Market, Van Ness, and South Beach neighborhoods, all associated with high density or development potential and substantial outdoor activities, be designed or adopt wind-baffling measures so as to not cause ground-level wind current in excess of 7 mph in places for seating and 11 mph in those for walking for no more than ten percent of the time year round, between 7 am and 6 pm, to minimize potential discomfort generated by excessive ground-level wind currents; and 26 mph for no more than one hour per year to secure pedestrian safety.

This research examines whether San Francisco's plan on ground-level wind currents made the city's public open spaces more comfortable and what is the impact on use of sustainable transportation modes. More specifically, it studies (1) whether the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment; (2) whether the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco; and (3) whether the plan achieves a wind comfort level that would increase the residents' willingness to use sustainable transportation modes.

Two types of methods were adopted in this research: wind tunnel tests and field studies. The wind tunnel tests, carried out in 2013 at the Center for Environmental Design Research (CEDR), use a boundary layer wind tunnel in which the wind movement in a selected urban area is simulated through use of a scale model of the area's built form. The field study, carried out from July 2012 to December 2012, consisted of pedestrian survey combined with on-site collection of microclimate data, such as wind speed, temperature, relative humidity, and solar radiation. The two methods are effective in addressing the relationships that the sub-research questions seek to examine and the nature of the variables that need to be measured. They also successfully

incorporate a mixed-method approach that amalgamates qualitative methods such as observation, interview, and mapping with quantitative statistical analyses.

This research presents the following findings. First, San Francisco's wind planning has changed the city's urban form so as to provide a more wind comfortable environment. Through a series of simulations using the boundary layer wind tunnel and comparing the wind speed ratios at 318 locations in the selected sites of Yerba Buena, Van Ness, Civic Center, and Mission Bay North in the 1985 and 2013 urban form conditions, it was discovered that the overall mean wind speed ratio dropped by 22 percent from 0.279 in 1985 to 0.218 in 2013. It means that the urban forms of the four sites have been changed so that the expected actual ground-level wind speeds have decreased by the same rate. However, there still exist a number of excessively windy places in San Francisco that are associated with specific urban form conditions, including direct exposure of street orientation to the west wind, high-rise building façades that directly meet the ground, and continuous street walls.

Second, through on-site surveys and microclimate measurements, it was discovered that wind speed significantly affects people's perceived outdoor comfort and that 11 mph is an effective criterion that determines outdoor thermal comfort in San Francisco. Significant differences are found in the frequency distributions of people's responses to all of the four comfort measures, which are thermal sensation, wind sensation, wind preference, and overall comfort. Also, the net effects of equivalent wind speed on the comfort measures are strong when the speed is less than 11 mph but become weaker when the speed is 11 mph or higher, meaning that there exists a difference in how much wind determines comfort between the two wind conditions. However, a wide range of dimensions on how people perceive wind and comfort exists, including adaptation, surrender, and avoid, which makes it difficult to judge the effectiveness easily.

Third, the research findings suggest that San Francisco's wind planning does not achieve a wind comfort level that would increase people's willingness to use sustainable transportation modes. It was found that higher wind levels discourage people to wait at transit stop with no shelter, to bike, to walk outside, or to sit outside. Also, significant differences with regard to people's willingness to use sustainable transportation modes exist between when the equivalent wind speed is less than 11 mph and when it is 11 mph or higher. However, the net effects of equivalent wind speed in both wind conditions were not statistically significant, indicating that the criterion does not successfully determine whether people are comfortable enough to be willing to use sustainable transportation modes. Although the criterion was not originally developed to consider the use of sustainable transportation modes, it can be suggested that the criterion can be revised.

A wide range of solutions must be studies for cities in varied climate regions. Cities and regions should not only study and develop their own climate-based ways to make a more climate-responsive city but also vigorously evaluate their effectiveness. Collaboration and cooperation between urban design, urban climatology, and many other relevant fields of expertise is crucial in future research and practice.

To Ji Eun and Sean

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CHAPTER 1. INTRODUCTION

This chapter delivers a brief introduction and motivation of this dissertation research. It also presents the primary research question and three research sub-questions, and walks through the main contents of the rest of the dissertation.

1.1 Introduction

In 1985, spurred by the residents' strong interest in the quality of the built environment and in securing comfort in public open spaces, San Francisco became one of the first cities in North America to adopt a downtown plan, supplemented by planning code, on ground-level wind currents to mitigate the effects of adverse wind.[1] Since then, the plan has mandated that new developments in the downtown and four additional areas in Rincon Hill, South of Market, Van Ness, and South Beach neighborhoods, all associated with high density or development potential and substantial outdoor activities, be designed or adopt measures so as to not cause ground-level wind current in excess of seven miles per hour (mph) in areas of public seating and eleven mph in areas with heavy pedestrian use for no more than ten percent of the time year round, between 7 am and 6 pm, to secure acceptable comfort; and 26 mph for no more than one hour per year to secure acceptable pedestrian safety (City of San Francisco, 1985).[2] These criteria were identified by a number of empirical studies in 1970s that examined the relationship between the mechanical effect of wind on people's acceptable range of comfort and safety.[3]

Beginning in 1985, all new developments or additions to existing buildings in the five designated areas of the city have been required to provide in their environmental impact review (EIR) process an in-depth wind tunnel study. The study should examine the effect of the proposed development or addition on the ground-level wind environment in adjacent public open spaces such as streets, plazas, and parks. This planning approach to mitigate the negative impacts of building-induced wind has been enacted in other North American cities as well, notably New York, Boston, and Toronto, all of which benchmarked San Francisco's approach (American Society of Civil Engineers Task Committee on Outdoor Human Comfort, 2004).

However, despite the plan being in effect for almost 30 years, virtually no studies have empirically evaluated its effectiveness in making San Francisco's public open spaces

[1] New York City adopted the Midtown Zoning in 1982 that included standards for preserving access to daylight and air in public streets (City of New York, 1982).
[2] Related plan and planning code are detailed in Chapter 3.
[3] It should be noted that a clear distinction originally exists between standards that protect pedestrians from the adverse effects of the mechanical force of wind and the thermal effect of wind as a cooling agent in the human body's thermal regulatory system together with heating from the sun, temperature, humidity, metabolic rate, and clothing. The former comes out of a life-safety regulatory tradition, while the latter is defined as physiological comfort. In San Francisco's Downtown Area Plan, the latter was used to demonstrate that in San Francisco's climate, sun access to public space and protection from wind as a cooling agent is important, indicating that comfort was considered as a "standard" in the planning process. However, such "comfort" was not codified in San Francisco, rather standards that represent protection from the mechanical force of the wind was codified.

comfortable from excessive ground-level wind currents for its users. As climate responsiveness and resilience are becoming key tasks of planning and design today, it is time to revisit the plan and examine whether or not such an approach has been successful in accomplishing its primary original goal. In addition, given the current pressing need for cities to encourage the use of sustainable transportation modes, it is particularly important to investigate whether the plan has achieved wind comfort levels that increase people's willingness to use public transit and bike, and promote pedestrian activity. In this sense, the outcome of this study may provide useful insights for planners, designers, architects, and engineers in making livable and sustainable cities, and shed light on wind comfort issues in cities with high-density urban core or new business districts located in other parts of the world.

1.2 Motivation

Figure 1. A pedestrian holds hair as wind gusts in downtown San Francisco (Image courtesy of Mark Murrman, 2010).

In history, wise city builders noticed the impact of wind on people's daily lives and considered it something to be carefully adapted to or controlled in making cities. However, in the era of advanced Capitalism when cities vigorously compete with each other by attracting business and consumers into their commercial space, the physical forms of buildings and cities have become contextless of their climate (Gehl, 2010). Unlike the wise, today's speculative city builders have filled up downtowns with high-rise buildings, smoothly surfaced with the latest curtain wall technology, in pure box shapes in a system of perpendicular grids and made them the dominant urban landscape. Local and regional climate and the resulting microclimate conditions are often not considered in design in favor of values such as efficiency and feasibility. As a result, in many cities today, especially those associated with cool climates such as San Francisco, Chicago, Boston, New York, and even Canary Wharf, London, public streets and open spaces between high-rise developments are left with fierce winds and considerable shade as shown in Figure 1.

Some recent efforts have been made to make wind-comfortable cities. Since the late twentieth century, a group of urban designers attempted to incorporate wind into their practice and research (e.g. Lynch (1962), Whyte (1980, 1988), Hough (1984, 2004), Spirn (1984), Gehl (1987, 2010), and Bosselmann (1998, 2008)) and a number of urban climatologists and building scientists carried out research on air movement in cities and comfort of pedestrians (e.g. Jensen (1958, 1961), Davenport (1960, 1972), Penwarden (1973), Isyumov and Davenport (1975), Lawson and Penwarden (1975), Givoni (1976, 1998), Hunt, Poulton, and Mumford (1976), Jackson (1978), Lawson (1978), Melbourne (1978), and Arens (1981)). However, most urban designers lack relevant knowledge, such as the basics of fluid dynamics and simulation techniques, to carry out wind-related studies, and scientists narrowly focus on the methodological completeness of models and simulations and rarely discuss implications for urban planning and design policy. The linkage between the two groups has been very weak, the San Francisco case being one of the very few exceptions, in which the two groups successfully have collaborated with each other.

The effort to make more wind-comfortable urban environments is closely associated with some key issues and challenges planners and designers face today, which are examined in this dissertation. In the recent decades, buildings have become taller and downtowns have become denser with an increasing the number of high-rise buildings worldwide, generating windy pedestrian environments. The buildings are inducing faster winds from higher altitudes to the ground level and affecting people's perceived outdoor thermal comfort. Therefore, preventing uncomfortable wind conditions has emerged as a crucial element in achieving streets and open spaces that are walkable and livable to achieve goals that include promotion of vibrant public realm and the use of sustainable transportation modes, which is defined as taking public transit, bicycling, and walking. With regard to walking, sitting outside is included as another dimension of outdoor pedestrian activity besides walking, and thus added to the definition in this research. These goals are directly connected to resource efficiency and social vibrancy, both of which are key aspects of urban sustainability. Wind also can be utilized to mitigate the adverse effects of urban heat island by promoting natural ventilation.

1.3 Research Questions

This research incorporates an innovative mixed-method approach that combines traditional qualitative urban design research methods, such as observation, interview, and mapping, with quantitative urban climatology methods, which include statistical analyses, in order to fill in research gaps and seek robust findings that come from mixed methods research. The overarching research question explored throughout this dissertation is:

Has San Francisco's plan on ground-level wind currents made the city's public open spaces more comfortable and what is the impact on use of sustainable transportation modes?

This research question is broken down into three specific research sub-questions. The sub-questions and chapters in which they are discussed are listed below:

Sub-question #1: Urban form and Wind (Chapter 5)
Has the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment?

Sub-question #2: Wind and Comfort (Chapter 6)
Are the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco?

Sub-question #3: Wind, Comfort, and Use of Sustainable Transportation Modes (Chapter 7)
Does the plan achieve a wind comfort level that would increase people's willingness to use sustainable transportation modes?

1.4 Research Overview

The following chapters provide a detailed analysis of the overarching research question and research sub-questions.

Chapter 2 introduces several examples of city building cases in history in which wind was considered as a major element in laying out streets and siting buildings. It also presents a review of the relevant literature. While there exists only a handful of literature that empirically studies the consequences of wind planning in San Francisco, this chapter looks into a wide range of literature from the field of urban design, as well as of urban climatology, building science, and their related fields. It also reviews interdisciplinary approaches that attempt to bridge the two groups of fields and emphasizes the need for further expansion of such efforts.

Chapter 3 provides the climate and wind planning contexts of San Francisco. It presents the climatic characteristics of the city with a specific focus on its wind environment. It also walks through several key incidents in San Francisco's downtown planning history between the 1960s and 1980s and presents the establishment of 1985 Downtown Area Plan and Planning Code that

adopted principles on ground-level wind currents. Details of the Plan and Code and the stipulated wind speed criteria are also outlined in this chapter.

Chapter 4 presents the main research methodology of this dissertation, which combines a series of wind tunnel studies and a six-month field study composed of survey and on-site collection of microclimate data. It also discusses how each method is applied to the three research sub-questions and introduces the four selected study sites in San Francisco, which are Yerba Buena, Van Ness, Civic Center, and Mission Bay North areas.

Chapter 5 explores the first research sub-question, *has the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment*? It studies the relationship between urban form and wind by carrying out a series of wind tunnel studies, using scale models that represent urban forms of the four areas in 1985 and 2013. Wind speed ratios at a total of 318 locations are measured and compared to examine how the wind environment has changed after the plan was implemented.

Chapter 6 explores the second research sub-question, *are the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco?* By analyzing data collected from the field study and using ordinal logistic, simple logistic, and piece-wise regression models, it measures the relationship between wind and comfort.

Chapter 7 explores the third research sub-question, *does the plan achieve a wind comfort level that would increase the residents' willingness to use sustainable transportation modes?* It studies the relationship between wind and use of sustainable transportation modes, which include using transit, bicycling, and sitting outside. Ordinal logistic, simple logistic, and piece-wise regression models are used in analyzing data.

Chapter 8 presents a summary of the dissertation, suggests policy implications, and discusses contributions, limitations, and future research opportunities regarding this research.

CHAPTER 2. WIND AND THE CITY

This chapter presents a wide range of literature on urban form, wind, and outdoor comfort. While only a limited number of studies directly evaluate the effectiveness of San Francisco's planning efforts to mitigate the negative impacts of excessive ground-level wind currents, this chapter covers related literature more generally. It is categorized into those from urban design field and from urban climatology, building science, and related fields, and is followed by critical discussions on the interdisciplinary research gap. This chapter concludes by an overview on the relationship between building form and wind.

2.1 Literature on the Evaluation of San Francisco's Wind Planning

San Francisco's planning approach to mitigate the negative impacts of excessive ground-level wind currents on pedestrians have been mentioned multiple times by a number or researchers since its first implementation in 1985. These include Loukaitou-Sideris and Banerjee (1993), Lang (1994), Bosselmann (1998), Marcus and Francis (1998), Punter (1999), Brown and DeKay (2001), Gehl (2010), and Donn (2011), whom mentioned the significance of wind planning in San Francisco. However, these studies proceeded no further than superficially introducing this planning measure. In addition, studies by Arens, Ballanti, Bennett, Guldman, and White (1989) and Arens and Bosselmann (1989) presented how the wind speed criteria were developed and what empirical researches they were built on, but did not examine the effectiveness of the criteria in promoting outdoor comfort.

Several studies attempted empirical analysis. White (1992) studied the validity of San Francisco's ground-level wind speed criteria using wind tunnel simulations. Bosselmann, Dake, Fountain, Kraus, Lin, and Harris (1988), Zacharias, Stathopoulos, and Wu (2004), and some groups of students of the College of Environmental Design at the University of California, Berkeley (Bosselmann, 2008), examined the relationship between microclimate conditions and pedestrian comfort and behavior in a number of public open spaces in downtown San Francisco. However, their main focus was on the immediate relationship while little consideration was paid to the planning measures' overall effect on wind. Rather, Zacharias et al. (2004) called for the necessity of studying the effects of wind on spatial behavior in San Francisco in light of its wind planning standards.

In this sense, no study so far has empirically studied whether San Francisco's plan on ground-level wind currents have made the city's public open spaces more comfortable and have promoted the use of sustainable transportation modes.

2.2 Vernacular Urban Form and Historical Attempts

Vernacular settlements and architecture established in a non-planned manner over a long period of time offer good examples of microclimatic conditions influencing the layout of street grids and positioning of buildings. In old Scandinavian towns, Gehl (1987, p. 177, 2010, pp. 171–173) argues that careful consideration has been given to local climate. The narrow streets and close-packed low, attached buildings with inner courtyards, as exemplified in Figure 2, effectively block the cold northwest wind in winter while drawing more sunlight, keeping their streets and open spaces safe from uncomfortable microclimatic conditions. In cities located in hot, arid climate regions such as Tunis, Tunisia as shown in Figure 3, Brown and DeKay (2001, p. 83) suggest that the narrow streets and tall buildings create shading abundant enough to keep cities' streets cool and comfortable from the blazing sun.

Figure 2. Cold winds are diverted over rooftops in Gudhjem, Denmark (Image Courtesy of Jan Sognnes, 2007).

Figure 3. Aerial view of Tunis, Tunisia (Source: Brown and DeKay (2001, p. 83)).

Planned attempts to create microclimatically comfortable urban settlements date back to the ancient Egypt when the town of Kahan, as shown in Figure 4, was laid out around 2,000 BC in a way that houses for workers shielded the hot desert winds for those for officials (Aynsley, Melbourne, & Vickery, 1977). Feng Shui, which is known to have been first implemented in the Zhou Dynasty in the 10th century BC China and have influenced city building in many Asian countries, emphasized the need for orienting towns and buildings safe from the cold northwest wind as presented in Figure 5. Vitruvius Pollio of Rome, in Book 1 of this *De Architectura* (BC 1C, reprinted in 2005) [4], emphasized the importance of securing health and safety when choosing sites and incorporating a regular layout of street grid oriented to protect the settlement from cold winds.

In the 15th- and 16th-century Italian Renaissance, the Vitruvian theory was succeeded by Alberti and Palladio. Especially, Palladio argued for the need to make streets ample and broad in cities with cool climates and narrow in cities in hot climates (Rykwert, 1976). In the 16th-century Spain, King Philip II also implemented the Vitruvian principles in site selection, orientation, and layout of street grids in his new colonies in America and the Philippines, considering local climate and sanitation (Broadbent, 1990; Kostof, 1991; Lynch, 1981). Since the 18th century, Charleson, South Carolina, has been built in a way that allows the cool southwest breezes in summer (Brown & DeKay, 2001) as shown in Figure 6.

[4] *De Architectura* in English means "On Architecture." It is usually published under the name of *Ten Books on Architecture*.

In 19th-century Paris and early 20th-century New York, setback regulations and bulk controls on buildings were imposed on the design of new buildings to allow more direct sunlight to reach public sidewalks. As illustrated in Figure 7, in Letchworth and Welwyn garden cities in the U.K. in the beginning of 20th century, the industrial quarter was planned on the east side of the town so the prevailing winds would blow smoke away from the city (Aynsley et al., 1977). In the 1929 U.S., the Regional Plan of New York and Its Environments, more famous for a monograph on the Neighborhood Unit, suggested a set of layout principles for buildings and blocks in suburbs that would allow more sunlight and ventilation in the area for the residents' health (Heydecker & Goodrich, 1929).

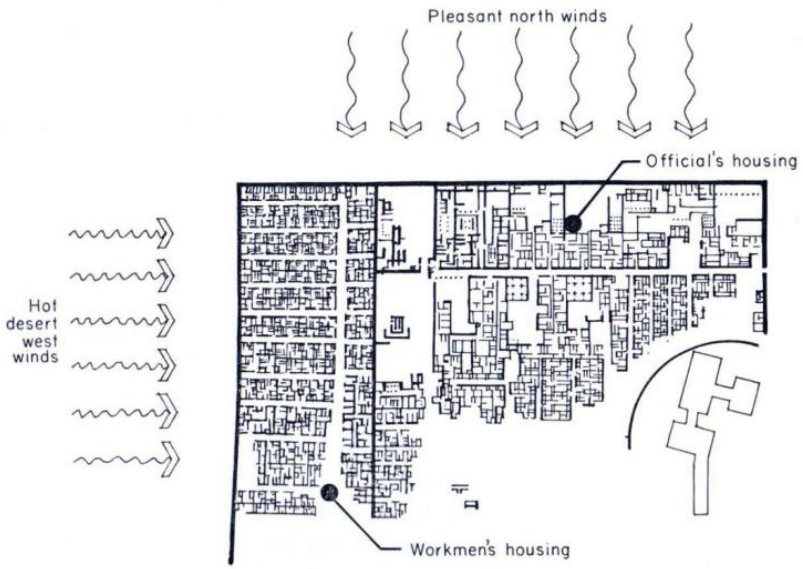


Figure 4. Housing layout in Kahan, Egypt, around 2000 B.C. (Source: Aynsley et al. (1977, p. 2).

Figure 5. Settlements in Hapcheon, Korea, in the 19th century, influenced by Feng Shui (Source: Kyujanggak Institute for Korean Studies, Seoul National University).

Figure 6. 1856 Plan of Charleston, South Carolina (Source: Brown and DeKay (2001, p. 114)).

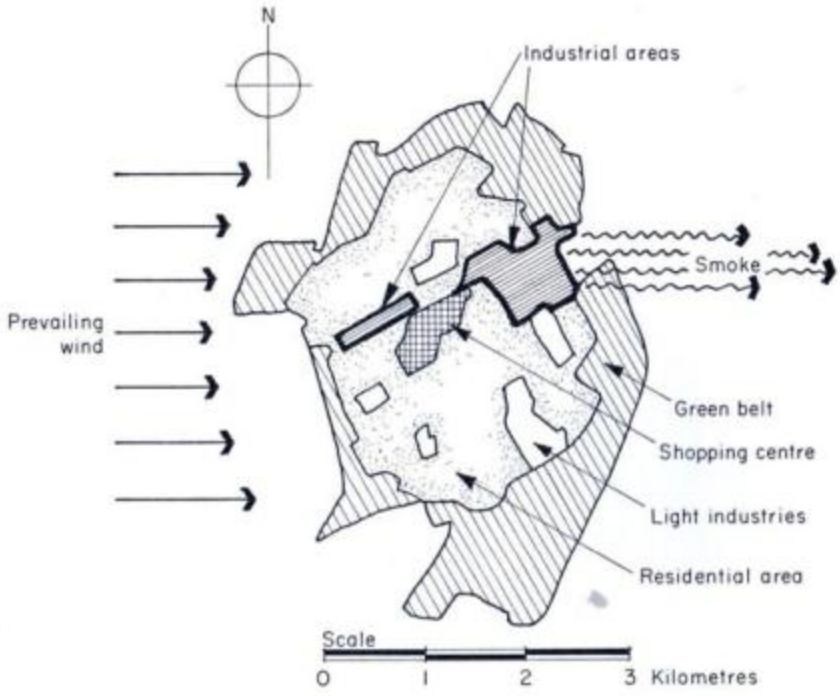


Figure 7. Plan of Letchworth indicating location of industrial areas and prevailing winds (Source: Aynsley et al. (1977, p. 10).

2.3 Contemporary Urban Design Theory

More recently, concerns about microclimatic conditions generated by urban form and the resulting environmental quality and people's comfort have drawn many urban designers' attention, notably the livability and ecology theorists. The livability theorists, influenced by the seminal works of Kevin Lynch (1962, 1981) and Jane Jacobs (1961), are interested in how the city works for its inhabitants as well as how comfortable and enjoyable they can be (Southworth, 2003). Designing public spaces that provide and secure users' comfort has been one of their prime interests and is associated with additional values they emphasize such as walkability and vitality (A. Jacobs & Appleyard, 1987; Lynch, 1981; Southworth, 2003). With regard to microclimate such as sun, wind, and noise, they emphasize its significance in promoting the quality of outdoor urban spaces that affects people's comfort and behavior such as walking, standing, and sitting (Lynch, 1962; Marcus & Francis, 1998; Whyte, 1980, 1988). The livability theorists also argue that in order to provide an appropriate level of outdoor comfort to pedestrians, various dimensions of urban form, including block size, open space size, street width and linearity, building masses and spacing, and building heights, should be well considered in urban design (Bosselmann, 1998, 2008; Gehl & Gemzøe, 2004; Gehl, 1987, 2010).

The ecology theorists, initiated by Ian McHarg (1962), seek to integrate the natural environment with urban design and promote ecologically sustainable urban space (Van der Ryn & Calthorpe, 1986; Van der Ryn & Cowan, 1996). They approach microclimate as a crucial element that should be considered in the design of the built environment and focus on the effect of various urban forms on air movement, amount of sunlight let into the city, vegetation, and urban heat island. They also suggest alternative ways of ecological design that mitigate unfriendly microclimatic situations and argue that the orientation of buildings, streets, and parks can be used to funnel desired breezes and block unwanted winds to capture heat or reduce its absorption (Hough, 1984, 2004; Spirn, 1984).

2.4 Literature from Urban Climatology, Building Science, and Related Fields

Awareness of urban climatology was first recorded in the mid-18th century when explorers reported that they witnessed differences air temperature between town and countryside, and extraordinary hot climate occasions on the east coast of the U.S. (Emmanuel, 2005). Later in the 19th and early 20th century, studies on inadvertent urban climate modifications and radiative cooling, and development of instruments for climate research have been carried out (Landsberg, 1981).

Wind and the Built Environment

In the second half of the 20th century, the concept of the terrestrial boundary layer, a vertical profile of wind, was recognized. It embodies the vertical variation of wind speeds in a layer of the atmosphere that is slowed by the roughness of grass, trees, buildings, and numerous other sources of surface drag. The wind velocity increases with height, eventually reaching a constant

value at the top of the boundary layer (Givoni, 1998). This vertical distribution was first mathematically explained by Jensen (1958, 1961), who suggested a logarithmic law of the vertical profile of wind, and Davenport (1960), who developed an exponential formula called the "power law." [5] In practice, the difference between the two models is small. The boundary layer changes in the vertical wind profile over urban, suburban, and rural areas are presented in Figure 8. The upper wind is equal for each boundary layer, and is the gradient wind that is unaffected by surface roughness and follows the atmospheric pressure gradients between high and low pressure zones.

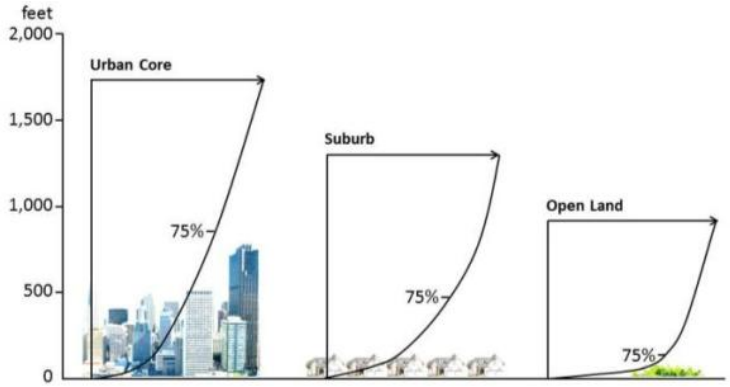


Figure 8. Boundary wind layer.

Beginning in the 1960s and 1970s, studies on wind started to prosper when awareness was raised about unfavorable wind changes associated with the construction of new urban buildings (Durgin & Chock, 1982). Researchers reported on uncomfortable and dangerous wind conditions in cities that made walking difficult, even knocking pedestrians off their feet (Lawson & Penwarden, 1975; Penwarden, 1973; Wise, 1971). Such concerns triggered studies on the mechanical effect of steady winds, non-uniform winds, and wind gusts on people (Hunt et al., 1976; Jackson, 1978; Lawson & Penwarden, 1975; Murakami & Deguchi, 1981; Murakami, Iwasa, & Morikawa, 1986). Some studies, in succession of Beaufort Scale originally developed in 1805, presented various sets of criteria on wind comfort and safety (Arens, 1981; Bottema, 2000; Hunt et al., 1976; Isyumov & Davenport, 1975; Lawson, 1978; Melbourne, 1978; Murakami et al., 1986; Penwarden, 1973; Soligo, Irwin, Williams, & Schuyler, 1997; Willemsen & Wisse, 2007), some of which are introduced in the next chapters.

A body of research focuses on wind movement patterns around buildings. Following the seminal work by Jensen and Franck (1963), who examined the wind-sheltering effect of buildings in open country, researchers have experimentally been studying the resulting wind environment around various building settings or types of structures, including street canyons (Ahmad, Khare,

[5] Davenport's (1960) Power Wind Law is described as $\frac{V_Z}{V_G} = \left(\frac{Z}{Z_G}\right)^{\rho}$, where

V_Z: wind speed at height Z; V_G: gradient wind velocity occurring above the boundary layer; Z: height for which wind speed V_Z is computed; Z_G: height at which the V_G is first observed; ρ: empirical exponent which depends on the surface roughness, stability, and temperature gradient.

& Chaudhry, 2005; Blocken, Stathopoulos, & Carmeliet, 2008; Ca, Asaeda, Ito, & Armfield, 1995; Jamieson, Carpenter, & Cenek, 1992; Nakamura & Oke, 1988; Stathopoulos & Storms, 1986; Stathopoulos & Wu, 1995), high-rise buildings (Isyumov & Davenport, 1975; Jones, Alexander, & Burnett, 2004; Tsang, Kwok, & Hitchcock, 2012), sport stadium (Blocken, Stathopoulos, & Carmeliet, 2008), various arrangements of buildings (Brown & DeKay, 2001; Zhang, Gao, & Zhang, 2005), and vegetation (B. Lin, Li, Zhu, & Qin, 2008; Mochida, Tabata, Iwata, & Yoshino, 2008; Robinette, 1972).

In addition, Donn (2011) provided a detailed review on lessons from 25 years of wind planning experience in Wellington, New Zealand, a city that has not only enforced strictly enforced regulations on building design but also provided applicable guides for urban designers and architects. After reviewing, he proposed a new set of criteria for comfort and safety in urban environments by redefining the criteria based on data from the city in order to facilitate public debates about the merits of wind planning among planning officials and the general public.

Comfort Models

Another group of researchers have been developing outdoor thermal comfort models or indices that incorporate various microclimate elements, including wind, and the concept of energy balance of the human body. As shown in Figures 9 and 10, Olgyay (1963) developed the Bioclimatic Chart which delineates a comfort range determined by relative humidity, temperature, radiation, and wind speed, and was followed by Givoni (1976) who suggested the Building Bioclimatic Chart which also defines a comfort range but additionally takes into account passive cooling by ventilation, thermal mass, evaporative cooling, and passive solar.

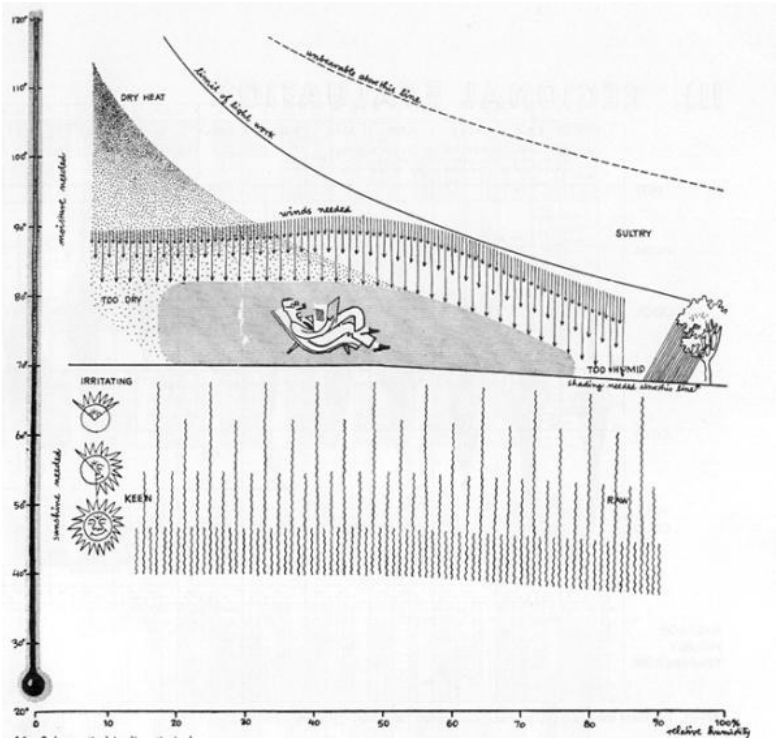


Figure 9. Olgyay's (1963) Bioclimatic Chart and its comfort zone determined by relative humidity, temperature, radiation, and wind speed.

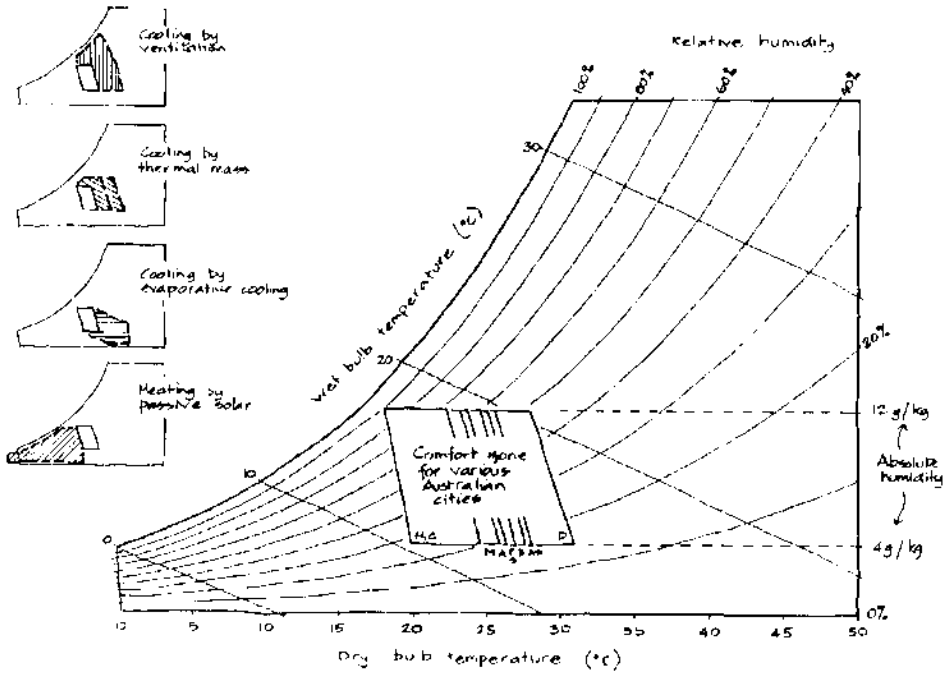


Figure 10. Givoni's (1976) Building Bioclimatic Chart that incorporates passive cooling (adapted by United Nations Centre for Human Settlements (1990, p. 85) from Givoni (1976)).

Various thermal comfort models have been developed assess thermal conditions. Two well-known examples are Fanger's PMV/PPD model and Gagge's Pierce Two-Node model. Fanger (1972), using a heat balance equation of human body, proposed the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. PMV is an index that combines six primary factors of thermal comfort (metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity) to predict the mean value of thermal sensational votes on a seven-point thermal sensation scale (-3: cold; -2: cool; -1: slightly cool; 0: neutral; 1: slightly warm; 2: warm; 3: hot). PPD is related index that establishes a quantitative prediction of the percentage of thermally dissatisfied people voting -3, -2, +2, or +3 on the thermal sensation scale.[6] The acceptable thermal environment, in which 80% of the people are satisfied, defined by the PPD/PMV model is when $-0.5 < PMV < +0.5$ and $PPD < 10$. While Fanger's PMV/PPD model assumes a steady state of equilibrium, Gagge's Pierce Two-Node heat balance model considers transient conditions, allowing the changes in body temperature with exposure time to be evaluated (Gagge, Stolwijk, & Hishi, 1971; Gagge, 1973).

The two-node model computes a thermal comfort model index, is the Standard Effective Temperature (SET) developed by Gagge, Fobelets, and Berglund (1986). SET is an index that indicates the warmth of an environment and is defined as the temperature of an imaginary environment (relative humidity = 50%, air speed < 0.1 m/s; and air temperature equals radiant temperature), in which the total heat loss from the skin of an imaginary person (1.0 met and 0.6 clo) is equal to that of the person in the actual environment. This index enables air speed effects on thermal comfort to be related across a wide range of air temperatures, radiant temperatures, and humidity ratios.

With respect to outdoor thermal comfort, the Wind Chill index, which reflect the perceived decrease in air temperature due to wind, has been developed since the 1940s (American Society of Civil Engineers Task Committee on Outdoor Human Comfort, 2004). More recently, Höppe and Mayer (1987) and Mayer and Höppe (1987) developed the Physiological Equivalent Temperature (PET), which is defined as the air temperature of an imaginary environment (water vapor pressure = 12 hPa (or relative humidity = 50%), air speed = 0.1 m/s; and air temperature equals radiant temperature), in which the total heat loss from the skin of an imaginary person (work metabolism 80 W of light activity plus basic metabolism and 0.9 clo) is equal to that those outside. Using a heat balance model to compute the index, PET enables a person to compare the integral effects of complex thermal conditions outside with indoors (Höppe, 1999).

2.5 Building Form and Wind

Literature has also identified the substantial influence of the physical form of buildings on the surrounding ground-level wind environment, thus affecting people's outdoor thermal comfort. This section presents a brief overview of several building form characteristics that are accused for generating excessive ground-level winds.

[6] The mathematical relationship between PMV and PPD is as follows:
$PPD = 100 - 95 \cdot exp(-0.03353 \cdot PMV^4 - 0.2179\ PMV^2)$.

The first is building height. High-rise buildings are frequently criticized for adversely affecting the ground-level wind environment (American Society of Civil Engineers Task Committee on Structural Wind Engineering, 2012; Aynsley et al., 1977; Brown & DeKay, 2001; Givoni, 1998). As shown in Figure 11, especially in the case of rectilinear building forms, faster winds at higher altitudes are drawn down to the ground-level along the smooth façade of the building via a mechanism called "downwash." When the wind hits the ground, it becomes turbulent and creates vortexes, generating an uncomfortable wind environment for pedestrians. The wind also travels around the building, generating the "corner effect." On the leeward side of the building, a spiraling upward flow called "wake effect" creates turbulent wind environment. Another building form characteristic is the distance between buildings. When two or more buildings are located close to each other, the flowing wind is accelerated between the buildings through a channel, which is called the "Venturi effect." Researchers suggest that setting up fences or utilizing vegetation can be useful in mitigating the adverse effects of accelerated winds between buildings (American Society of Civil Engineers Task Committee on Structural Wind Engineering, 2012). In addition, researchers have argued that high-rise buildings located among lower buildings (Givoni, 1998) creates strong downward wind currents in the surrounding area. Others suggested that continuous street walls composed of uniform building facades (City of San Francisco, 1985) also result in greater wind accelerations.

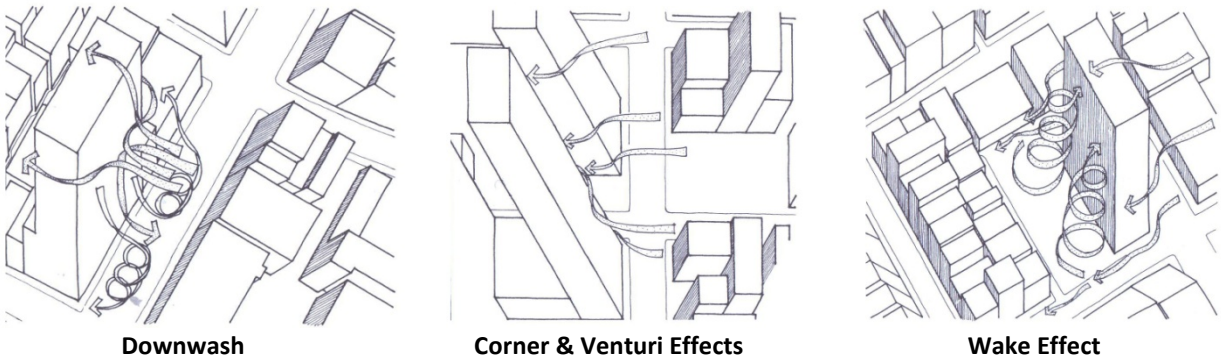


Figure 11. Various wind movement patterns around a high-rise building: downwash, corner effect, and wake effect (Source: Brown and DeKay (2001, p. 99)).

In response, several studies and reports have presented design principles that can mitigate the adverse effects of wind. Especially in the case of high-rise buildings, as shown in Figure 12, several ways have been proposed to block the faster winds coming down to the ground level from higher altitudes, generating discomfort. These solutions include installing canopies just above the pedestrian level, adopting building setbacks, and maintaining gradual changes in building heights. could effectively secure a more comfortable pedestrian environment (Bosselmann et al., 1984; Brown & DeKay, 2001; City of San Francisco, 1985; Wellington City Council, 2000).

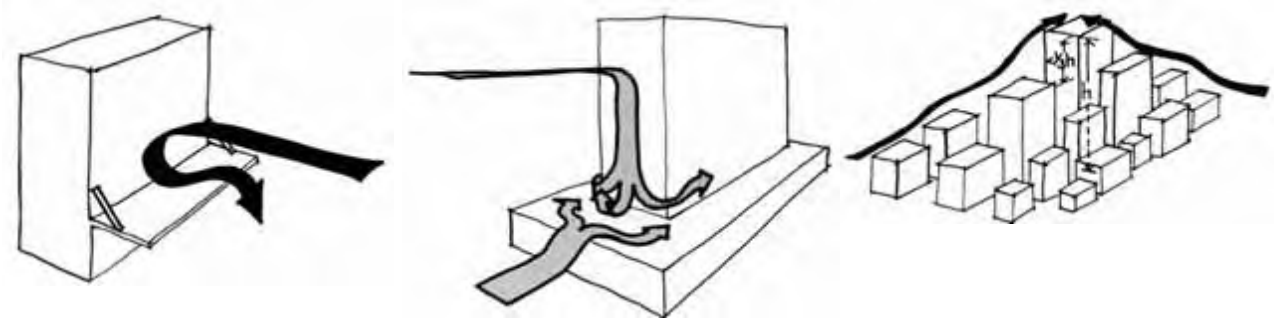


Figure 12. Example building forms can mitigate the adverse effects of wind on pedestrians (Source: Wellington City Council (2000)).

2.6 Assessment of Existing Literature and Interdisciplinary Approaches

This section provides an assessment of existing literature on wind and urban form. It also reviews the interdisciplinary approaches by a growing number of researchers and makes a case that such an approach should be reinforced in this research.

Assessment of Existing Literature

Given a common academic interest of the two distinct groups of wind, comfort, and design fields, it is difficult to overlook that a wide gap exists between the two. Not much attention has been paid to developing a comprehensive approach that melds qualitative, normative design ideas with quantitative simulation methods. Critically speaking, the urban design approaches on wind and comfort, mostly by the livability and ecology theorists, are no more than normative arguments that reiterate those from past research. They do not provide any additional empirical findings and substantive evidences in their arguments. At the same time, urban climatologists and building scientists use state-of-the-art simulation techniques and models. However, their approaches excessively focus on the criteria or models themselves and the scientific completeness of methods, while seeking little connection to local planning and design policies.

Calls for cooperation between the two groups of fields were made more than half a century ago. Lynch (1962, p. 102) emphasized the need for urban designers to understand the microclimate conditions in cities by saying the following:

> *"Neglect of these (microclimate) factors is bound to produce a worsening of climate in the act of building. Attention to them, even with our present incomplete knowledge, can improve it substantially. It remains true, however, that we have much to learn about climate, particularly about its application to the art"*

Olgyay (1963) and Givoni (1976) suggested a series of neighborhood and urban design solutions that respond to regional climate and microclimate characteristics. Penwarden (1973) and Jackson

(1978) provided seminal guidance on wind effects and the resulting thermal comfort for design practice. They were followed by a number of urban climatologists and building scientists who argued for collaboration (Barlag & Kuttler, 1990; DeSchiller & Evans, 1996; Eliasson, 2000; Givoni, 1998; Nikolopoulou & Steemers, 2003; Willemsen & Wisse, 2007).

Interdisciplinary Approaches

These calls have remained largely unheeded with the exception of a small group of studies that used interdisciplinary approaches. They include a series of studies on microclimatic environment and comfort in relation to urban form in San Francisco (Arens et al., 1989; Bosselmann et al., 1984; Bosselmann, Flores, & O'Hare, 1983), Toronto (Bosselmann, Arens, Dunker, & Wright, 1990), and Wellington, New Zealand (Donn, 2011).

Fortunately, there have been more interdisciplinary approaches since the 2000s. Capeluto, Yezioro, and Shaviv (2003) evaluated the design of a new business district in Tel Aviv from and argues foe the need to adopt design standards based on wind and sunlight performance. Lenzholzer and van der Wulp (2010) interviewed users' of Dutch public plazas and found that width of the square, spatial openness and appearance of materials have a significant influence on thermal comfort. The American Society of Civil Engineers (2004; 2012; 2011) published several guidebooks on wind, aerodynamics, and thermal comfort for planners and designers. Ng (2009) and Ng, Yuan, Chen, Ren, and Fung (2011) and assessed wind environment in various urban morphological settings in Hong Kong and suggested a set of urban design guidelines for better air ventilation. Szűcs (2013) studied the relationship between wind speed and outdoor activities in Dublin and found that a number of extremely windy locations are found in the city and that windy urban environment can restrain frequentation of urban space. Middel, Häb, Brazel, Martin, and Guhathakurta (2014) analyzed the impact of various residential building types on microclimatic conditions in Phoenix and argued for the need of compact urban forms to achieve effective cooling as an urban heat island mitigation strategy.

Despite the small number, these studies reveal that there is a growing concern on the needs for interdisciplinary research to develop and implement solutions for urban environmental issues. They include climate change, urban heat island, and urban resiliency, all of which have emerged recently as key challenges in planning especially since 2010. What remains to be explored and reinforced is the comprehensive approach that bridges the two distinctive groups of fields, which would result in a series of applicable, concrete, effective, place-based research findings. In this sense, this dissertation research follows this interdisciplinary trajectory by incorporating technological simulation techniques to evaluating an urban policy and to examining people's behavior.

CHAPTER 3. SAN FRANCISCO'S CLIMATE AND WIND PLANNING

This chapter discusses the climate context of San Francisco and the background story of how the city's implementation of wind planning. It also introduces the planning objectives and policies on wind and comfort conditions in the Downtown Area Plan section of the San Francisco General Plan and related Sections in the Planning Code.

3.1 Climate of San Francisco

"*The coldest winter I ever spent was a summer in San Francisco.*"

Although this quote is incorrectly attributed to Mark Twain, the actual source of these words is unknown. However, it is essentially one of the best descriptions of San Francisco's unique climate. Characterized by moist mild winters and dry cool summers, the city's climate falls under the typical cool-summer Mediterranean climate, or Csb, according to the Köppen climate classification,[7] and under Climate Zone 3C (Warm-Marine) according to the ANSI/ASHRAE/IES Standard 90.1-2013.[8 & 9] As shown in Figure 13, temperatures usually range between 40 and 60 °F in winter and 50 and 80 °F in summer. The monthly wind speed averages in winter are the lowest at 6 – 7 mph and in summer the highest around 11 mph.

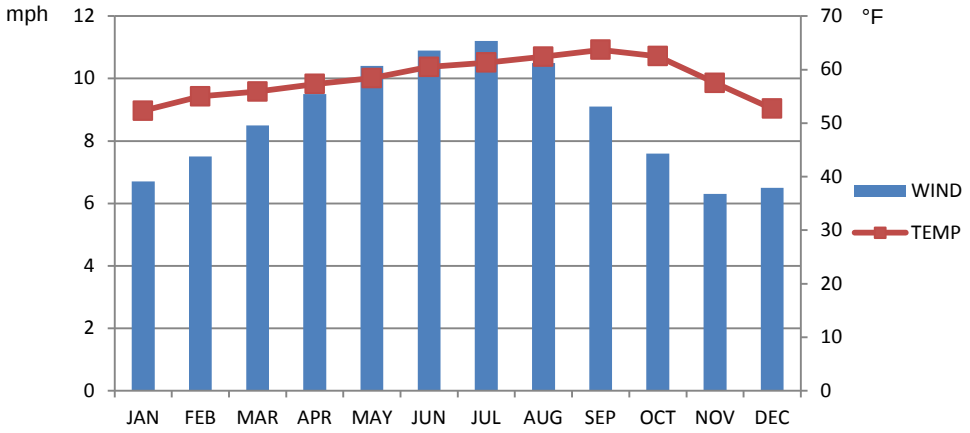


Figure 13. San Francisco's monthly average wind speed and temperature (Source: National Climatic Data Center (http://www.ncdc.noaa.gov/)).

[7] In the Köppen climate classification, "C" zones have an average temperature above 50 °F in the warmest months and between 27 and 64 °F in the coldest months. "s" represents dry summers. "b" refers to the average temperature in the warmest month below 72 °F with at least two months averaging above 50 °F.
[8] ANSI stands for the American National Standards Institute, ASHRAE for the American Society of Heating, Refrigerating, and Air Conditioning Engineers, and IES for the Illuminating Engineering Society of North America.
[9] In the ANSI/ASHRAE/IES Standard 90.1-2013, "C (marine)" zone is defined to meet the following criteria: average temperature of the coldest month between 27 and 65 °F; average temperature of the warmest month below 72 °F; at least four months with average temperatures over 50 °F; and dry season in summer.

Many people would think of San Francisco as a windy city, but it is not the windiest city in the U.S. Table 1 shows that the city's annual average wind speed is 8.7 mph, substantially lower than that of other major U.S. cities that are notorious for fierce wind such as Boston, Oklahoma City, Wichita, and Chicago. One interesting fact about the annual wind speed distribution in San Francisco is that wind is usually faster in summer (11.2 mph in July) and slower in winter (6.3 mph in November), while most cities experience faster winds in winter and slower winds in summer. However, the wind speed level of San Francisco in summer can never be underestimated since it reaches up to a similar level with that of Chicago and even higher than New York in winter. The cool temperatures in summer, wide variance in microclimatic conditions due to the dynamic topography, and downtown skyscrapers that accelerate winds are the key factors that make the residents of San Francisco feel cold and windy from mid-Spring to mid-Autumn.

Table 1. Annual and monthly average wind speeds (mph) of major U.S. cities.[a]

Rank	City	Ave	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Boston, MA	12.3	13.7	13.6	13.6	13.0	12.0	11.2	11.0	10.8	11.2	11.8	12.5	13.3
2	Oklahoma City, OK	12.2	12.5	13.1	14.3	14.2	12.5	11.8	10.8	10.4	10.8	11.8	12.3	12.3
3	Wichita, KS	12.2	11.9	12.3	13.8	14.0	12.3	12.2	11.2	11.1	11.6	11.8	12.1	11.7
4	Milwaukee, WI	11.5	12.6	12.2	12.7	12.8	11.5	10.4	9.7	9.5	10.4	11.4	12.4	12.2
5	Dallas-Fort Worth, TX	10.7	11.0	11.7	12.6	12.4	11.1	10.7	9.7	8.9	9.3	9.7	10.7	10.8
6	Kansas City, MO	10.6	11.1	11.1	12.3	12.3	10.4	9.9	9.2	8.8	9.5	10.5	11.2	10.9
7	Minneapolis-St. Paul, MN	10.5	10.5	10.4	11.3	12.2	11.1	10.4	9.4	9.2	10.0	10.6	11.0	10.4
8	Cleveland, OH	10.5	12.2	11.8	12.0	11.5	10.0	9.2	8.6	8.2	8.9	9.9	11.7	12.0
9	Chicago, IL	10.3	11.6	11.3	11.8	11.9	10.5	9.3	8.4	8.2	8.9	10.0	11.1	11.0
10	Tulsa, OK	10.2	10.3	10.7	11.9	11.9	10.6	9.9	9.3	8.8	9.1	9.6	10.3	10.1
	...													
18	New York, NY	9.1	10.4	10.6	10.8	10.1	8.7	8.0	7.5	7.3	7.9	8.6	9.6	9.9
	…													
26	Seattle, WA	8.8	9.5	9.3	9.4	9.3	8.9	8.6	8.1	7.8	8.0	8.3	9.0	9.6
27	**San Francisco, CA**	**8.7**	**6.7**	**7.5**	**8.5**	**9.5**	**10.4**	**10.9**	**11.2**	**10.5**	**9.1**	**7.6**	**6.3**	**6.5**
	…													
44	Phoenix, AZ	6.2	5.3	5.8	6.6	6.9	7.0	6.7	7.1	6.6	6.3	5.8	5.3	5.1
	…													
46	Los Angeles, CA	5.1	5.5	5.8	5.9	5.7	5.5	4.8	4.4	4.3	4.5	4.6	5.2	5.2

Notes: a. Cities with population over 300,000; see Appendix A for complete table.
Source: National Climatic Data Center (http://www.ncdc.noaa.gov/).

The Central Valley, as shown in Figure 14, is a flat plain surrounded by the Coast Ranges on the west and the Sierra Nevada mountain range on the east that stretches approximately 50 miles from west to east and 450 from north to south, inland from and parallel to the Pacific Ocean. It plays a key role in increasing the wind speed of San Francisco in summer. In summer, the Valley's daytime temperatures usually reach 100 °F, and regular heat waves frequently bring up temperatures exceeding 115 °F, generating extensive updrafts. Then a large cool air mass from the Pacific Ocean is induced to fill in the gap and passes over San Francisco where the Coast Ranges discontinue momentarily at the Golden Gate Bridge, generating a high level of wind in the city.

Figure 14. Location of San Francisco and Central Valley.

3.2 From the Manhattanization of San Francisco to 1985 Downtown Area Plan

San Francisco's planning on ground-level wind currents was first shaped by a series of trends, including the Manhattanization of San Francisco in the 1960s and 1970s, Anti-High-Rise Movement in the early 1980s, Proposition K of 1984, and the enactment of a new Downtown Area Plan in 1985.

Beginning in the mid-1960s when suburbanization was nearing its apex throughout the country, San Francisco was one of the few cities that not only maintained its downtown but also accelerated its growth (Vettel, 1985). One of the consequences of such growth was the rapid increase of square footage of office space in downtown that doubled between 1965 and 1983, most of which was accommodated in newly constructed high-rise office towers in the Financial District (Keating & Krumholz, 1991), resulting in the so-called "Manhattanization" of San Francisco. Figure 15 illustrates that many of the buildings that dominate San Francisco's urban skyline today, including the Transamerica Pyramid, 555 California Street, McKesson Plaza, and One Embarcadero Center, were constructed in this period.

Figure 15. Completion year of major high-rise buildings in downtown San Francisco.

However, citizens started to raise concerns on the adverse impact of downtown development on city's residential neighborhoods, housing, mass transit, employment, and historic buildings, which initiated the "Anti-High-Rise Movement" in the early 1980s (Hartman, 2002). One of their concerns was the deteriorating environmental quality of San Francisco's public open spaces, which was supported by critics who argued that existing planning measures, including incentive zoning and design reviews, failed to provide outdoor spaces that provide amenities people feel welcome and comfortable (Loukaitou-Sideris & Banerjee, 1993, 1998). Although the City had already required a wind study for new high-rise buildings as a part of its environmental review process since the 1970s (Arens et al., 1989), many of the city's downtown public open spaces became uncomfortable places to walk or stay due to excessive ground-level winds and shades induced by the surrounding high-rise buildings (Hartman, 2002; Vettel, 1985).

Two studies carried out by researchers in the Institute of Urban and Regional Development (IURD) at the University of California, Berkeley provided technical support to the citizens' concerns. One study in 1983 analyzed sun access in downtown streets and open spaces that are located adjacent to sites with strong development potential for high-rise buildings. Based on a series of simulations, the study recommended that new developments should be designed to provide sun access to sidewalks at midday and to public open spaces for relaxation (Bosselmann et al., 1983). The second study in 1984 examined the effects of new developments on sun and wind conditions at the street level, evaluating their combined effects on the pedestrian outdoor thermal comfort. As shown in Figure 16, using a series of boundary layer wind tunnel simulations and comfort modeling, it found that many places in San Francisco are under threat of wind environment adverse enough to produce discomfort, and recommended that the ground-level wind conditions in San Francisco can be significantly improved by better building designs and securing gradual changes in building heights, as illustrated in Figure 17 (Bosselmann et al., 1984).

Figure 16. Example images of IURD's wind tunnel test results in the Van Ness area (Source: Bosselmann et al. (1984, pp. 88–89)).

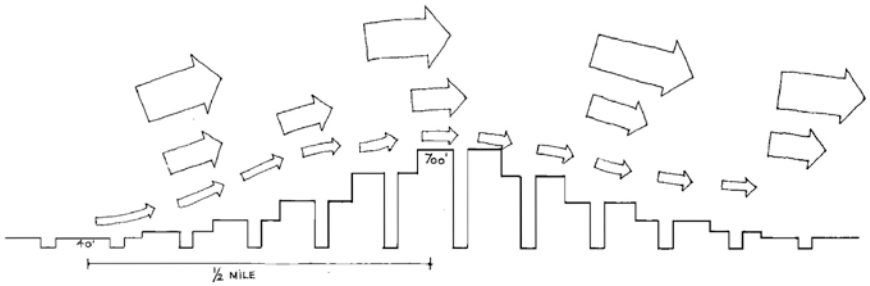


Figure 17. Gradual changes in urban skyline may improve the general wind condition in downtown San Francisco (Source: Bosselmann et al. (1984, p. 139)).

Sunlight was the first microclimate element that gained political support. In June 1984, Proposition K, a voter referendum measure also known as "no new shadows" or "sunshine" rules, was approved by 61 percent of the voters (Lai, 1988). It prevented the development of any structure over 40 feet tall that would cast a shadow on a city-owned public open spaces, and mandated preservation of sun access as important amenity (Arens & Bosselmann, 1989; Loukaitou-Sideris & Banerjee, 1993; Punter, 1999; Vettel, 1985). Then in July 1985, the Downtown Area Plan as a part of San Francisco General Plan was enacted by the Board of Supervisors by a 6 to 5 vote after its original issue in 1983 (Lai, 1988).[10] Composed of 8

[10] San Francisco's 1985 Downtown Area Plan is also famous for being the first downtown plan in the U.S. that imposed limitations on growth in pursuit of vitality and efficiency (Keating & Krumholz, 1991). It implemented bulk and height controls (decreased floor area ratios), removal of density bonus, encouragement of new developments in South of Market (partly using transfer of development rights), restrictions on supply of new office floor space, and "linkage" provisions for equitable development (Vettel, 1985). Under this Plan, the allowable floor-area-ratio of new buildings in the Financial District was lowered from 14:1 to 9:1, and permissive building heights were also lowered from 700 feet to 550 feet. Also, a tight cap on new office floor space was established at 950,000 square feet (sqft) per year over the following 3 years, and was later modified to 500,000 sqft in the 1986 Proposition M. (Lai, 1988).

elements, 23 objectives, and 72 policies [11], the Plan included objectives and policies on wind, as well as those on sun access.

3.3 Wind-Related Contents in Downtown Area Plan

Table 2 introduces wind-related objectives and policies found in the Open Space and Urban Form elements of San Francisco's Downtown Area Plan. Each element includes one objective and one implementation policy that in combination provide planning principles on ground-level wind currents in the downtown. In the Open Space element, Objective 10 and Policy 10.5 emphasize that the minimization of adverse wind is crucial to well-designed open spaces, allowing accessibility and usability for its users. In the Urban Form element, Objective 14 and Policy 14.2 suggest the need for creating and maintaining comfortable pedestrian environments by regulating the physical form of new developments that would generate ground-level wind currents in the surrounding streets and open spaces. Guidelines on building designs that effectively reduce wind speed and comfortable wind speed in places for walking and sitting are also provided.

Table 2. Wind-related contents in Downtown Area Plan.

Element	Objective	Policy
Open Space	*Objective 10* Assure that Open Spaces are Accessible and Usable.	*Policy 10.5* Address the need for human comfort in the design of open spaces by minimizing wind and maximizing sunshine
Urban Form	*Objective 14* Create and Maintain a Comfortable Pedestrian Environment.	*Policy 14.2* Promote building forms that will minimize the creation of surface winds near the base of buildings. Variation in ground level wind impacts is related to several factors: • Exposure of the building to the prevailing wind direction, the more exposed a building is, the greater the volume and momentum of the wind intercepted, and the greater the potential for wind accelerations at street level. • The shape, area and uniformity of the upwind facade. Relatively large, uniform facades typically result in greater wind accelerations than do narrow or complex facades with numerous setbacks. These factors should be taken into account in the massing and detailing of new buildings. Exposed facades should use setbacks at various levels, and other configured shapes and design features, to reduce wind impact. In buildings of a size likely to cause problems, wind tunnel tests of alternative building masses should be undertaken and the results employed in selecting the shape of the building. As a general rule, a building form should not be used which causes wind speeds to exceed eleven miles per hour in areas where people are walking and seven miles per hour where people are sitting.

Source: San Francisco General Plan (http://www.sf-planning.org/ftp/General_Plan/index.htm).

[11] The eight elements of the 1985 Downtown Area Plan are Space for Commerce, Space for Housing, Open Space, Preserving the Past, Urban Form, Seismic Safety, Pedestrian Network Classification of Elements, and Fundamental Principles for the Downtown Pedestrian Network.

3.4 Wind-Related Contents in Planning Code

In the San Francisco Planning Code, there are five sections that present details of the wind planning: sections 148, 249.1, 243, 263, and 825. Section 148 was established simultaneously with the 1985 Downtown Area Plan while the others were implemented later as they became necessary.

Implemented Areas

The five sections designate implementation of wind regulation in five zoning districts: Downtown Commercial (C-3) Districts, Van Ness Special Use District, Folsom & Main Residential/Commercial Special Use District, South of Market Residential/Service Mixed Use (RSD) 40-X/85B Height District, and Downtown Residential (DTR) Districts. As summarized in Table 3, areas currently contained within these zones include 479 parcels on 496 acres of land. Permitted density and building height in the five zones are generally high, implying that areas with high density or development potential are prone to a high level of ground-level wind currents.

Table 3. Adopted year, location, and zoning information by each Planning Code section.

Planning Code Section	Adopted Year	Implemented Zoning District		Permitted Density (FAR)	Permitted Height (ft)	Total Area (acre)	Total Number of Parcels
148	1985	Downtown Commercial (C-3) Districts	Downtown Office (C-3-O)	18:1	75 – 550	80	67
			Downtown Office Special Development (C-3-O (SD))	18:1	150 – 450	79	48
			Downtown Retail (C-3-R)	6:1	85 – 400	54	29
			Downtown General Commercial (C-3-G)	6:1	65 – 320	97	63
			Downtown Support (C-3-S)	5:1	50 – 320	44	14
			Total	-	-	354	221
243	1988	Van Ness Special Use District		4.8:1	80 – 130	69	174
249.1	1985	Folsom & Main Residential/Commercial Special Use District		5:1[a]	400	5	2
263.11	1990	South of Market Residential/Service Mixed Use (RSD) 40-X/85B Height District		1.8:1[a]	80 – 130	1	1
825	2013	Downtown Residential (DTR) Districts[b``]	Rincon Hill DTR District	No limit[c]	40 – 200	30	66
			South Beach DTR District	No limit[c]	40 – 200	37	14
			Total			67	80
Total				-	-	496	479

Notes: a. Applies to non-residential use only; b. Does not include Transbay Downtown Residential (TB-DTR) District; c. Applies to residential use only.
Source: San Francisco Planning Department (http://www.sf-planning.org/).

As shown in Figure 18, the five zones are all located in the northeastern part of San Francisco along Market Street and Van Ness Avenue and near South Beach. Figure 19 presents their current status, either already have been developed or being under development potential.

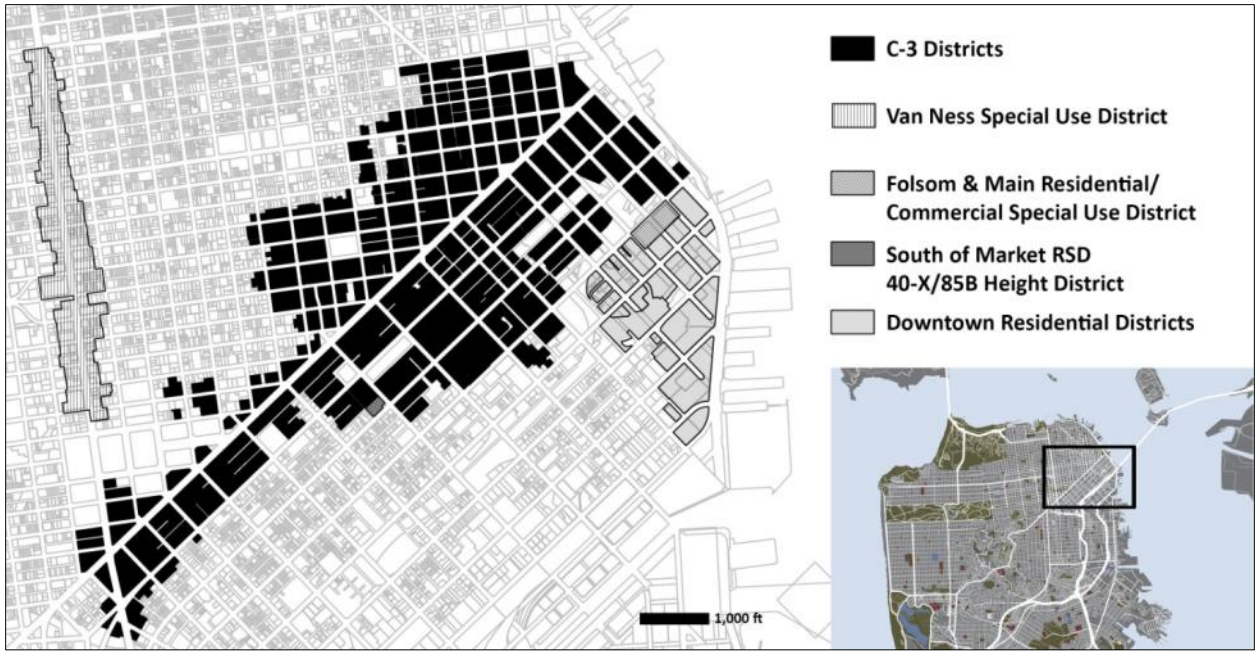


Figure 18. Areas subject to wind planning in San Francisco.

Composed of Districts for office (C-3-O), retail (C-3-R), general Commercial (C-3-G), support (C-3-S), and special office development (C-3-O (SD)), the Downtown Commercial (C-3) Districts cover a large portion of the Financial District, as well as Chinatown, Civic Center, and South of Market (SOMA) neighborhoods. These neighborhoods have long been associated with the highest density in the city, ceaselessly being filled with extensive high-rise developments. The largest pedestrian traffic in the city and a wide range of pedestrian activities are frequently observed in major streets, such as Market, Montgomery, Kearny, and Powell Streets, and in public open spaces, including Union Square, Yerba Buena Gardens, United Nations Plaza, and the Embarcadero.

The Van Ness Special Use District, established in 1988, has been an area with high development potential under the Van Ness Avenue Area Plan which fostered new high-density mixed-use developments and pedestrian-friendly environment along the Van Ness Avenue corridor between Broadway Street in the north and Golden Gate Avenue in the south. The linear cluster of automobile showrooms and service facilities in the 1980s has become a major transit corridor with gradually increasing number of mixed-use apartment buildings. The district also carries the 25-story Holiday Inn Golden Gateway Hotel built in 1973, as well as the 12-story Cathedral Hill Hotel built in 1959, on which a new 226-foot tall hospital building is proposed.

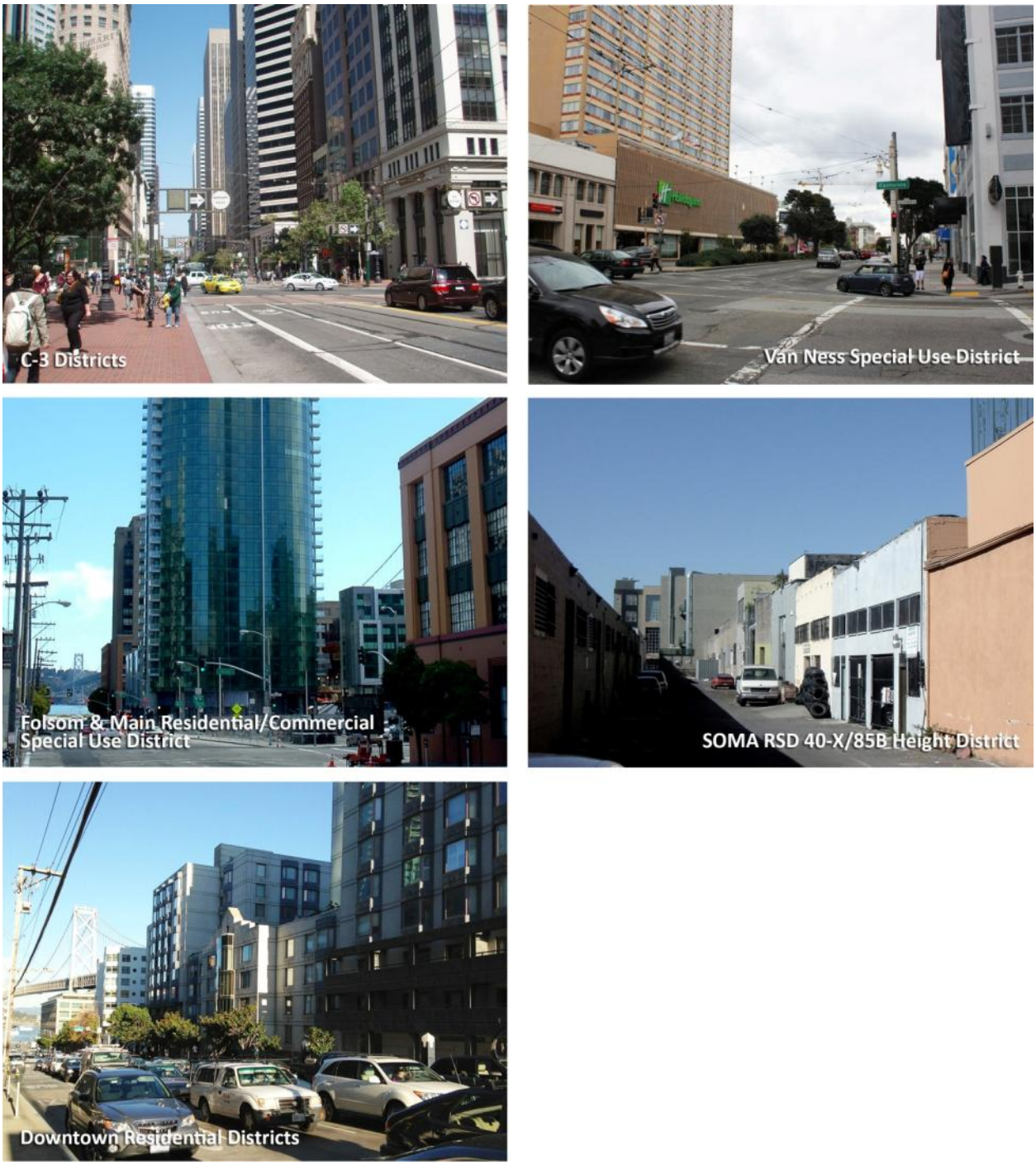


Figure 19. Development status of the five areas, as of 2013, where wind planning code is applied

The Folsom & Main Residential/Commercial Special Use District, established in 1985, is composed of two parcels that are located on each side of Main Street south of Folsom Street in the Rincon Hill Neighborhood. The district has been designated to convert under-utilized and outmoded industrial areas to high-density development that mixes residential, office, and retail

close to the downtown. As of 2014, the parcel on the east side of Main Street is the venue of The Infinity, a 650-unit mixed-use condominium consisting of two high-rise towers, 37 and 41 stories, and two low-rise buildings,. The other parcel on the west is currently being used as a parking lot.

The South of Market Residential/Service Mixed Use (RSD) 40-X/85B Height District was established in 1990. Located in the west side of 5th Street, the district is composed of six parcels on one block. Its main land use is light industrial, being filled with two-story warehouses and substantial surface parking. However, there exists high potential for redevelopment as many of the blocks on the other side of 5th Street has been completely redeveloped into a high-density neighborhood.

Downtown Residential (DTR) Districts were established in 2005 to promote transit-oriented, high-density mixed-use residential neighborhoods in under-utilized industrial and commercial areas in and near the downtown. The Transbay Downtown Residential (TB-DTR) District was implemented in 2006 and the Rincon Hill Downtown Residential (RH-DTR) and South Beach Downtown Residential (SB-DTR) Districts in 2011. Today, the two latter districts accommodate many high-rise or large-scale condominiums, including the 60-story One Rincon Hill.

Technical Guidelines

While each section in the Planning Code designates its individual area of implementation, the technical guidelines on wind speed criteria are almost identical. A summary of wind speed criteria for comfort and hazard, preexisting condition, exceptional cases, and documentation from Planning Code sections 148, 243, 249.1, 263.11, and 825 are as follows.[12]

- Buildings and additions to existing buildings should be shaped, or other wind-baffling measures should be adopted, so that the developments will not cause ground-level wind currents to exceed, more than 10 percent of the time year round, between 7 am and 6 pm, the comfort level of 11 mph equivalent wind speed in areas of pedestrian use and 7 mph equivalent wind speed in public seating areas.
- An exception may be granted, allowing the building or addition to add to the amount of time that the comfort level is exceeded by the least practical amount if (1) it can be shown that a building or addition cannot be shaped and other wind-baffling measures cannot be adopted to meet the requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question, and (2) it is concluded that, because of the limited amount by which the comfort level is exceeded, the limited location in which the comfort level is exceeded, or the limited time during which the comfort level is exceeded, the addition is insubstantial.
- No exception is granted to developments that cause equivalent wind speeds to reach or exceed the hazard level of 26 mph for a single hour of the year.
- Wind tunnel test procedures and results should be included in the project's Environmental Impact Review.

[12] Source: San Francisco Planning Department (http://www.sf-planning.org/). See Appendix B for full Planning Code.

3.5 Wind Speed Criteria

Arens et al. (1989) describe how San Francisco's criteria on ground-level wind speed was been developed. The criteria are composed of comfort and safety criteria, time interval of interest, and the maximum amount of time per year that the limit may be exceeded. A noteworthy point is the adoption of "equivalent wind speed" in the Planning Code. It is defined as an hourly mean wind speed adjusted to incorporate the effects of gustiness of wind on pedestrians (City of San Francisco, 1985). The gustiness metric is "turbulence intensity." It is the root-mean-square, or standard deviation, of wind speeds measured over a period of time, divided by the mean speed. Equivalent wind speed and turbulence intensity are calculated follows:

$$U_{eqv} = \overline{U} \times (1 + \alpha I)$$

$$\mathrm{I} = \frac{1}{\overline{U}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (U_i - \overline{U})^2}$$

where

- U_{eqv}: equivalent wind speed
- $\overline{U}$: mean wind speed
- α: constant
- I: turbulence intensity
- U_i: wind speed measured at i

The constant, α, represents how much turbulence intensity is reflected in the calculation of the equivalent wind speed. Its value varies between zero and four depending on how much weight is given to gust as opposed to constant wind (Lawson, 1978). In San Francisco, three was selected as the value of α, based on two studies that researched people's comfort in thermal conditions like those that exist in the city. One is by Hunt et al. (1976) who studied the effect of gust on people's comfort level by exposing them to various wind turbulence levels in a wind tunnel in a relatively cool condition (63 °F). The other is by Jackson (1978) who carried out a series of pedestrian surveys in Wellington, New Zealand, on days with relatively cool temperatures (55 °F – 77 °F) and found that the overall comfort level of pedestrians surveyed and the equivalent wind speed are best matched when α is three.

The two comfort equivalent wind speed criteria, seven mph in seating areas and eleven mph in pedestrian area, were established based on research findings dating from the 1970s and 1980s. The former, is based on findings by Davenport (1972), Penwarden (1973), Melbourne (1978), and Arens (1981); and the latter by Penwarden and Wise (1975), Hunt et al. (1976), and Melbourne (1978).[13] The time interval of interest, between 7 am and 6 pm, was chosen by the Planning Department to represent the period when the city's population is most exposed to the wind (Arens et al., 1989). The maximum allowable time per year that wind speeds can exceed the allowable wind speeds, 10 percent of the time year round, was decided based on a study by Penwarden (1973) who found that substantial complaints on wind were reported by shoppers in

[13] See Appendix C for wind speed criteria suggested in each study.

urban retail areas when the comfort limit of wind speed was exceeded more than 10 percent of the time.

The safety equivalent wind speed criterion, 26 mph, was also established based on studies by Penwarden (1973), Hunt et al. (1976), Jackson (1978), and Melbourne (1978), all of which suggested 44 mph as the safety criterion. The difference between 26 and 44 mph is because of the discrepancy between the averaging period lengths. 26 mph was derived based on a mean wind speed over an averaging period of one hour, while 44 mph was based a three second. The greater likelihood of strong winds occurring over three seconds had to be revised to incorporate the likelihood over the one hour period. Accordingly, the criterion was adjusted to 26 mph by multiplying 44 with 0.6, an approximate ratio estimated by Lawson (1978).

3.6 Wind Planning Cases

This section introduces two recent development cases in San Francisco to introduce how San Francisco's wind planning is applied and present the widely shared consideration of wind in the city. The first is 706 Mission Street – The Mexican Museum Residential Tower and the other is the Redevelopment Plan of Treasure Island. Both developments are underway as of 2014. 706 Mission Street was chosen since it is a typical high-rise development in the Financial District, and the Redevelopment Plan of Treasure Island was selected for being a neighborhood-scale project that incorporates wind in its layout of blocks and streets.

The Mexican Museum Residential Tower

Located at 706 Mission Street in the Financial District, the 47-story 551-foot high Mexican Museum Residential Tower has been designed to accommodate spaces for residence, retail, office, and museum. The building sits on a C-3-R zoned parcel, for which a wind tunnel simulation of the building's surrounding ground-level wind test has been mandated. As shown in Figure 20, RWDI, a wind engineering consulting firm, carried out a series of wind tunnel tests, measuring wind speed ratios at 109 locations in streets and plazas around the proposed building. The firm found that development of the new building would not significantly change the existing wind condition of the area as the existing ambient wind level was relatively high. By applying an annual wind speed distribution of San Francisco, they also anticipated that the wind speeds would exceed the comfort criteria at 65 locations and the safety criterion at three locations, therefore recommending relevant landscaping or wind screen that slows down or blocks excessive wind (RWDI Consulting Engineers & Scientists, 2012).

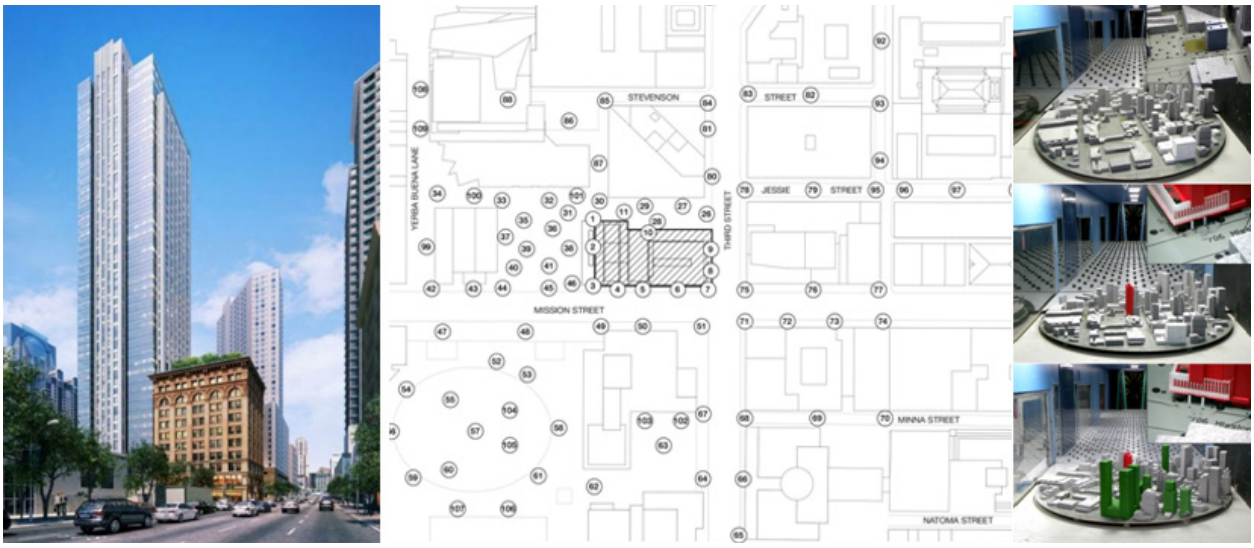


Figure 20. Wind planning of the Mexican Museum Residential Tower (Sources: San Francisco Planning Department (2012, p. IV.I.7); RWDI Consulting Engineers & Scientists (2012, pp. 22–24))

Treasure Island Redevelopment Plan

Treasure Island is a reclaimed piece of land that sits in the San Francisco Bay Area between San Francisco and Oakland, California. It was originally developed in 1937 as a venue of the Golden Gate International Exposition held in 1939. Directly connected to Yerba Buena Island in its east, Treasure Island has been operated by the United States Navy as a naval station until 1997, when the City of San Francisco took over part of the island that was not owned by the United States Coast Guard. The redevelopment plan of Treasure Island, issued in 2011, incorporates the dominant west wind as a major factor in laying out a new street grid to provide a more livable, sustainable environment for 8,000 new residences, although the area is without any wind planning regulations in effect. As illustrated in Figure 21, the street grid was planned to minimize the effects of wind on neighborhood public spaces, resulting in a unique non-orthogonal grid (Treasure Island Development Authority, 2011). ESA, a wind engineering consultant, executed a series of wind tunnel tests by measuring wind speed ratios at a total of 200 locations. They expected that the anticipated wind speeds locations would exceed the comfort criteria at 126 and the safety criterion at 49 locations after the proposed development has been completed; therefore design measures that mitigate potential wind hazards should be incorporated (San Francisco Planning Department, 2011)

Figure 21. Wind planning of Treasure Island Redevelopment Plan (Sources: San Francisco Planning Department (2011, p. IV.I.39–IV.I.41); Treasure Island Development Authority (2011, pp. 4–5, 18))

Discussion

The two recent on-going development cases in San Francisco demonstrate that wind planning is a crucial part of planning and development practice in the city and have become a process that planners, designers, architects, and developers frequently engage in. The Mexican Museum Residential Tower case reveals that the city's wind planning is an influential factor that affects the design of buildings and its landscaping. The Treasure Island Redevelopment Plan suggests that the prevailing wind direction is a key design element of neighborhood planning, and that new residential areas should be protected from excessive winds.

CHAPTER 4. RESEARCH METHODOLOGY

This chapter provides an overview of the methodology used in this research. It begins with the selection of methods for each research sub-question and discusses the areas within San Francisco selected for study and their contexts. It also details the two methods: wind tunnel test using a boundary layer wind tunnel and field study that includes pedestrian surveys and on-site collection of microclimate data.

4.1 Research Design

This section identifies independent and dependent variables of each research sub-question. It is important that the variables are measurable by methods widely used by researchers. It also discusses data collection and methods.

Sub-question #1: Has the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment?

The independent variable of this research sub-question is *urban form*. More specifically, it refers to the change in urban form as a result of implementation of the plan. It can be measured by identifying the differences in urban form between 1985, when the plan was first implemented, and 2013, the present time. It also takes into account two additional issues. One is to what degree the changes in urban form were affected by the plan, in other words, the number or percentage of parcels affected by the plan in an area. The other is the degree of change in urban form since 1985, which is the number or percentage of parcels, on which new development or redevelopment was carried out since 1985. The dependent variable is *wind environment*, which is best represented in terms of *wind speed* measured at a number of locations.

Sub-question #2: Are the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco?

Although the independent variable of this research sub-question is *wind speed criteria*, 7, 11, and 26 mph, it is more convenient to designate *wind speed* as the independent variable for analysis purpose, and analyze the effectiveness the criteria in a secondary analysis. Among the three criteria, only the effectiveness of the 11 mph criterion was studied. The effectiveness of 7 mph, the comfort criterion for seating areas, was not studied because of the difficulty of execution[14], and 26 mph, the safety criterion, was not studied because of its very low probability of occurrence. The dependent variable is *outdoor comfort*, which is measured by various scales adopted in related studies and codes that measure people's thermal or wind comfort, sensation, and preference.

[14] To test the effectiveness of 7 mph, participants would need to be seated throughout the survey. This was impractical because the survey was carried out on public streets.

Sub-question #3: Does the plan achieve a wind comfort level that would increase people's willingness to use sustainable transportation modes?

The independent variable of this research sub-question is *wind speed criteria*; however, it is also more appropriate to use *wind speed* as the independent variable, and incorporate the criteria for secondary analysis. The dependent variable is *willingness to use sustainable transportation modes*, which are defined to include taking public transit, bicycling, walking, and sitting outside. Willingness is chosen instead of actual use of each mode to examine the direct impact of wind speed on people's attitude.

Data Collection and Methods

Based on the discussions above, a wide range of empirical data is required, including those on urban form, wind speed, outdoor comfort, and willingness to use sustainable transportation modes. Urban form can be approximated with scale models created from publicly available information on the physical configuration of blocks and buildings. With regard to wind speed, direct collection of data was required because the several publicly available sources of wind speed data are not adequate. The San Francisco Public Utilities Commission (SFPUC) and the Bay Area Air Quality Management District (BAAQMD) provide meteorological data measured at 20 locations and three locations, respectively, in San Francisco.[15] However, these data can only be utilized for reference since their meteorological sites are usually situated on building rooftops or towertops that have virtually no public access. With regard to outdoor comfort and willingness to use sustainable transportation modes direct collection of data was also required since no publicly available data sources exist.

As summarized in Table 4, two types of methods were adopted in this research: wind tunnel tests and field studies. The wind tunnel tests use a boundary layer wind tunnel in which the wind movement in a selected urban area is simulated through use of a scale model of the area's built form. The field study consisted of pedestrian survey combined with on-site collection of microclimate data, such as wind speed, temperature, relative humidity, and solar radiation. The two methods are effective in addressing the relationships that the sub-research questions seek to examine and the nature of the variables that need to be measured. They also successfully incorporate a mixed-method approach that amalgamates qualitative methods such as observation, interview, and mapping with quantitative statistical analyses.

[15] The meteorological data provided by the San Francisco Public Utilities Commission (SFPUC) are collected every five seconds, and that by the Bay Area Air Quality Management District (BAAQMD) every one hour.

Table 4. Research sub-questions and corresponding methods.

Research Sub-Question	Method	
	Field Study	Wind Tunnel Study
Has the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment?		• Make scale models. • Measure wind speed ratios at selected locations.
Are the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco?	• Survey perception of comfort. • Collect microclimate data.	
Does the plan achieve a wind comfort level that would increase the residents' willingness to use sustainable transportation modes?	• Survey willingness to use sustainable transportation modes. • Collect microclimate data.	

4.2 Study Area Selection and Context

This section presents the selected study areas and their contexts. Selection of specific sites within each study area for the wind tunnel tests and field studies are discussed in the following sections.

Selection Criteria

It is unrealistic to examine San Francisco to its full extent or all areas or parcels where the city's Planning Code on ground-level wind currents have been implemented. It is also unreasonable to select only the implemented areas or parcels because the changes in urban form and the resulting wind environment in other parts of the city cannot be comparatively examined. Therefore, a set of criteria in selecting study areas for this research was adopted. The ideal area has:

- high development density, so that ground-level wind currents are frequently accelerated by tall buildings
- high level of ambient wind speed, so that a wide range of wind speed can be covered
- large volume of pedestrian traffic
- availability of various transportation modes
- implementation of San Francisco's key land use or transportation plans

In addition, whether and how many of the parcels in the selected areas are under the implementation of the wind planning were taken into consideration. In other words, the degree which the wind planning requirements were invoked was considered. From these criteria, four study areas were selected: the Financial District, Van Ness Avenue Corridor, Civic Center, and Mission Bay North as shown in Figure 22. Although the four areas represent only a small subset of San Francisco's diverse urban form and wind environment, they provide an opportunity to effectively identify the net effects of the plan on ground-level wind currents and the relationship between urban form, wind, comfort, and use of sustainable transportation modes.

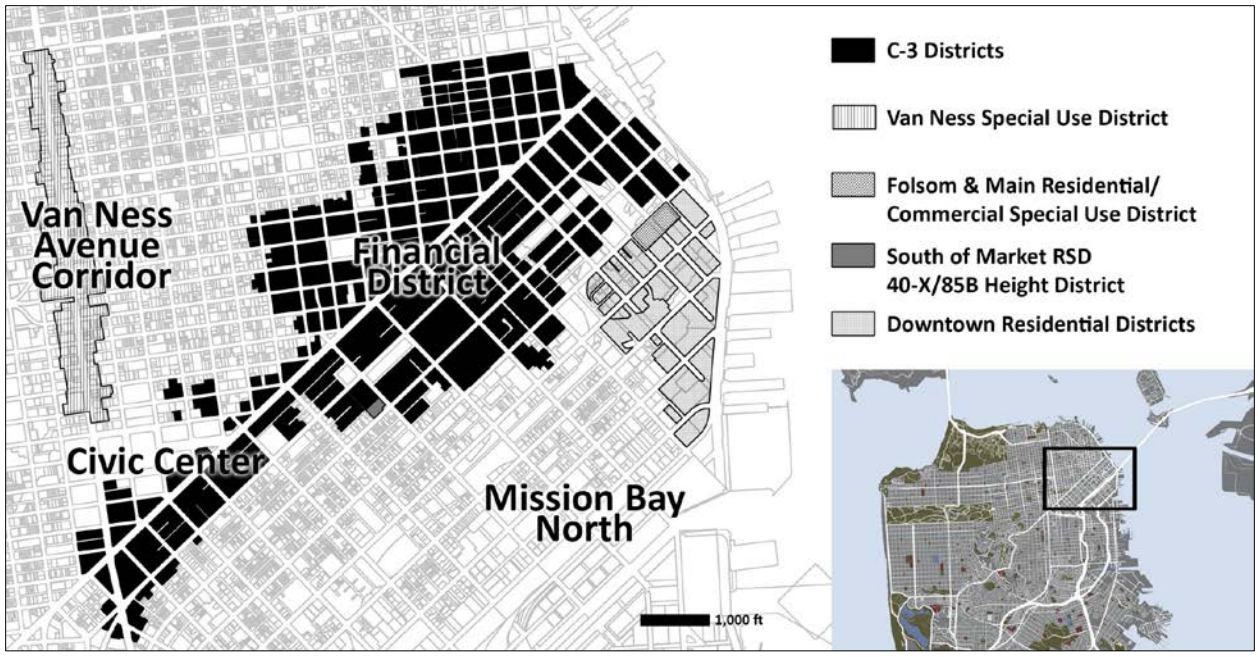


Figure 22. Location of the Financial District, Van Ness Corridor, Civic Center, and Mission Bay North study areas, and the areas subject to San Francisco's wind planning.

Financial District

Located in the northeastern end of the city, the Financial District is the central business district of San Francisco. The dominant land use types include office, retail, and mixed use. It is filled with high-rise buildings that accommodate corporate headquarters and global firms. Many interesting open spaces of various sizes are located between tall buildings. A large volume of pedestrian traffic is observed in most streets of the area. As the area's main axis, Market Street serves numerous transportation modes, which include bicycle, Bay Area Rapid Transit (BART) train, and San Francisco Municipal Railway (Muni) light rail, cable car, and bus. It is also the venue of the Better Market Project, launched in 2011 by the City of San Francisco, which seeks to revitalize and re-establish the street environment. Almost all parts of the District are zoned C-3, where wind planning applies. Market Street, running southwest-northeast, usually carries the prevalent west wind from the Pacific that is frequently accelerated by high-rise buildings.

Van Ness Avenue Corridor

Van Ness Avenue is a major thoroughfare in San Francisco that runs north-south between the South of Market and Marina District neighborhoods. The Pacific Heights and Western Addition neighborhoods are located to the west and the Russian Hill, Nob Hill, and Civic Center neighborhoods to the east. Development density along the corridor is medium to high, with buildings generally ranging from three to ten stories. Under the Van Ness Area Plan adopted in the late 1980s, residential and mixed uses have been increasing along the corridor. The Avenue carries seven bus routes, as well as a large volume of pedestrian traffic that is mostly

concentrated at intersections with major east-west streets. It is also the venue of the Van Ness Bus Rapid Transit (BRT) plan launched in 2008 by the San Francisco County Transportation Authority as the city's first full-featured BRT project. Van Ness Avenue is famous for being one of the windiest places of the city, especially around major high-rise buildings along the corridor. The Van Ness Special Use District, one of the five areas designated by San Francisco Planning Code for wind planning implementation, covers the southern half of the corridor.

Civic Center

Civic Center is a neighborhood in San Francisco that contains many government and cultural institutions such as the City Hall, Supreme Court, public library, museums, and auditoriums. Land use is relatively intense, with most buildings ranging up to eight stories and several skyscrapers reaching over twenty stories. A large volume of pedestrian traffic, mostly office workers and tourists, is observed in many parts of the area. A wide range of transportation modes is available as the area is bounded by two major transit corridors, Market Street in the south and Van Ness Avenue in the west. Civic Center experienced a substantial change in its urban form since 1985. Several civic and cultural buildings have been reconstructed, and a few high-rise buildings have been built. The neighborhood experiences high wind speeds throughout the year. Fox Plaza and P. B. Federal Building have been notorious for generating the worst ground-level wind currents in the city (City of San Francisco, 1985). The San Francisco Public Utilities Commission Headquarters Building, constructed in 2012, was designed with a wind turbine that utilizes the high winds in this area to generate electricity. However, wind planning has not been implemented in most parts of Civic Center.

Mission Bay North

Also known as China Basin, Mission Bay North is a new residential area in San Francisco. Originally an active industrial waterfront, today the area houses high-density luxury residential condominiums, offices, and retail, mostly developed along King Street, the main corridor of the area, in the mid-2000s. As a vibrant community, a large volume of pedestrian traffic is found in many locations, especially near the Caltrain Station and AT&T Park. The area accommodates a wide range of transportation modes, including bicycle and Muni light rail and bus. A groundbreaking change is expected to occur in the area as the new California High-Speed Rail will pass through this area before arriving at the Transbay Transit Center in the South of Market. Also the City of San Francisco is currently reviewing redevelopment plans for the Caltrain Station railyards and considering demolition of the freeway structures of I-280. This neighborhood also experiences high levels of wind, which is often accelerated by recent high-rise developments, some of which reach up to 21 stories. The Mission Bay Redevelopment Plan implemented in 1998 mandates wind review for all projects that exceed 100 feet in height based on the general California Environmental Quality Act (CEQA) requirements (San Francisco Redevelopment Agency, 1998a).[16] However, no parcel in the area has been designated for extensive wind study by the Planning Code.

[16] The San Francisco Redevelopment Agency Commission has been succeeded by the Office of Community Investment and Infrastructure.

4.3 Method 1: Wind Tunnel Study

A series of wind tunnel studies were carried out to examine whether San Francisco's wind planning has changed the city's urban form so as to provide a more wind-comfortable environment. In this study, an emphasis has been paid to locations that are associated with sustainable transportation modes – sidewalks, transit stops, open spaces, and bike lanes. To examine how the urban form and wind environment has changed, scale models were created that represent the urban form in 1985 and 2013 of four sites located within each of the four study areas. The models were used in the boundary layer wind tunnel to simulate actual wind conditions. Wind speed ratios at selected locations were measured and compared.

Boundary Layer Wind Tunnel

Wind tunnels are widely used in aerodynamic research to study the effects of air moving past solid objects. They are used in a range of fields from the manufacturing of automobile and airplane to design of large structure such as buildings and bridges. While the use of wind tunnels dates back to the 18th century, one of the first notable attempts to adopt the wind tunnel test as a scientific research method was by the Wright brothers in the early 20th century when they studied the effects of airflow over various Flyers (Dodson, 2005).

Wind tunnels have been a very effective method for predicting wind speeds at the pedestrian level and wind loads on structures. General uses of a boundary layer wind tunnel are visualization of air flow and quantification of wind effects (American Society of Civil Engineers Task Committee on Urban Aerodynamics, 2011). More specifically, common techniques include measuring local pressures (on exterior of interior components of a structure), overall wind loads, high frequency force, aeroelasticity of structures, pedestrian winds, air quality, and terrain/topographic studies (American Society of Civil Engineers Task Committee on Wind Tunnel Testing of Buildings and Structures, 1999, pp. 5–6).

For studies on the wind environment in and around buildings, structures, and urban areas, a boundary layer wind tunnel, developed in the 1960s, is used. It is specifically designed to manipulate air flow to model the wind near the earth's surface in a scaled fashion (American Society of Civil Engineers Task Committee on Wind Tunnel Testing of Buildings and Structures, 1999).[17] To simulate a boundary layer, which starts at a low speed at the surface and increases with elevation, so-called "roughness elements," such as wood blocks or bricks, are placed on the floor of the wind tunnel to generate friction and turbulence of air movement, (Ryan, Berg, & Brown, 1990).

The boundary layer wind tunnel method has been validated by a number of aerodynamic scientists. Penwarden (1973), Isyumov and Davenport (1975), Carpenter (1990), Williams and Wardlaw (1992), and Isyumov (1995) compared the results from a boundary layer wind tunnel test with those from full-scale field measurements. They found that there exists a strong agreement between the two that can be acceptable for research as an effective predictive tool.

[17] See the turbulence characteristics of the atmospheric boundary layer in Section 2.4

On the other hand, computational fluid dynamics (CFD), a branch of fluid dynamics that uses numerical methods and algorithms by using computer softwares to solve problems that involve fluid flows as exemplified in Figure 23, is increasingly being used in addressing issues the traditional boundary layer wind tunnel has been dealing with (American Society of Civil Engineers Task Committee on Outdoor Human Comfort, 2004; American Society of Civil Engineers Task Committee on Urban Aerodynamics, 2011). A group of scholars have being validating the CFD method at the urban scale by comparing its results with those from wind tunnels (Blocken & Carmeliet, 2007; Blocken, Stathopoulos, Saathoff, & Wang, 2008; Meroney, Leitl, Rafailidis, & Schatzmann, 1999).

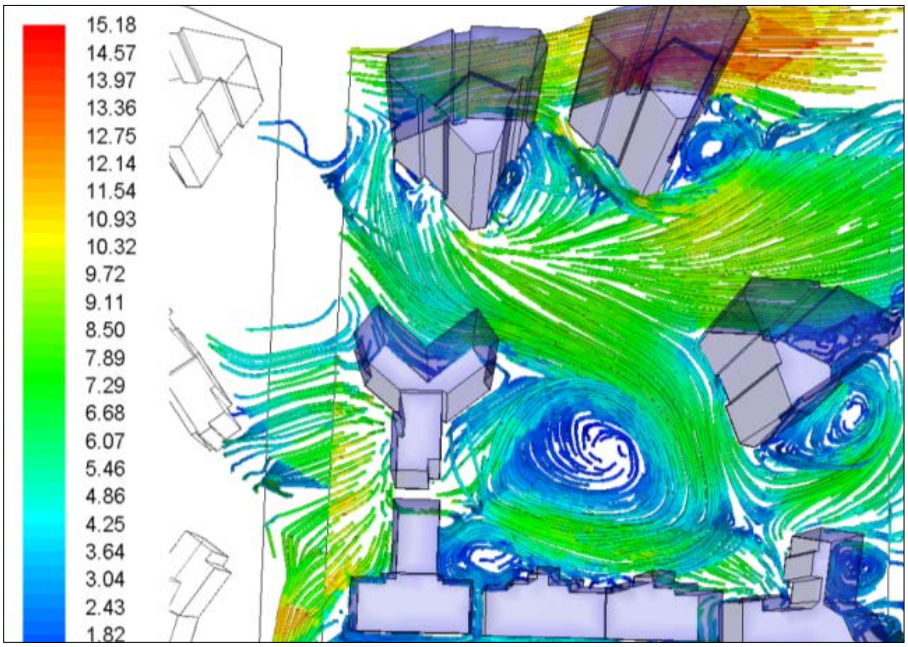


Figure 23. An example of CFD simulation of an urban area using ©Fluent.

However, the effectiveness of adopting CFD in urban and architectural research and practice is still controversial. Advocates argue that CFD is not restricted by scale and can be tested in full scale whereas wind tunnel testing can only go as large as the size of the tunnel (Blocken & Carmeliet, 2006). They also argue that it is becoming more cost effective than wind tunnel testing or field measurements (Stathopoulos, 2006) and speeds up the preliminary design process by comparing designs and implementing changes quickly (Jones et al., 2004). On the other hand, CFD is frequently criticized for generating results that can be erroneous since turbulence models it adopts are based on assumptions that cannot fully address the complexity and uncertainty of turbulence in the real world (American Society of Civil Engineers Task Committee on Urban Aerodynamics, 2011). It is also relatively weak when addressing complex building forms or dense environments and has been partially validated at the urban scale.[18] In practice, the

[18] Out of the many CFD softwares used by architects today, Envi-Met and UrbaWind are the only ones that have been validated.

application of CFD has been primarily for making preliminary evaluations of the wind flows around a project while wind tunnel testing is still being used as the industry standard (American Society of Civil Engineers Task Committee on Outdoor Human Comfort, 2004).

The wind tunnel method was used for this research. Although making scale models and running wind tunnel tests requires substantial time and cost, and is therefore less convenient than CFD, the wind tunnel has been the most reliable method in both research and practice as an industrial standard. The boundary layer wind tunnel used is located in the Center for Environmental Design Research (CEDR) in the College of Environmental Design at the University of California, Berkeley. It was built in 1981 as an open circuit type[19], one of the most common types of boundary layer wind tunnels. As described in Figure 24 and 25, the interior of the wind tunnel is 1.5 meters (5 feet) high, 2.1 meters (7 feet) wide, and an 19.5 meters (42 feet) long (Schiller, 1989). When the fan operates, air is induced through the bellmouth. Models are placed on a two-meter diameter turntable and are usually in the range of 1:200 to 1:500 scales. As the air flows along the tunnel, a boundary layer of an urban setting is created by wood blocks, bricks, the turbulence grid, and trip fence. The reference Pitot tube suspended from the ceiling is to measure the reference wind speed, based on which wind speed ratios are calculated.

The original anemometer installed in this wind tunnel was not used in this research, because it was out of order and not available for use. Instead, measurement of wind speed at various locations was carried out by using an anemometer, TSI Velocicalc© Air Velocity Meter 8346 shown in Figure 26. It has a hot wire sensor embedded in a probe that measures wind speed and temperature and calculates flow rate and average of the readings.[20] The anemometer was help by hand but at the same time kept steady by being placed firmly on the model's plate. It was also rotated to collect the maximum wind speed value at each measurement point. Any obstacles (e.g. arms) that would interfere with wind or the anemometer were kept out of the way.

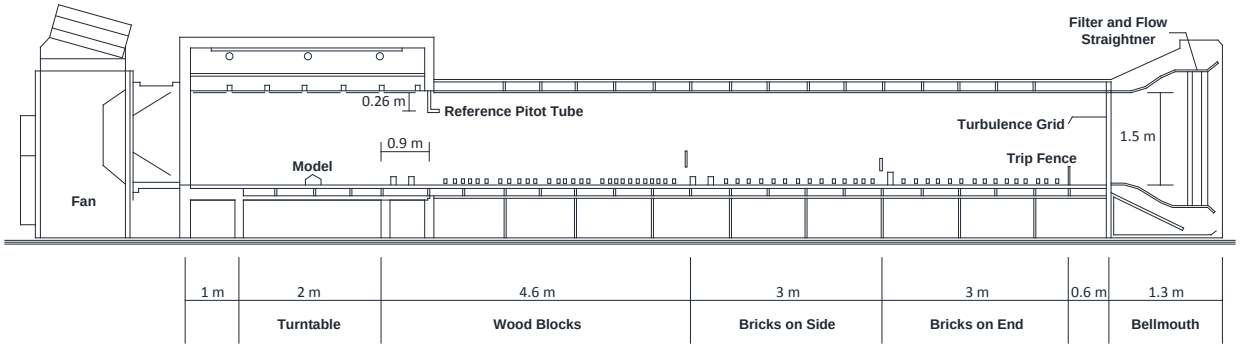


Figure 24. Cross sectional diagram of boundary layer wind tunnel at CEDR (adapted from Schiller (1989)).

[19] An open circuit type wind tunnel allows air to enter the tunnel from the room or atmosphere and discharge into the room or atmosphere, while a closed circuit recirculates the wind flow.

[20] Specifications of the anemometer: air velocity range: 0 – 6,000 feet per minute; temperature range: 0 to 140 °F; air velocity accuracy: +/- 3% of reading or +/- 3 feet per minute; and temperature accuracy: +/- 0.5 °F.

Figure 25. Boundary layer wind tunnel at CEDR.

Figure 26. TSI Velocicalc© Air Velocity Meter 8346.

Study Site Selection

For the boundary layer wind tunnel simulation, one site in each of the four study areas was selected, as shown in Figure 27. The four sites were selected in a way that their size fits on the turntable of the wind tunnel in a 1"=30' scale. Their shape is a rectangle that covers approximately 45 acres where each side ranges between 1,200 and 1,800 feet with a consideration of 300-foot wide buffers on all sides of the rectangle. The sites also effectively represent each area's development characteristics.

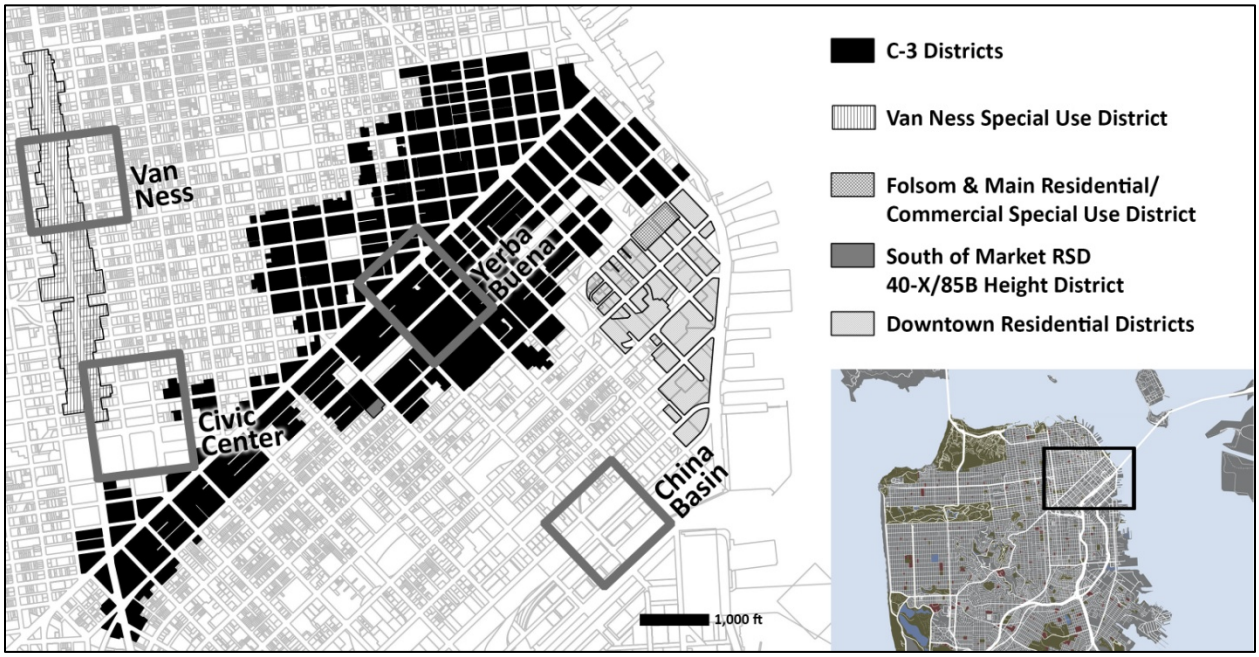


Figure 27. Location of the Yerba Buena, Van Ness, Civic Center, and China Basin study sites selected for wind tunnel study, and the areas subject to San Francisco's wind planning.

Figure 28. Site selection in the Financial District.

Figure 28 shows the selected site in the Financial District. Covering an area of 1,200 by 1,600 feet (44.1 acres), the site is surrounded by Annie Street in the northeast, Howard Street in the southeast, and 4th Street in the southwest. It encompasses parts of Market, Mission, and 3rd Streets. The site covers 68 parcels, all of which are subject to the wind planning. Major open spaces in this site include Yerba Buena Gardens, Yerba Buena Lane, and Jessie Square.[21] Market Street is the busiest area in this site where a very large volume of pedestrians and arrays of shops, cafes, and restaurants exist. BART and Muni light rail, cable cars, and buses pass along this street as well. Yerba Buena Gardens and Jessie Square are places where many people sit or lie down to relax. The site also carries many tall buildings such as St. Regis Hotel and Residences (41 stories), Four Seasons Hotel and Residences (40), the Paramount (40), Marriot Marquis (39), The Westin (35), and W Hotel (32), and historic buildings such as St. Patrick's Church (built in 1872), Chronicle Building (1890), which is now the Ritz Carlton Club and Residences, Central Tower (1898), Aronson Building (1903), and the Contemporary Jewish Museum, which used to be Jessie Street Power Station (1907). For convenience, this site is called "Yerba Buena" in the rest of the dissertation.

[21] While Yerba Buena Gardens is a publicly owned space, Yerba Buena Lane and Jessie Square are privately owned.

Figure 29. Site selection in the Van Ness Avenue Corridor.

Figure 29 shows the selected site in the Van Ness Avenue Corridor. Covering an area of 1,440 by 1,360 feet (45.0 acres), the site is surrounded by Clay Street in the north, Larkin Street in the east, Bush Street in the South, and Franklin Street in the west. It encompasses parts of Van Ness Avenue and Sacramento, California, Pine, and Polk Streets (Figure 15). The site covers 191 parcels, 40 (20.9%) of which are subject to the wind planning. While there are no major public open spaces in this site, Polk Street carries many shops and restaurants, a high volume of pedestrians, and buses and bicycles. Pedestrians are also found on Van Ness Avenue usually at the point where it meets California and Pine Streets. Also, the California Cable Car route begins at the Van Ness Avenue and California Street intersection, where many tourists are frequently gathered waiting for the cable car. Building heights in this site are generally between two and five stories, with a few exceptions which include the Holiday Inn Golden Gateway (25 stories), San Francisco Towers (13), Terrace Apartments (12), and 1700 California (11). Historic buildings include 1415 Van Ness Ave (built in 1906), Maple Hall (1906), 1200 Van Ness Ave (1911), and Royal Theatre (1916). The dominant land use is residential with some mixed, commercial, and industrial uses. For convenience, this site is called “Van Ness” in the rest of the dissertation.

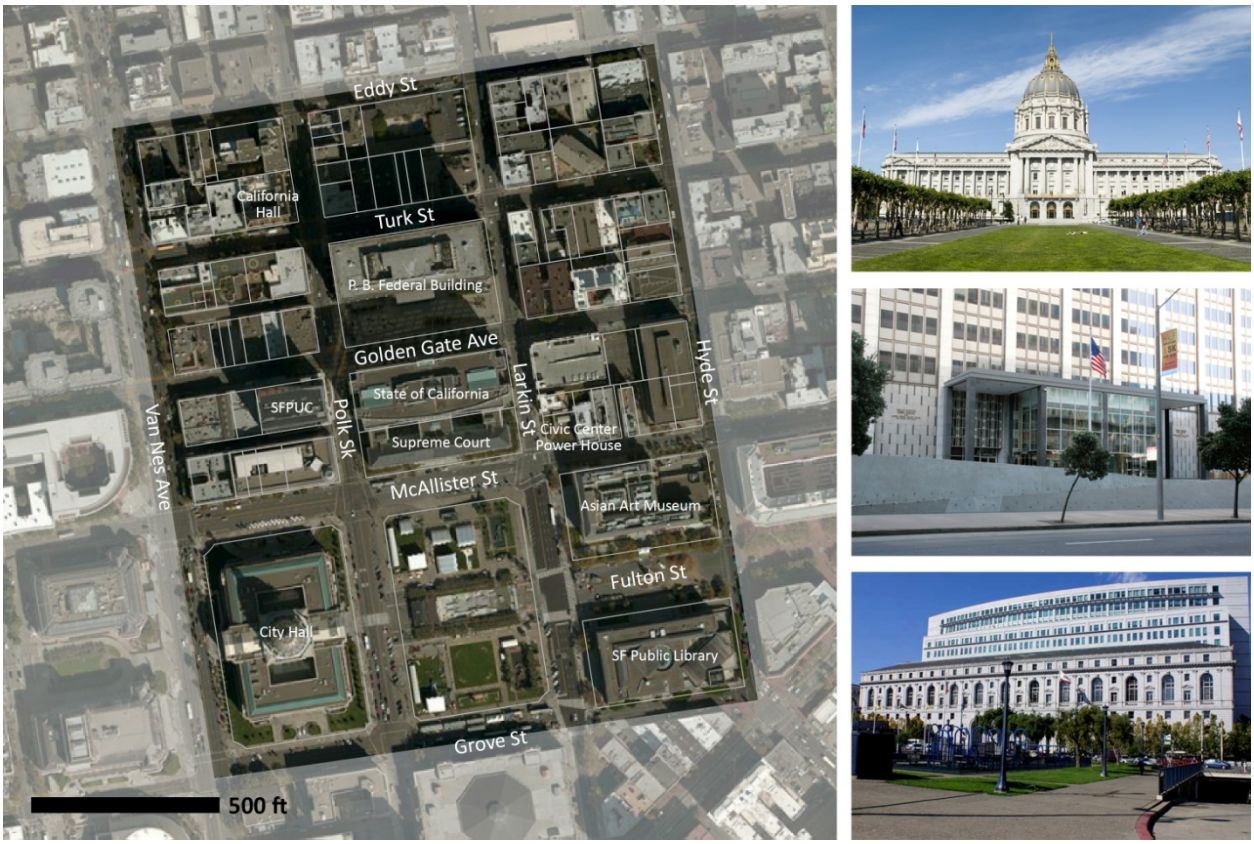


Figure 30. Site selection in Civic Center.

Figure 30 shows the selected site in the Civic Center area. Covering an area of 1,440 by 1,670 feet (55.2 acres), the site is surrounded by Eddy Street in the north, Hyde Street in the east, Grove Street in the south, and Van Ness Avenue on the west. It encompasses parts of Turk, Polk, McAllister, Larkin, and Fulton Streets, and Golden Gate Avenue (Figure 16). The site covers 92 parcels, 9 (9.8%) of which are subject to the wind planning. Major public open spaces include the Civic Center Plaza located in the direct east of City Hall and the setback areas in front of several civic buildings, including P. B. Federal Building, Asian Art Museum, and San Francisco Public Library. A bicycle lane is found on Polk Street. While the southern half of the site is filled with civic and cultural buildings, the northern half has more residential and mixed uses. Most building heights in the site are generally low, ranging between two and six stories high, except for several high-rise buildings which include P. B. Federal Building (22 stories), the State of California Building (15), and the San Francisco Public Utilities Commission (SFPUC) Headquarters Building (13). Historic buildings in this site are City Hall (built in 1900), Supreme Court of California (1900), Civic Center Power House (1900), and California Hall (1912). For convenience, this site is called “Civic Center” in the rest of the dissertation.

Figure 31. Site selection in Mission Bay North.

Figure 31 shows the selected site in Mission Bay North. Covering an area of 1,360 by 1,340 feet (41.8 acres), the site is surrounded by 3rd Street in the northeast, Mission Creek in the southeast, and partly by Bluxome and Lusk Streets in the northwest. It encompasses parts of Townsend, King, Berry, and 4th Streets. The site covers 44 parcels, all of which are not subject to the wind planning. No major open spaces exist in this site, except for one at the Caltrain Station and several inner courtyards of residential towers. Townsend and King Streets carry many shops, cafes, and restaurants. Most pedestrian activities occur on 4th and King Streets, and increase rapidly when there is a baseball game at AT&T Park located just northeast of the site. Buses and bicycle lanes exist on Townsend Street, and Muni light rails runs along King and 4th Streets. Notable buildings include Caltrain Station, the China Basin, and several high-rise luxury condominiums along King and Berry Street, which include the Beacon (17 stories) and Avalone (17). Building heights in the north of Townsend Street are relatively low, generally ranging between two and four stories. For convenience, this site is called “Mission Bay North” in the rest of the dissertation.

Reconstructing Urban Form in 1985 and 2013

The next step was to build scale models and compare urban form in 1985 and 2013 of the four selected sites. Information on blocks, parcels, land use, streets, buildings, transit, and bicycle

lanes was gathered from a wide range of sources. For 1985 urban forms, Sanborn Maps obtained at the Earth Sciences and Map Library at the University of California, Berkeley, were used. The maps provide block configuration, building footprint, and number of building stories circa 1985.[22] [23] In addition, relevant satellite images, photographs, and documents were used for crosschecking. For 2013 urban forms, publicly available online resources provided by the City of San Francisco were used. GIS data on blocks, parcels, streets, and buildings were downloaded from San Francisco Data[24], a data portal website that provides a wide range of data about San Francisco. Detailed information on each parcel or building was collected at San Francisco Property Information Map[25], a website that provides zoning and property information at the parcel level, such as parcel number, assessed property value, building permits, project history, year built, building and parcel areas, and number of units and stories.

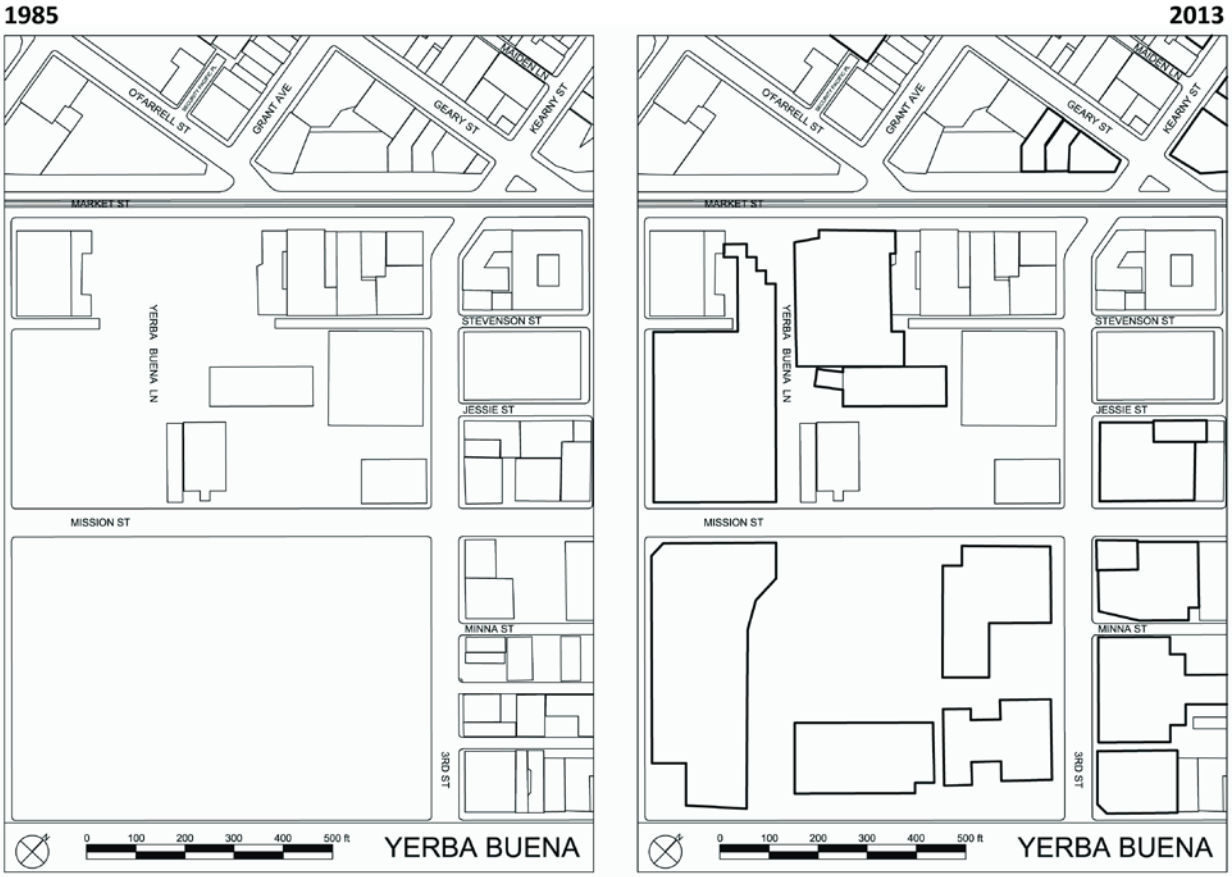


Figure 32. 1985 and 2013 urban forms of Yerba Buena.

[22] Sanborn Maps between 1867 and 1970 have been digitized and are available online with limited access. Those after 1970 exist in microfilm format at the Earth Sciences and Map Library.
[23] The Sanborn Maps on San Francisco are composed of 11 volumes, each presenting different part of the city. Since the volumes are not produced every year, those from the closest years from 1985 were used – Yerba Buena from 1984 and 1986, Van Ness from 1986, Civic Center from 1984, 1986, and 1987, and Mission Bay North from 1984.
[24] https://data.sfgov.org/
[25] http://propertymap.sfplanning.org/?dept=planning

Figure 32 illustrates that a number of significant changes have occurred in the urban form of Yerba Buena between 1985 and 2013. First came the construction in 1998 of Yerba Buena Gardens on what had been a large surface parking area. Yerba Buena Lane, which was under construction in the mid-1980s, now accommodates the Contemporary Jewish Museum renovated in 2008 and several skyscrapers such as Marriot Marquis and Four Seasons Hotel and Residences constructed in 1989 and 2001 respectively. High-density redevelopment has occurred along 3rd Street including the Paramount (3rd and Jessie) built in 2002, St. Regis Hotel and Residences (3rd and Mission) in 2005, San Francisco Museum of Modern Arts (3rd and Minna) in 1995, and W Hotel (3rd and Howard) in 1999. North of Market Street, notable changes include the renovation of Chronicle Building (Market and Geary), on which eight stories were added to the existing structure in 2005, and One Kearny (Market and Kearny) which was renovated in 1988.

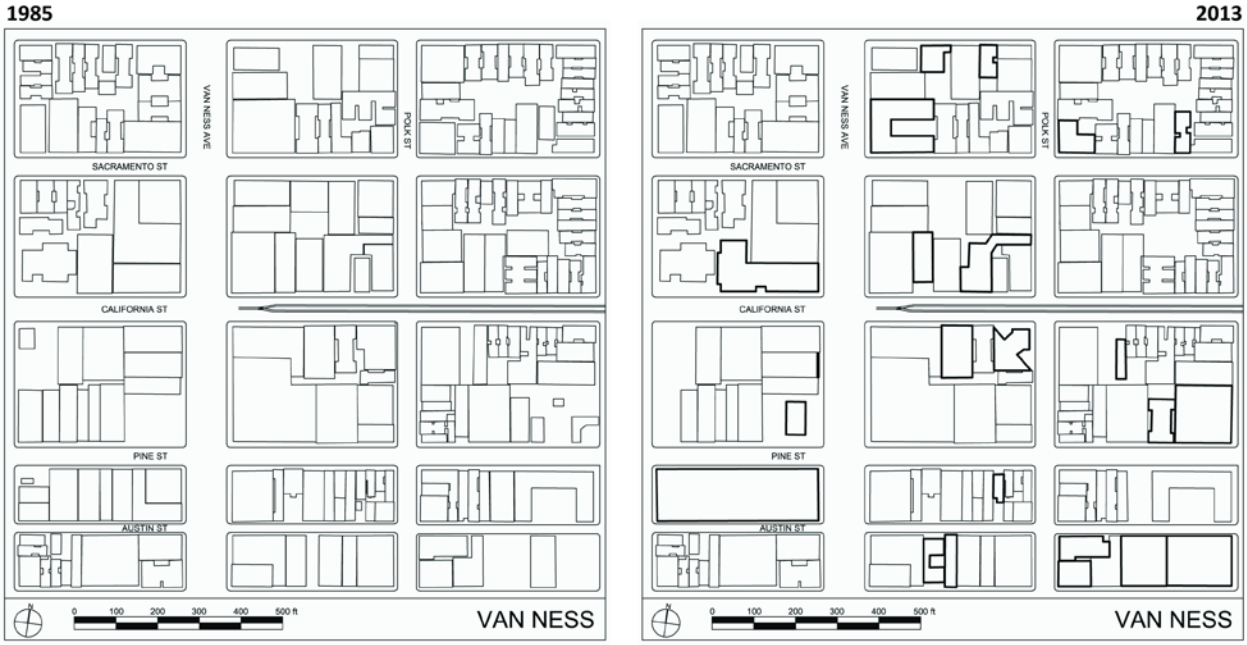


Figure 33. 1985 and 2013 urban forms of Van Ness.

Figure 33 shows that Van Ness experienced relatively limited change in its urban form between 1985 and 2013, except for several large-scale residential redevelopment projects along Van Ness Avenue that consolidated several former industrial lands. San Francisco Towers (Van Ness and Pine) built in 1997 was a redevelopment that consolidated nine parcels, and 1700 California (Van Ness and California) completed in 1987 consolidated two. Changes in other parts of the site have been scattered, mostly being renovation or redevelopment of individual buildings, infill projects, or consolidation of parcels in small scale.

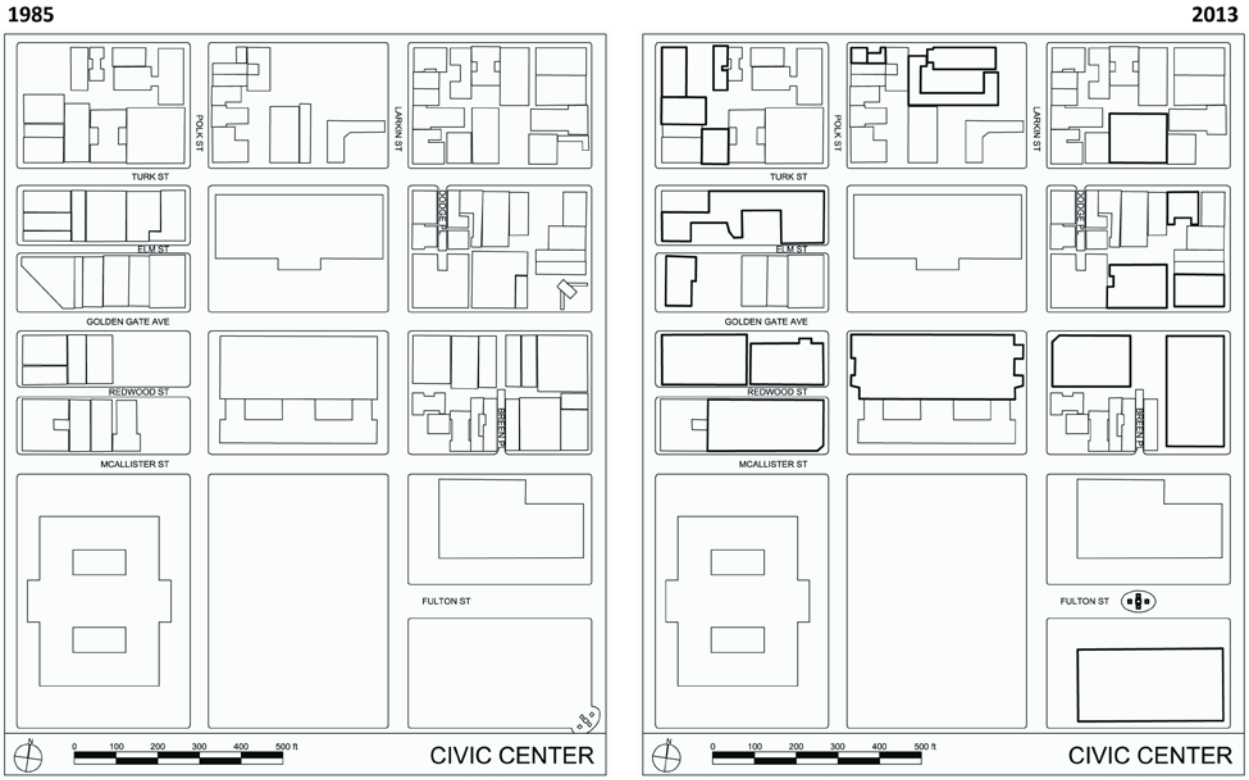


Figure 34. 1985 and 2013 urban forms of Civic Center.

Civic Center has also experienced substantial changes to its urban form between 1985 and 2013 as shown in Figure 34. Although major landmark buildings located in the site such as City Hall, P. B. Federal Building, Asian Arts Museum, and the Supreme Court of California were unchanged, new construction, redevelopment, and infill have occurred at both large and small scales. The new San Francisco Public Library (Larkin and Fulton) was constructed in 1995. Major redevelopment or reconstruction projects that consolidated multiple parcels include the 20-story State of California Building (Golden Gate and Polk) completed in 2003, Superior Court of California (McAllister and Polk) in 2001, the San Francisco Public Utilities Commission Headquarters Building (Redwood and Polk) in 2012, and Tenderloin Community School (Turk and Polk) in 1998. In addition, several small-scale infill and redevelopment projects took place in the north of Golden Gate Avenue.

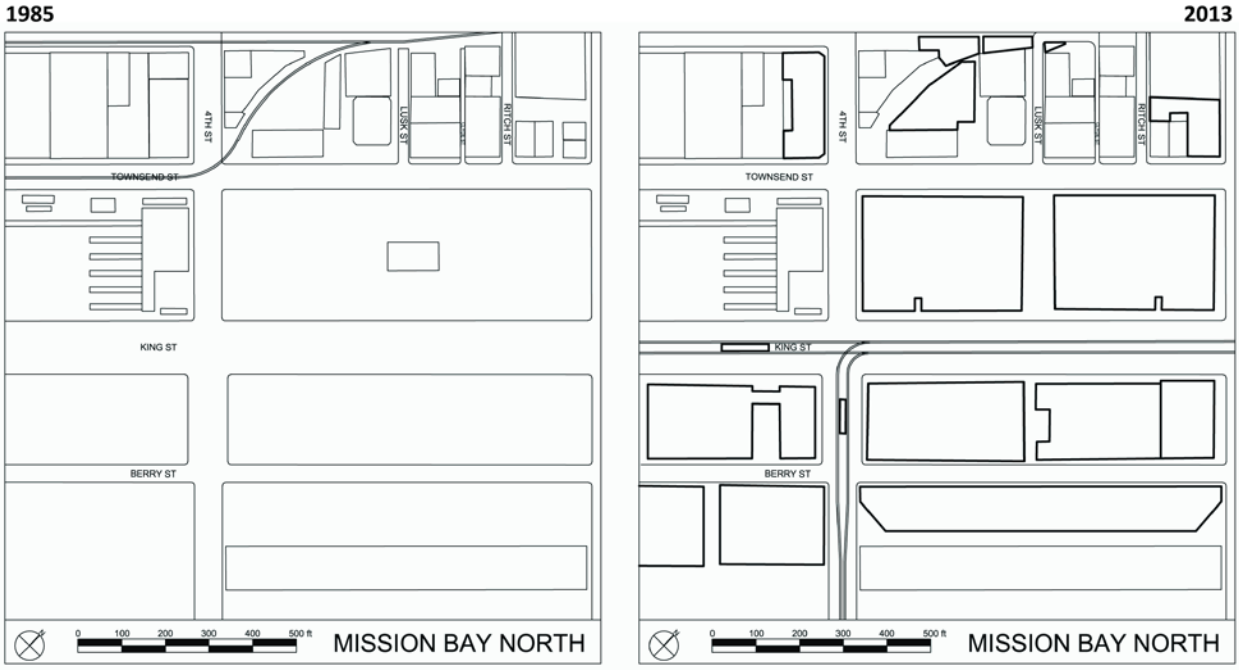


Figure 35. 1985 and 2013 urban forms of Mission Bay North.

Figure 35 presents that Mission Bay North has experienced the most change between 1985 and 2013 of the four selected sites. In 1985, the site was mostly used for railyards and their supporting facilities owned by the Southern Pacific Railroad Company (San Francisco Redevelopment Agency, 1998b). In 1998, San Francisco launched the Redevelopment Plan for the Mission Bay North Project Area, transforming the site into a wealthy neighborhood with luxury condominiums, shops, and restaurants along King Street, and high-tech research functions along Berry Street (City of San Francisco, 2012).

Measurement Locations

When carrying out simulations using a boundary layer wind tunnel, it is widely accepted that the more measurement locations the better (American Society of Civil Engineers Task Committee on Outdoor Human Comfort, 2004). However, there is always a limit to the number of measurement locations due to practical reasons. Therefore, it is extremely important to identify the purpose of the simulation and establish criteria for selecting the measurement locations.

The main focus of this research is public open space, which includes streets and plazas, and places associated with sustainable transportation modes, such as transit stops and bicycle lanes. Accordingly, the following location types were selected in each site, based on conditions in 2013:

- Street corners: where sidewalks from two directions meet; from the wind environment perspective, where wind direction changes abruptly.
- Mid-blocks: every 100 – 150 feet on public sidewalks depending on block size.

- Transit stops: light rail, bus, and cable car stops; and BART and Muni exits.
- Bicycle lanes: every 100 – 150 feet on designated bicycle lanes or routes depending on block size.
- Open spaces: 100 – 150 feet apart from each other in plazas or car-free spaces.

Table 5 summarizes the 318 locations chosen in the four sites. A total of 74 locations were selected in Yerba Buena, 72 in Van Ness, 102 in Civic Center, and 70 and Mission Bay North. Among the 318 locations, 129 are mid-block points, 91 are street corners, and the rest are transit stops, bicycle lands, or open spaces. The table also shows the location numbers for each type. Figures 36, 37, 38, and 39 illustrate the exact locations where measurements were taken for each site on the 2013 urban form maps.

Table 5. Number of locations by type and location numbers in each site.

Site	Street Corner	Mid-Block	Transit Stop	Bicycle Lane	Open Space	Total
Yerba Buena	18 (1–17,43)	22 (19–20,22-33,35-42)	4 (18,21,34,44)	8 (45–52)	22 (53–74)	74
Van Ness	24 (1–24)	32 (25–56)	8 (57–64)	8 (65–72)	0	72
Civic Center	33 (1–32,76)	43 (33–75)	5 (77–81)	6 (82–87)	15 (88–102)	102
Mission Bay North	16 (1–16)	32 (17–48)	5 (49–53)	10 (54–63)	7 (64–70)	70
Total	91	129	22	32	44	318

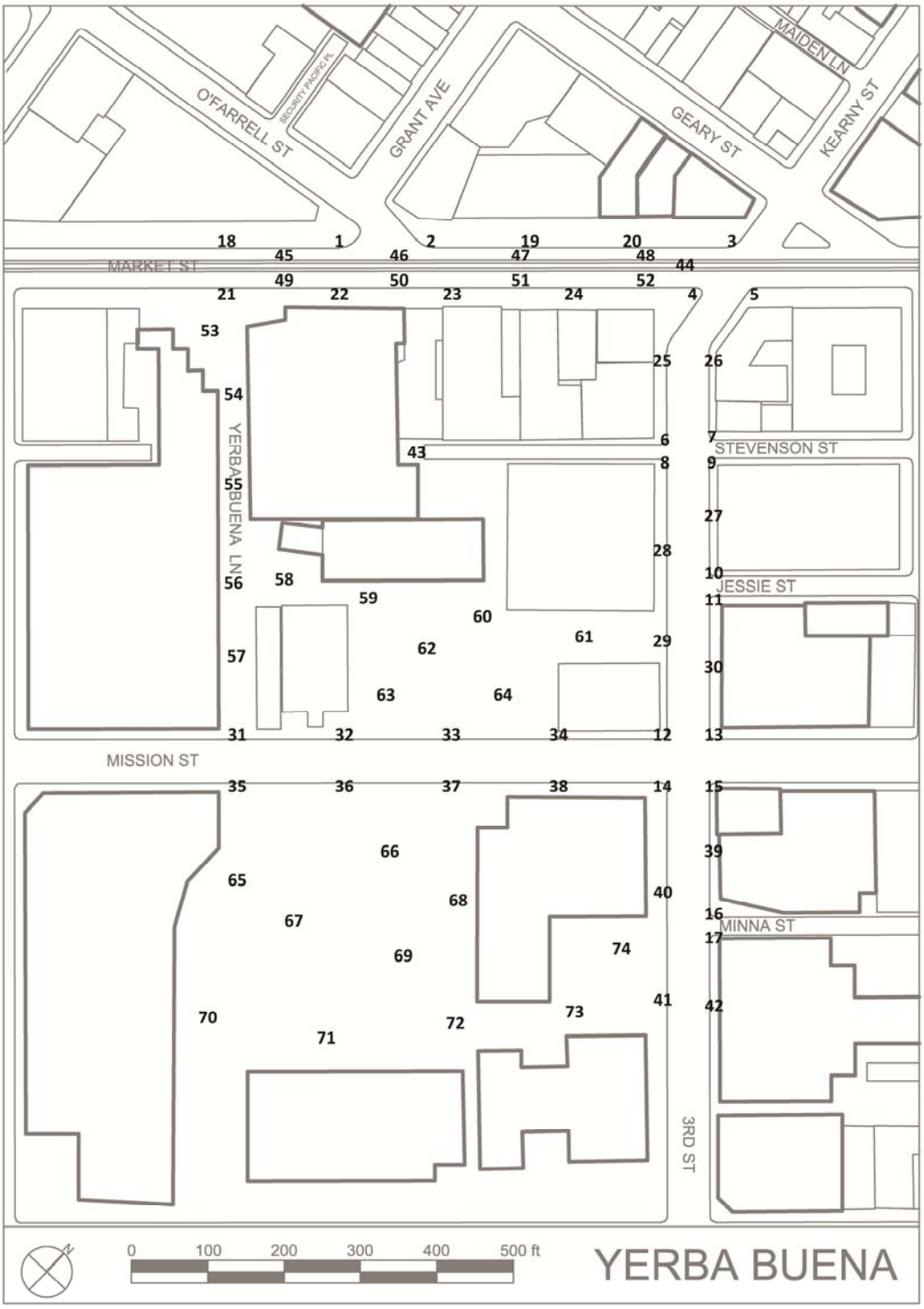


Figure 36. Measurement locations in Yerba Buena.

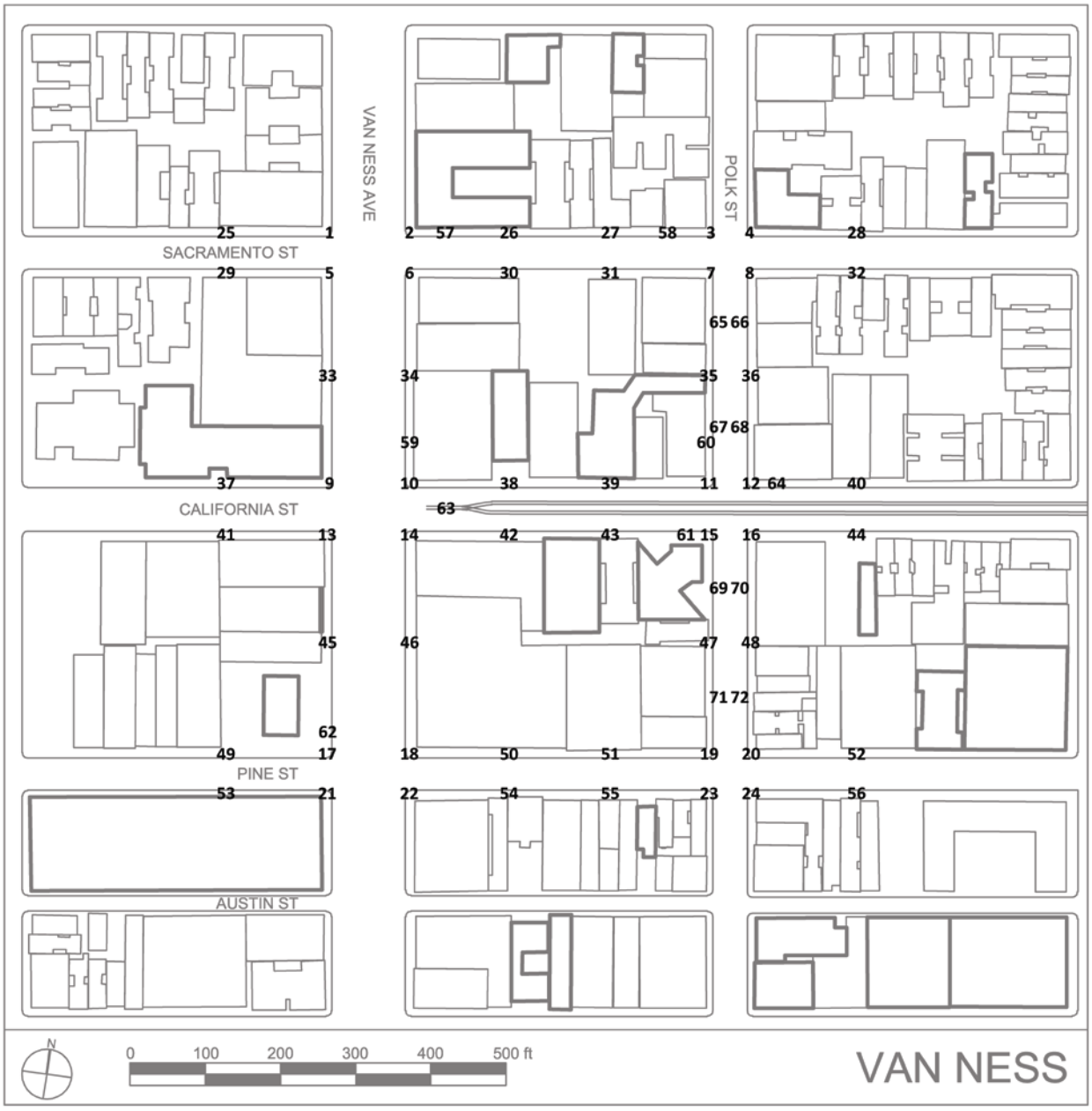


Figure 37. Measurement locations in Van Ness.

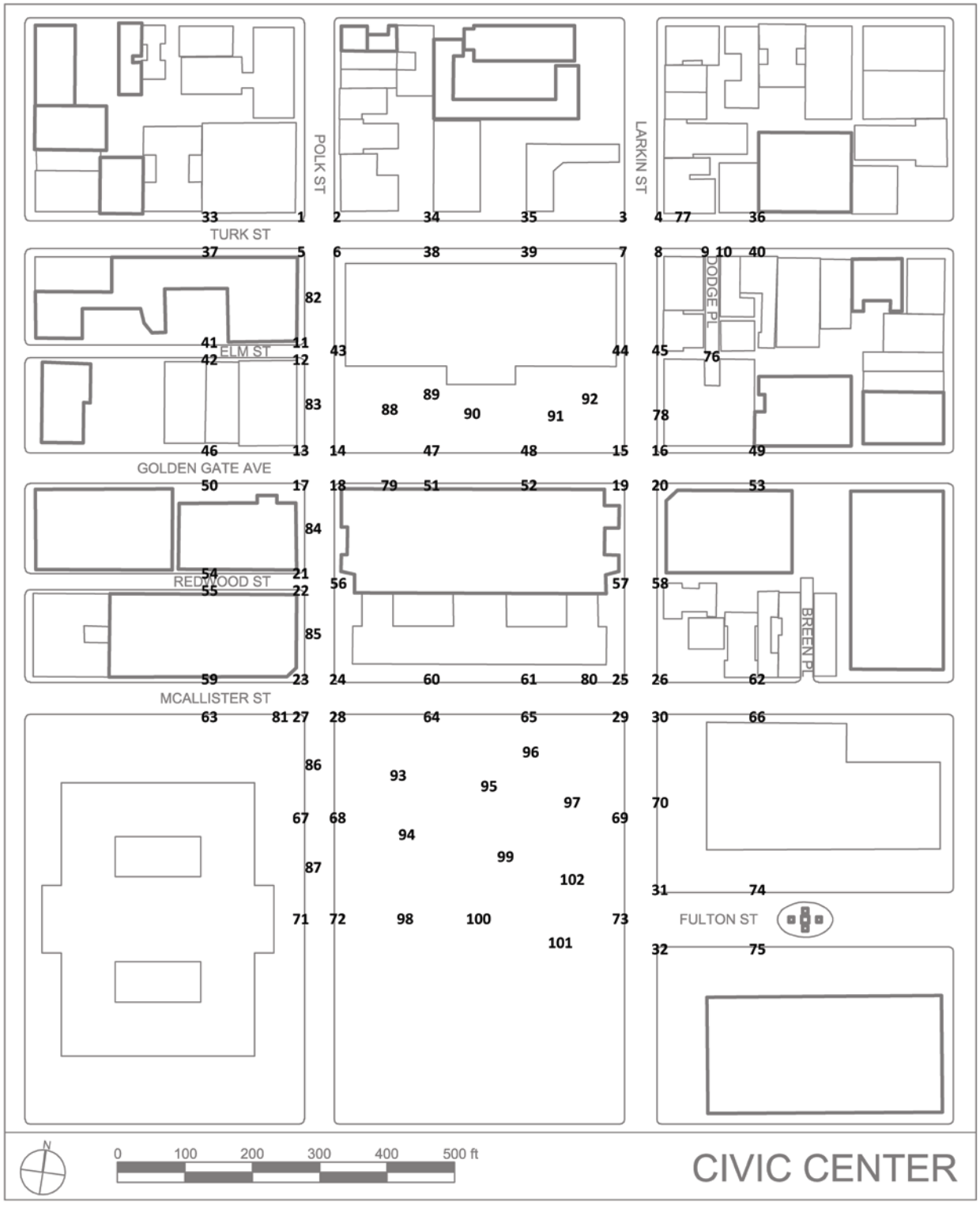


Figure 38. Measurement locations in Civic Center

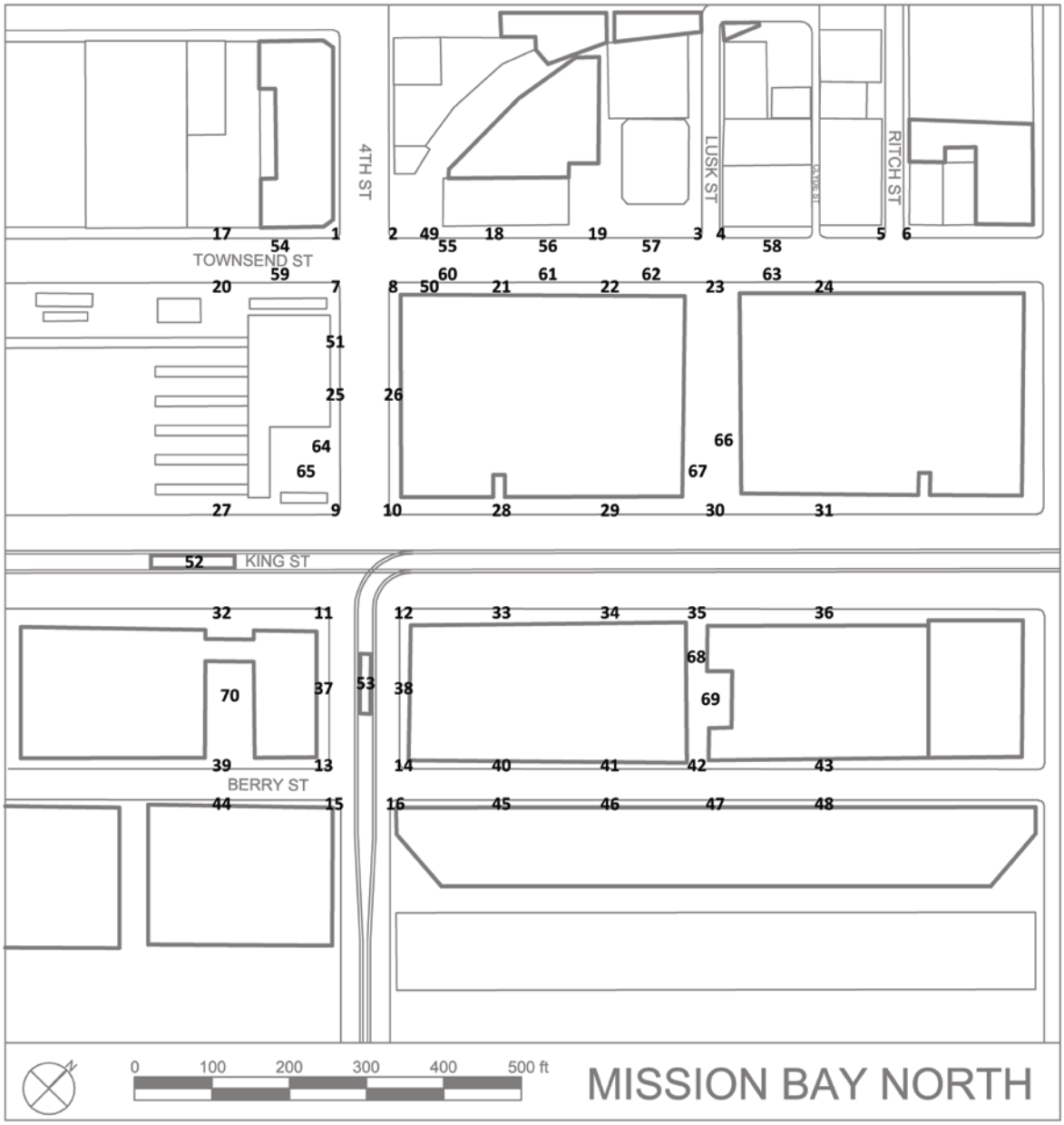


Figure 39. Measurement locations in Mission Bay North.

Scale Models

After selecting sites within the study areas, collecting information on urban form changes, and designating measurement locations, a set of scale models were made that represent urban form conditions in 1985 and 2013 of each of the four sites, for use in the wind tunnel tests. The models physically provide information on the configuration and location of blocks, parcels, streets, railroads, and buildings in each site. They also show the measurement locations.

The scale chosen for the models was 1 inch = 30 feet (1 : 360). It is not only one of the most used scales in wind tunnel practices but also the same scale that Bosselmann et al. (1984) used when making models using foam blocks in their study that provided a foundation for San Francisco's wind planning. Using this scale, each scale model measured approximately 40 to 60 inches long on each side.

Yerba Buena, Civic Center, and Mission Bay North are all located in the relatively flat parts of San Francisco. Particularly, Mission Bay North sits on a reclaimed land. The Van Ness site, in reality, slopes.[26] However, topography was not included in the scale model for two reasons. First, the main focus of this study is on the consequential wind environment of urban form change between 1985 and 2013. Second, representing topography on scale models for wind tunnel tests is difficult, especially when the study site is located on a slope and the wind is blowing from the top. If the scale model is cut at the site boundary, it is likely that the resulting cliff will generate an awkward wind environment, distorting the results. Assuming that the slope itself is not steep enough to make a significant impact, it can be acceptable not to incorporate topography in the model.

In addition, small design features of building surfaces, such as louvers, signboards, bay windows, and awnings, and street furniture, such as benches, ledges, lamp posts, and utility poles, and vegetation, such as trees and landscaping were also not included in the models for the following reasons. They might have some impact on the surrounding microclimate environment, but are generally too small to generate substantial impact on the surrounding wind environment and to represent as three-dimensional elements at the selected scale. With regard to vegetation, its air porosity would differ by type and trees usually experience seasonal changes, making it extremely difficult to express. Therefore, in this study, only building forms that are simplified to a certain level acceptable in related research and practice are represented in the scale models.

Instead of making two complete models of each site, representing 1985 and 2013 conditions, a more efficient method was developed. Typically, a scale model consists of a floor plate, volumes that represent buildings, and stickers that indicate measurement locations. For each site, a single floor plate was used for both 1985 and 2013 with only the buildings that existed in both years permanently glued to the floor plate. Buildings that existed in 1985 but were demolished by 2013 and those that did not exist in 1985 but were constructed by 2013 were made in a way that they could be adhered temporarily.

[26] The grade of California Avenue between Franklin Street and Polk Street is approximately 5 percent. It is not significantly steep, considering the many steep streets of San Francisco, and does not generate critical changes in the wind environment,

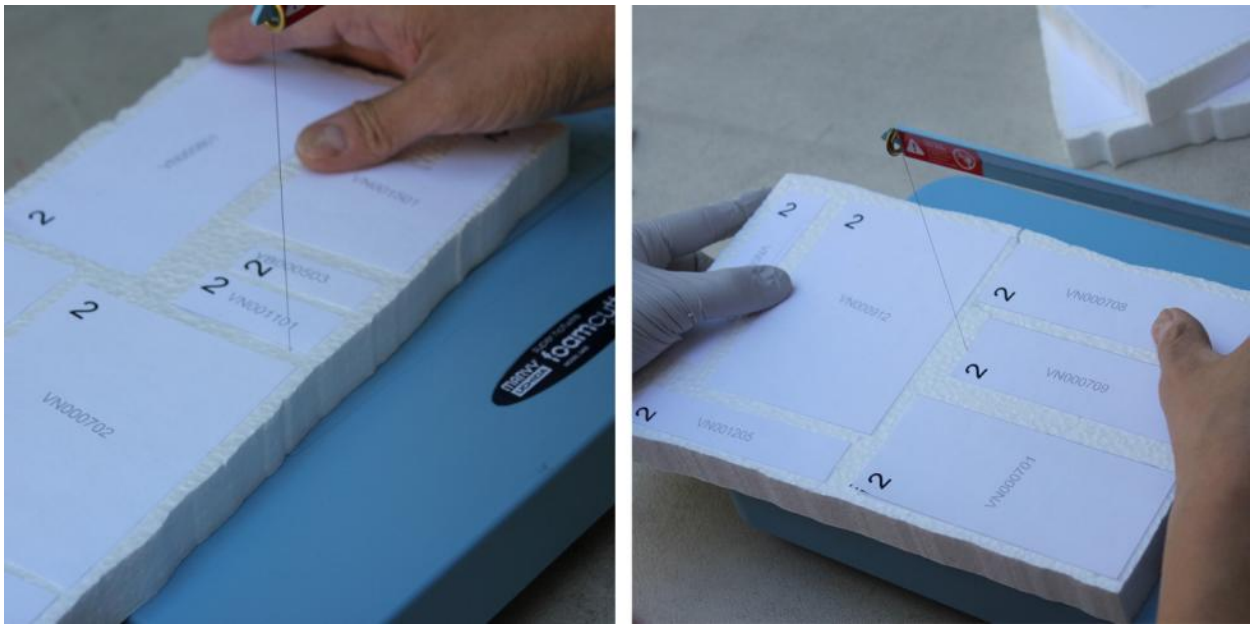


Figure 40. Cutting foam sheet with a hot wire foam cutter.

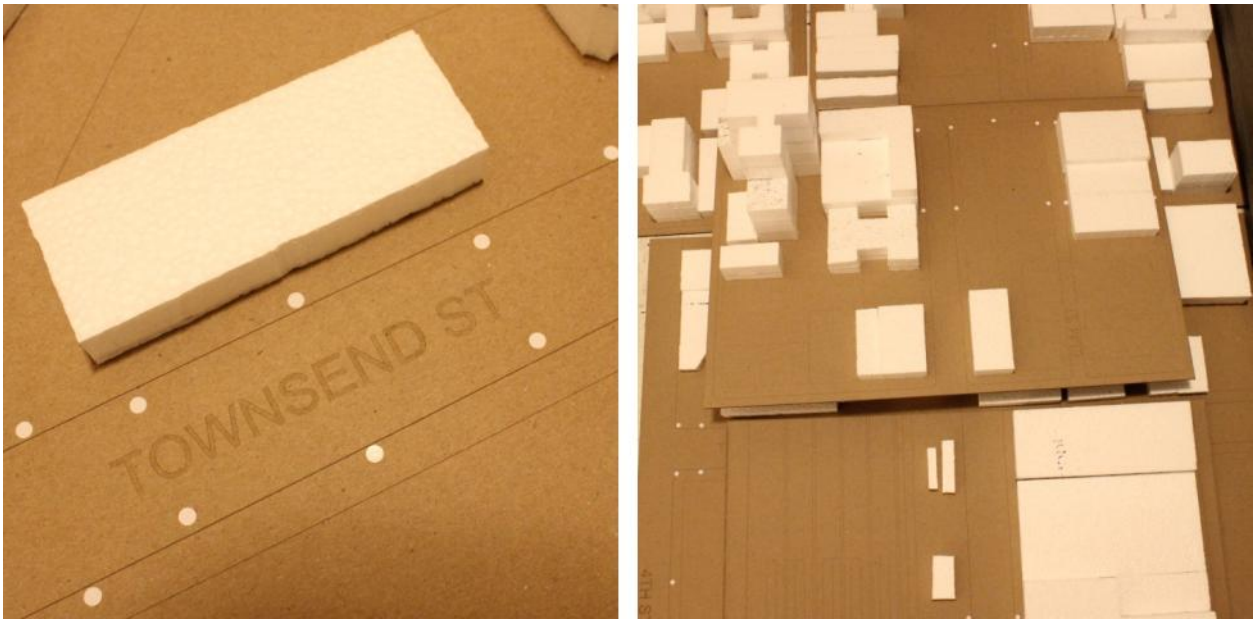


Figure 41. Foam pieces placed on laser-cut chipboards.

White foam sheets were used to make the building volumes. As shown in Figure 40, they were cut by a hot wire foam cutter and glued with other pieces when necessary. A total of approximately 500 building volumes were created and placed on the floor plates, as presented in Figure 41. Chipboard was used for the floor plates. They were cut and engraved by a laser cutter at the CAD/CAM Laboratory in the College of Environmental Design at the University of

California, Berkeley. The floor plates were additionally cut into four to six pieces so that they could be hand-carried. Blocks, railways, and building footprints were engraved on the floor plates. Lastly, small white stickers were placed at the measurement locations. Figures 42, 43, 44, and 45 show the models with all the building volumes, floor plates, and stickers in place, ready to be put in the wind tunnel.

Figure 42. Yerba Buena

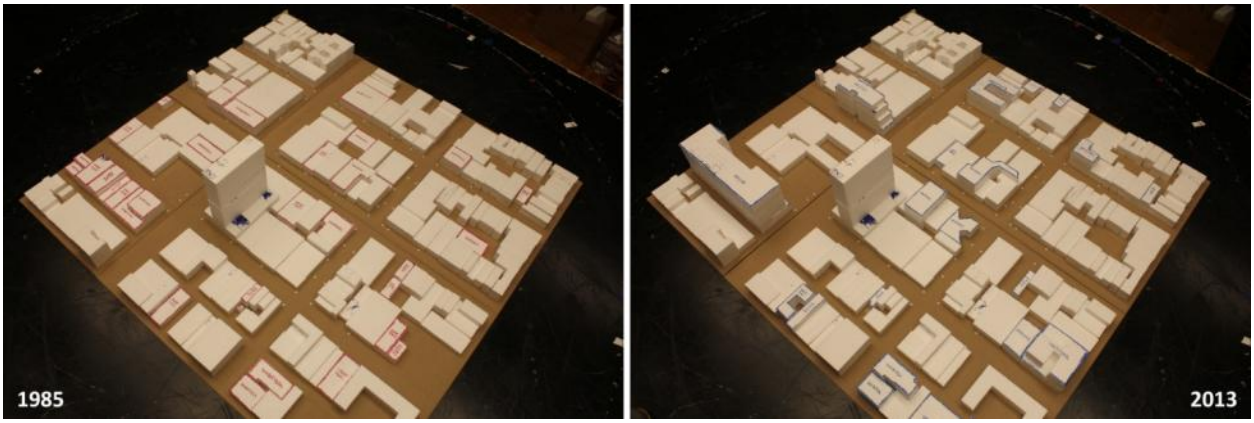


Figure 43. Van Ness

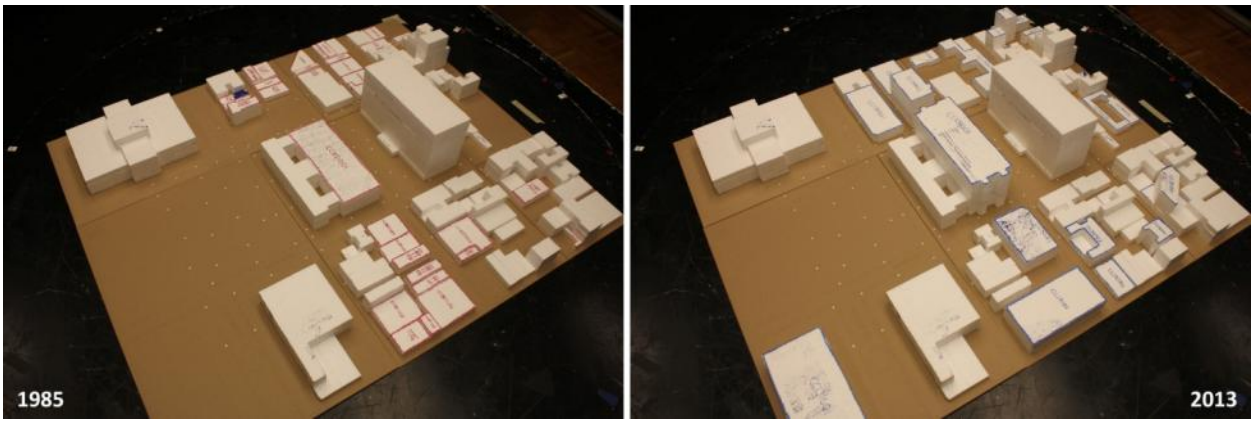


Figure 44. Civic Center

Figure 45. Mission Bay North

Measurement of Wind Speeds

The wind tunnel simulations were conducted during a three day period from November 18th to November 20th, 2014. As illustrated in Figure 46, the models were placed in a way that the wind blew from the west, simulating the prevalent wind direction in San Francisco. Wind speed was measured at each location at every second for 20 seconds, a period long enough to generate a mean wind speed value, using the TSI anemometer. The anemometer was help by hand but at the same time kept steady by being placed firmly on the model's plate in order to minimize errors. The probe, where the reading was taken, was always facing the direction from which the wind was blowing so that the maximum wind speed value at each measurement point could be collected. Any obstacles (e.g. arms and legs) that would interfere with wind or the anemometer were kept out of the way.

To collect the reference wind speed, base on which the wind speed ratio is calculated, the wind speed at the Pitot tube was measured five times during each simulation for Yerba Buena, Van

Ness, and Mission Bay North, and six times for Civic Center. This data was used to calculate mean wind speeds.

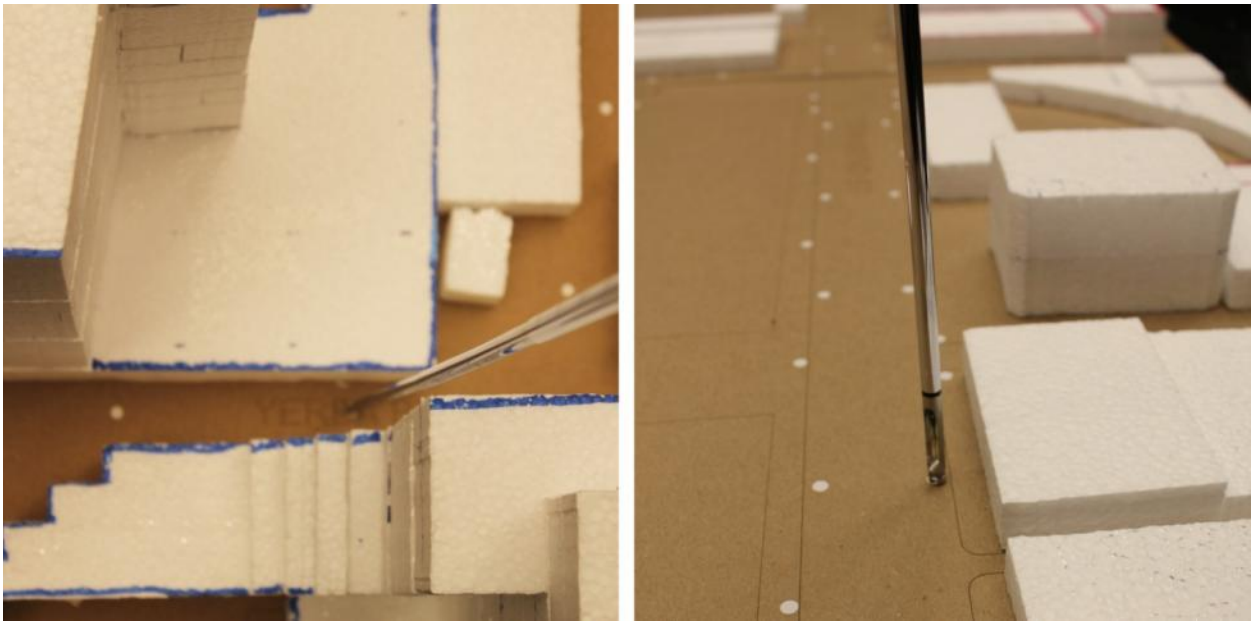


Figure 46. Measurement of wind speeds.

The wind speed ratio at each location was calculated using the mean wind speed measured at the location and the mean reference wind speed. A wind speed ratio is a value earned by dividing the wind speed at a location by the reference wind speed. In theory, the wind speed ratio of a location is constant regardless of wind conditions when the surrounding physical setting is the same. It is expressed as follows:

$$V_{r_i} = \frac{V_i}{V_{ref}}$$

where,

- V_{r_i}: wind speed ratio at location i
- V_i: measured mean wind speed at location i
- V_{ref}: reference (mean) wind speed

4.4 Method 2: Field Study

The field study carried out in this research involved surveying pedestrians and simultaneously collecting on-site microclimate data. The pedestrian survey focused on people's perception of outdoor wind comfort and their willingness to use sustainable transportation modes, which

include waiting for transit, bicycling, walking, and sitting outdoors. Microclimate data, including wind speed, temperature, solar radiation, and humidity, was collected, using a meteorological station and solar power meter. It was later paired up with the survey results. In this way, the relationship between microclimatic condition and people's perception of outdoor comfort and willingness to use sustainable transportation modes could be analyzed.

Survey Design

The first step was to identify what needed to be collected through the field study. To select relevant independent and dependent variables to examine the relationship between wind and comfort, two groups of sources were reviewed. One is the ANSI/ASHRAE Standard 55-2010, and the other is a body of literature that empirically studies people's outdoor thermal comfort.[27]

The ANSI/ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy is widely-used industry standard accepted and used in both practice and research, and is updated periodically.[28] Based on extensive laboratory and field data collection, the standard suggests six primary factors that must be addressed when studying thermal comfort. They are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. The standard also provides a seven-point thermal sensation scale that were developed for quantifying people's thermal comfort: -3: cold; -2: cool; -1: slightly cool; 0: neutral; +1: slightly warm; +2: warm; and +3: hot.

Twelve studies published since the 2000s that empirically examined people's outdoor thermal comfort in relation to microclimatic conditions and that have been cited in many other studies were reviewed. As summarized in Table 6, the studies were carried out for one or more seasons of the year in various parts of the world, including cities in the sub-tropical region and those in the Nordic countries. Their sample sizes are generally very large, ranging from 285 to 1,503. While a few studies used presence counting as an indicator of outdoor thermal comfort, most studies adopted surveys as their main research method, and applied various scales of measuring outdoor thermal comfort. Many of the studies adopted the seven-point thermal sensation scale used by the ANSI/ASHRAE Standard 55-2010. Other scales that were used include thermal acceptability, sensation of wind, sun, and humidity, preference for wind and sun, and overall comfort. They also asked about the participant's clothing and previous activities, which are related to clothing insulation and metabolic rate, respectively among the six factors the standard suggests. Some studies included questions on frequency and purpose of visit. Although not mentioned in Table 6, the studies collected microclimatic data including wind speed, temperature, humidity, and solar radiation.

[27] ANSI stands for the American National Standards Institute, and ASHRAE for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

[28] ANSI/ASHRAE Standard 55-2010 supersedes ANSI/ASHRAE Standard 55-2004. A more recent version, ANSI/ASHRAE 55-2013 was issued in late 2013 but was not adopted in this research because this research was carried out before the standard was issued.

Table 6. Summary of studies methods that empirically examines outdoor thermal comfort.

Study	Study Region	Studied Space	Season	Field Study Method	Questions on Microclimate and Comfort Asked in Survey	Sample Size
Nikolopoulou et al. (2001)	Cambridge, UK	Open spaces	Spring, Summer, Winter	Presence Counting, Survey	Thermal sensation (5p), Clothing	1,431
Zacharias et al. (2001)	Montreal, Canada	Plazas, Squares	Spring, Summer, Fall	Presence Counting, Observation	None	-
Spagnolo & de Dear (2003)	Sydney, Australia	Urban spaces	Summer, Winter	Survey	Thermal Sensation (7p), Wind & sun preference (3p), Clothing, Previous activity	1,018
Thorsson et al. (2004)	Göteborg, Sweden	Park	Summer, Fall	Presence Counting, Survey	Thermal sensation (7p), State of health, Time spent, Estimated temperature, Place of residence, Visit purpose, Clothing, Activity	285
Zacharias et al. (2004)	San Francisco, US	Plazas	Spring	Presence Counting, Observation	None	-
Katzschner et al. (2006)	Kassel, Germany	Open spaces	Spring, Summer	Presence Counting	None	-
Eliasson et al. (2007)	Göteborg, Sweden	Square, Park, Courtyard, Waterfront	All seasons	Survey, Observation	Thermal sensation (9p), Weather sensation (3p), Psychological comfort (3p), Clothing, Activity	1,379
Nikolopoulou & Lykoudis (2007)	Athens, Greece	Square, Seashore	All seasons	Presence Counting, Survey	Visit purpose, Previous activity	1,503
Thorsson et al. (2007)	Tokyo, Japan	Park, Square	Spring	Survey, Observation	Thermal sensation (7p), Climatic preference (5p), Emotional state, Clothing, Previous activity, Time spent	1,142
T. Lin (2009)	Taichung, Taiwan	Square	All seasons	Survey, Observation	Thermal sensation (7p), Thermal acceptability (7p), Wind & sun preference (7p), Clothing, Activity	505
Lenzholzer & van der Wulp (2010)	Netherlands	Squares	Spring, Summer, Fall	Survey	Thermal sensation (5p), Sun (3p) & wind (5p) sensation, Overall comfort (2p), Perception of space, Visit frequency & purpose, Previous activity	695
Cheng et al. (2012)	Hong Kong, China	Plaza	Summer, Winter	Survey	Thermal sensation (7p), Solar sensation (3p), Wind sensation (7p), Humidity sensation (3p), Wetness sensation (5p), Overall comfort (5p)	286

Among the twelve studies mentioned above, several presented that microclimate conditions influence people's outdoor activities (Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007; Katzschner, Bosch, & Röttgen, 2006; Nikolopoulou & Lykoudis, 2007; Thorsson, Lindqvist, & Lindqvist, 2004; Zacharias, Stathopoulos, & Wu, 2001; Zacharias et al., 2004). Others suggested the existence of thermal adaptation (T. Lin, 2009; Nikolopoulou, Baker, & Steemers, 2001; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007), indicating that people adaptively improve their comfort conditions.

Based on the resources reviewed above, a set of independent and dependent variables were selected that needed to be collected through the field study in order to examine the relationship between wind and comfort. They are listed and explained in detail in Table 7.

Table 7. List of variables for examining the relationship between wind and comfort

Variable			**Unit or Scale**	**Definition, Range, or Options**	**Collection Method**
Independent Variable	Individual	Gender	-	Female, Male	Recording by surveyor
		Visit frequency	-	4+/week, 1-3/week, 1-3/month, Rarely/first time	Survey
		Visit purpose	-	Wait for someone, Rest or linger, Have lunch/coffee, On way to somewhere, Others	Survey
	Location	Location	-	Yerba Buena, Van Ness, Civic Center, Mission Bay North	Recording by surveyor
	Thermal history and status	Metabolic rate	met	Energy generated inside the body due to various activities (1 met = 58.2 W/m^2)	Survey
		Time spent outside in the last 1 hour	minute	Degree of adaptation to the outdoor microclimatic conditions	Survey
		Clothing insulation	clo	Thermal insulation provided by garments and clothing ensembles (1 clo = 0.155 m^2•°C/W)	Recording by surveyor
	Microclimatic Condition	Equivalent wind speed	mph	Mean wind speed combined with wind turbulence	Meteorological station
		Temperature	°F	Air temperature	Meteorological station
		Solar radiation	W/m^2	Amount of solar energy received at unit area	Solar power meter
		Humidity	%	Relative humidity	Meteorological station n
Dependent Variable	Comfort	Thermal sensation	7p	Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm , Hot	Survey
		Wind sensation	One-way 5p	No wind, Slight wind, Moderate wind, Strong wind, Very strong wind	Survey
		Wind preference	3p	More wind, Neutral, Less wind	Survey
		Overall comfort	Binary	Yes, No	Survey

Among the many questions on demographic information that are frequently asked in a survey, participant's gender were recorded based on findings that women and men experience temperature in a different way (Jackson, 1978). Other demographic or socio-economic variables such as race, age, and income were not included. Visit frequency and purpose were included based on the hypothesis that they would affect one's expectation of microclimatic conditions or thermal comfort. For example, a person familiar with a windy place by making frequent visits would expect to experience substantial wind in the place.

It was hypothesized that location where people were surveyed would affect their perception of outdoor thermal comfort, based on the findings by Lenzholzer and van der Wulp (2010). Each area has different density, building heights, street widths, open space sizes, and building or floor materials, and these factors would affect both people's psychological and physiological awareness of their thermal comfort.

Metabolic rate and clothing insulation are both included in the list of key factors of thermal comfort proposed by the ANSI/ASHRAE Standard 55-2010 and were collected in many similar studies. In this survey, metabolic rate was not directly asked. Rather, the guidelines presented in the ANSI/ASHRAE Standard 55-2010 were followed which suggests asking the participants to write down what activities they engaged in and for how long in the past one hour. Each activity is converted to a *met* value, based on which a time-weighted average *met* is calculated.[29] Clothing insulation is another important variable since thermal sensation of a person wearing short-sleeve shirts and shorts would be different from another in full suit. Likewise, the insulation performance of each garment is converted to a *clo* value.[30] Time spent outside in the last one hour was included to incorporate the degree of adaptation to the outdoor microclimatic conditions. For example, a person who just got out of a warm office would feel differently from another who has been staying outside for 30 minutes.

The equivalent wind speed, which takes into consideration wind turbulence, cannot be directly collected by using the meteorological station, which logs wind speed. It has to be calculated based on the formula presented in Section 3.5. Solar radiation is the amount of solar energy received at unit area. What needs to be clarified is that solar radiation represents the warmth of sun not the brightness of sunlight.

Comfort is measured in four ways. The ANSI/ASHRAE Standard 55-2010 seven-point thermal sensation scale was adopted, in addition to a one-way five-point wind sensation scale, three-point wind preference scale, and binary overall comfort scale, all of were used in previous influential studies.

[29] See Appendix D for a list of *met* values for various activities. For example, a person who spent 45 minutes standing and 15 minutes walking in the last one hour has an average metabolic rate of $(45 \times 1.4 + 15 \times 1.8) / 60 = 1.5$ *met*.

[30] See Appendix E for a list of *clo* values for various garments and typical ensembles.

Table 8. List of variables for examining the relationship between wind and willingness to use sustainable transportation modes

Variable			Unit or Scale	Definition, Range, or Options	Collection Method
Independent Variable	Individual	Gender	-	Female, Male	Recording by surveyor
		Visit frequency	-	4+/week, 1-3/week, 1-3/month, Rarely/first time	Survey
		Visit purpose	-	Wait for someone, Rest or linger, Have lunch/coffee, On way to somewhere, Others	Survey
	Location	Location	-	Yerba Buena, Van Ness, Civic Center, Mission Bay North	Recording by surveyor
	Thermal history and status	Metabolic rate	met	Energy generated inside the body due to various activities (1 met = 58.2 W/m^2)	Survey
		Time spent outside in the last 1 hour	minute	Degree of adaptation to the outdoor microclimatic conditions	Survey
		Clothing insulation	clo	Thermal insulation provided by garments and clothing ensembles (1 clo = 0.155 m^2•°C/W)	Recording by surveyor
	Microclimatic Condition	Equivalent wind speed	mph	Mean wind speed combined with wind turbulence	Meteorological station
		Temperature	°F	Air temperature	Meteorological station
		Solar radiation	W/m^2	Amount of solar energy received at unit area	Solar power meter
		Humidity	%	Relative humidity	Meteorological station
	Use of Sustainable Transportation Modes	Frequency of transit use	One-way 3p	Rarely, Sometimes, Frequently	Survey
		Frequency of bicycling	One-way 3p	Rarely, Sometimes, Frequently	Survey
Dependent Variable	Willingness to use sustainable transportation modes	Discouragement for waiting at transit stop with no shelter	One-way 3p	No effect, Slightly, Strongly	Survey
		Discouragement for bicycling	One-way 3p	No effect, Slightly, Strongly	Survey
		Discouragement for walking	One-way 3p	No effect, Slightly, Strongly	Survey
		Discouragement for sitting outside	One-way 3p	No effect, Slightly, Strongly	Survey

No previous studies have assessed outdoor thermal comfort and people's willingness to use sustainable transportation modes, except several studies that examined the relationship between weather and transit use. Therefore, all the independent variables that were selected to examine the relationship between wind and comfort have been included. In addition, it was hypothesized

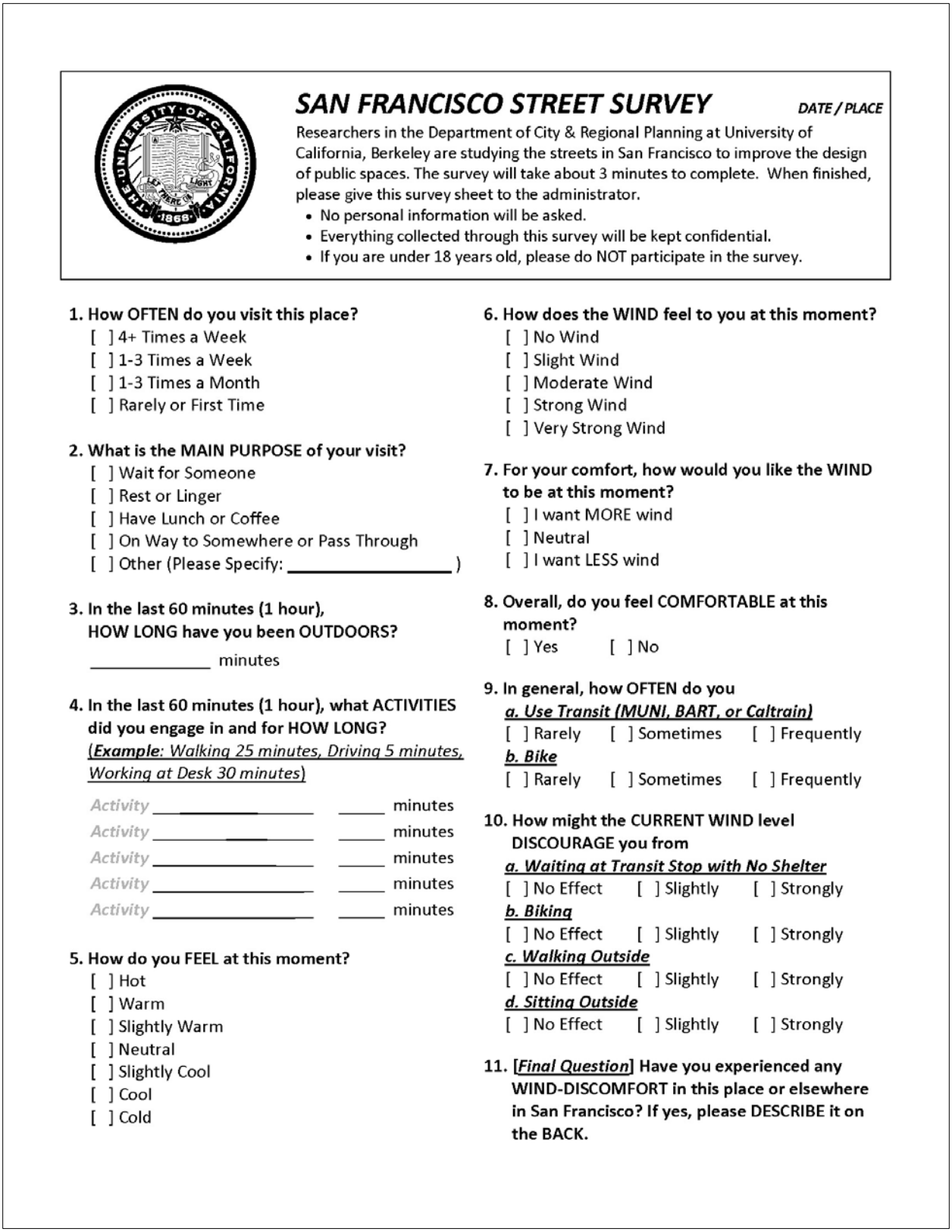
that the participant's use of the sustainable transportation modes at ordinary times affects their willingness to use them under various wind conditions.

Willingness to use sustainable transportation modes is examined in the opposite way. Instead of directly asking the participant's willingness, they were asked their degree of discouragement for waiting at a transit stop with no shelter, bicycling, walking, and sitting outside in three-point scale. In this way, it is more convenient to correlate the responses with the increase in wind speed.

In addition, two open-ended questions were asked at the end of the survey to collect qualitative data on wind and comfort to complement this research which is more inclined to obtaining quantitative data. One question is about places the participant experienced wind-discomfort in San Francisco, and the other is about the impacts of excessive wind on outdoor activities.

The variables and questions mentioned so far were embodied in eleven questions on a two-page questionnaire sheet shown in Figures 47 and 48. In addition, date, time, and location the survey was carried out were recorded at the top of the first page. This survey was approved by the Committee for Protection of Human Subjects (CPHS) and Office for the Protection of Human Subjects (OPHS) at the University of California, Berkeley on April 19, 2013.[31]

[31] See Appendix F for the official notice of approval for human research.



SAN FRANCISCO STREET SURVEY

DATE / PLACE

Researchers in the Department of City & Regional Planning at University of California, Berkeley are studying the streets in San Francisco to improve the design of public spaces. The survey will take about 3 minutes to complete. When finished, please give this survey sheet to the administrator.

- No personal information will be asked.
- Everything collected through this survey will be kept confidential.
- If you are under 18 years old, please do NOT participate in the survey.

1. How OFTEN do you visit this place?

[ ] 4+ Times a Week
[ ] 1-3 Times a Week
[ ] 1-3 Times a Month
[ ] Rarely or First Time

2. What is the MAIN PURPOSE of your visit?

[ ] Wait for Someone
[ ] Rest or Linger
[ ] Have Lunch or Coffee
[ ] On Way to Somewhere or Pass Through
[ ] Other (Please Specify: _____)

3. In the last 60 minutes (1 hour), HOW LONG have you been OUTDOORS?

_____ minutes

4. In the last 60 minutes (1 hour), what ACTIVITIES did you engage in and for HOW LONG?
(***Example***: *Walking 25 minutes, Driving 5 minutes, Working at Desk 30 minutes*)

Activity _____ _____ minutes
Activity _____ _____ minutes
Activity _____ _____ minutes
Activity _____ _____ minutes
Activity _____ _____ minutes

5. How do you FEEL at this moment?

[ ] Hot
[ ] Warm
[ ] Slightly Warm
[ ] Neutral
[ ] Slightly Cool
[ ] Cool
[ ] Cold

6. How does the WIND feel to you at this moment?

[ ] No Wind
[ ] Slight Wind
[ ] Moderate Wind
[ ] Strong Wind
[ ] Very Strong Wind

7. For your comfort, how would you like the WIND to be at this moment?

[ ] I want MORE wind
[ ] Neutral
[ ] I want LESS wind

8. Overall, do you feel COMFORTABLE at this moment?

[ ] Yes [ ] No

9. In general, how OFTEN do you

a. Use Transit (MUNI, BART, or Caltrain)
[ ] Rarely [ ] Sometimes [ ] Frequently
b. Bike
[ ] Rarely [ ] Sometimes [ ] Frequently

10. How might the CURRENT WIND level DISCOURAGE you from

a. Waiting at Transit Stop with No Shelter
[ ] No Effect [ ] Slightly [ ] Strongly
b. Biking
[ ] No Effect [ ] Slightly [ ] Strongly
c. Walking Outside
[ ] No Effect [ ] Slightly [ ] Strongly
d. Sitting Outside
[ ] No Effect [ ] Slightly [ ] Strongly

11. [*Final Question*] Have you experienced any WIND-DISCOMFORT in this place or elsewhere in San Francisco? If yes, please DESCRIBE it on the BACK.

Figure 47. Survey page 1.

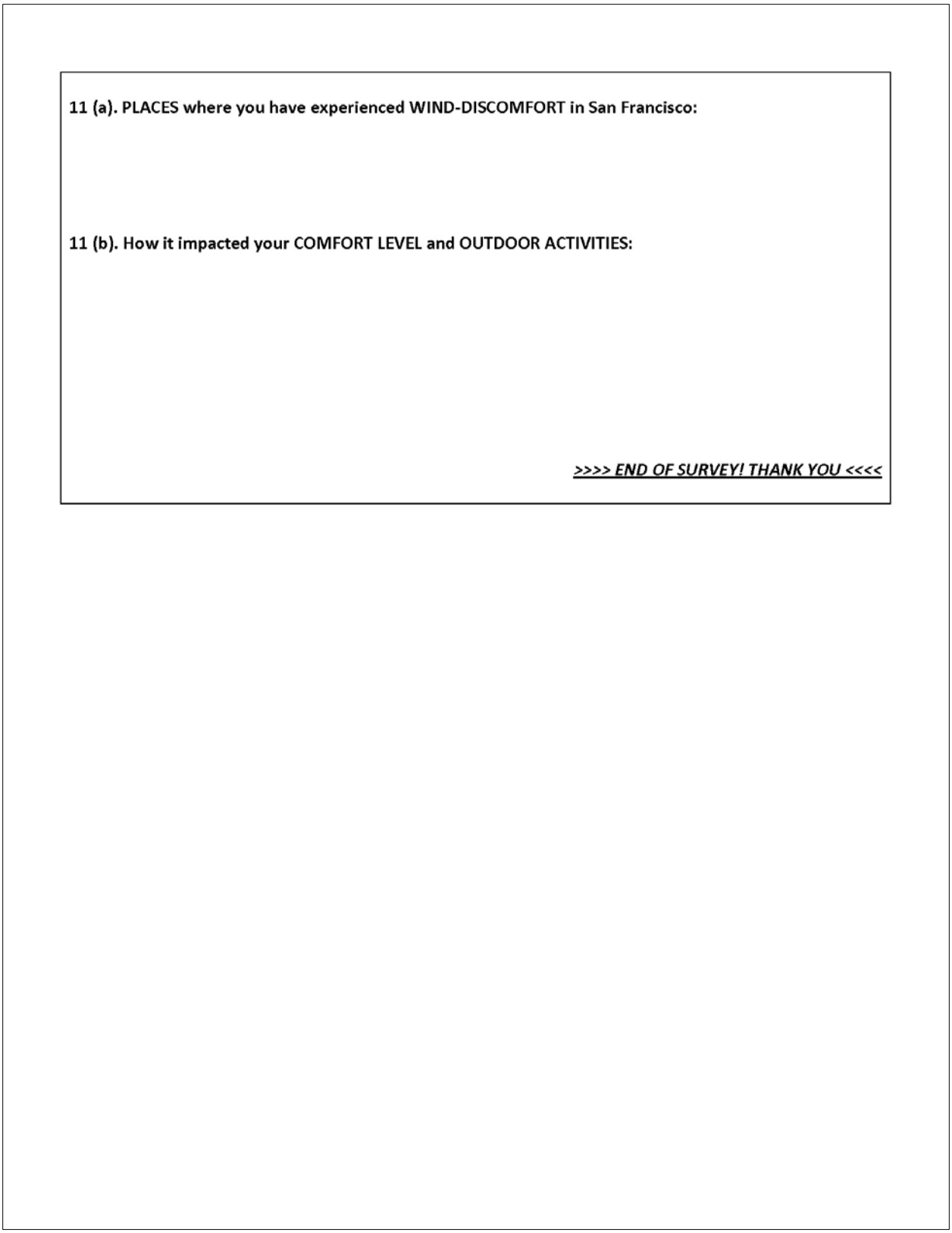


Figure 48. Survey page 2.

Collection of Microclimate Data

Microclimate data was collected by using two instruments, a meteorological station and a solar power meter. As shown in Figure 49, the meteorological station is composed of four parts: Kestrel 4500NV Weather Tracker, rotating vane mount, tripod, and signboard. The Weather Tracker collects various microclimate data and is placed on the vane mount which rotates with the wind. They are securely placed on the tripod that keeps the Weather Tracker at a height of 5 feet (1.5 meters) above the ground level. The signboard provided limited information about the study to attract pedestrians to participate. It stated that this is a UC Berkeley doctoral research project and that only three minutes is needed to complete the survey. It did not provide any information about the topics in order to minimize bias in the participants.

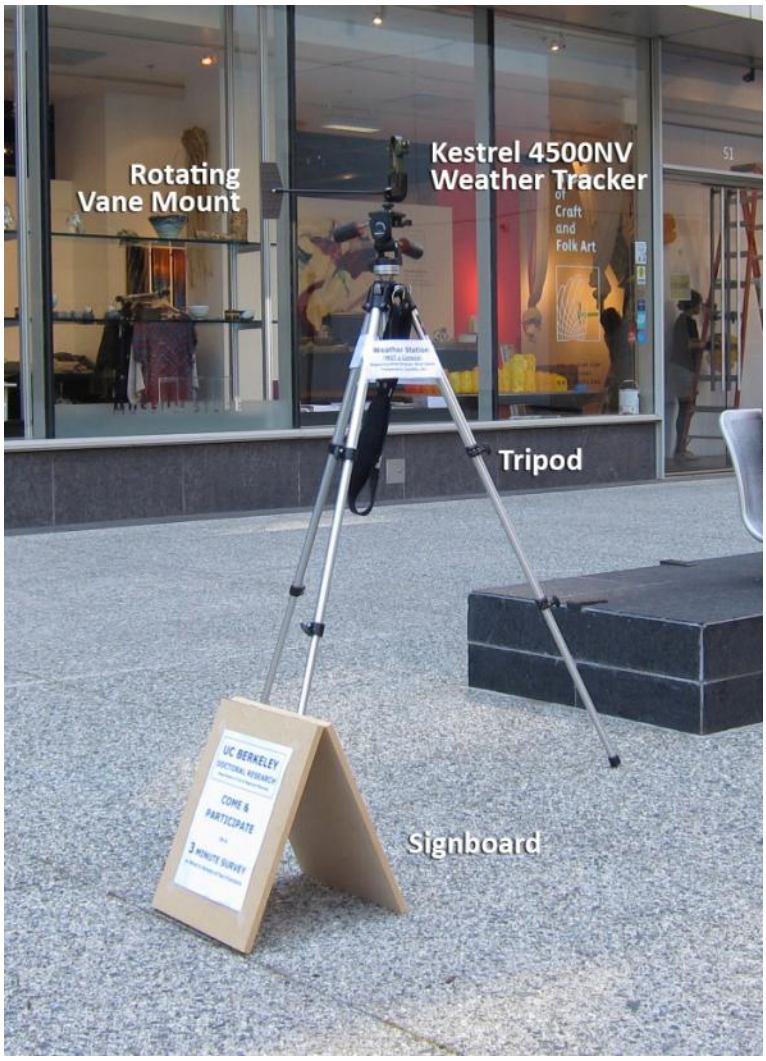


Figure 49. Meteorological station.

Kestrel 4500NV Weather Tracker, as shown in Figure 50, is an instrument that measures various microclimate data including wind speed, temperature, and humidity that need to be collected in this field study. It also measures a wide range of microclimate data, such as wind direction, crosswind, head/tailwind, and barometric pressure, calculates altitude, dew point, and wind chill, and logs up to 2,900 data points as frequent as every two seconds.[32]

Figure 50. Kestrel 4500NV Weather Tracker

While the Kestrel 4500NV Weather Tracker is capable of collecting a wide range of microclimate data, one variable it does not collect is solar radiation. Therefore, an Ambient Weather SP-216 Solar Power Meter was used to collect such data, as shown in Figure 51.[33] Rather than being mounted on a tripod, the meter was hand-held vertically above the ground surface at a height of 5 feet, away from any obstacles. By pressing a button, it provides a reading on solar radiation.

Figure 51. Ambient Weather TM-206 Solar Power Meter

[32] Operation range (and accuracy) of the Weather Tracker: wind speed: 1.3 – 134.2 mph (+/- 3%); temperature: 14.0 – 131.0 °F (+/- 0.9 °F); Humidity: 0 – 100% (+/- 3%).
[33] Operation range (and accuracy) of the Solar Power Meter: 0 – 1999 W/m^2 (+/- 10 W/m^2 or +/- 5%)

Field Study Locations

To keep consistency with the wind tunnel test, locations within each of the Yerba Buena, Van Ness, Civic Center, and Mission Bay North study sites were selected for the field study. The first step was to come up with a set of criteria. The ideal location has:

- high level of ambient wind speed, so that a wide range of wind speed can be covered
- high volume of pedestrian traffic, so that a large sample size can be acquired

To find an optimal location, an in-depth understanding of people's behavior in each site was crucial. A 800 feet by 500 feet section within each site was selected for a closer observation: Yerba Buena Lane in Yerba Buena, Van Ness Avenue and California Street intersection in Van Ness, P. B. Federal Building in Civic Center, 4th and King Streets intersection in Mission Bay North, and their surroundings.[34] In each of these sections, a 30- to 40-minute observation was conducted on a weekday afternoon to produce an activity map illustrating pedestrian counts, their activities, and the surrounding buildings and land use. As shown in Figures 52, 53, 54, and 55, the maps present what activities people were engaging in and where they took place.

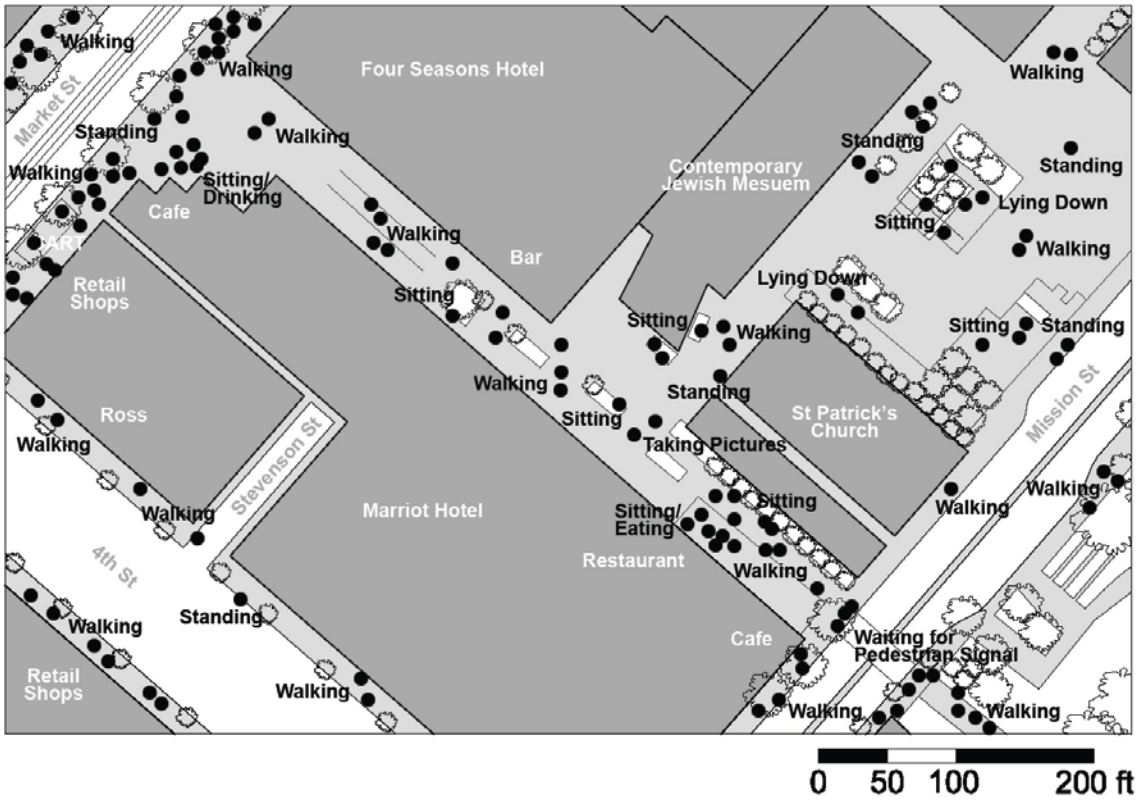


Figure 52. Activity map of Yerba Buena Lane and its surroudings.

[34] P. B. Federal Building is also the main venue of the study by Bosselmann et al. (1988) that examined the relationship between thermal comfort and outdoor behavior.

Figure 52 shows that Yerba Buena Lane is an area with diverse activities. These include sitting, walking, eating, standing, and taking pictures, many of which are connected to the Contemporary Jewish Museum and retail shops along the lane. On the other hand, Market and 4th Streets are mostly associated with walking, and Jessie Square with more stable activities such as sitting and lying down.

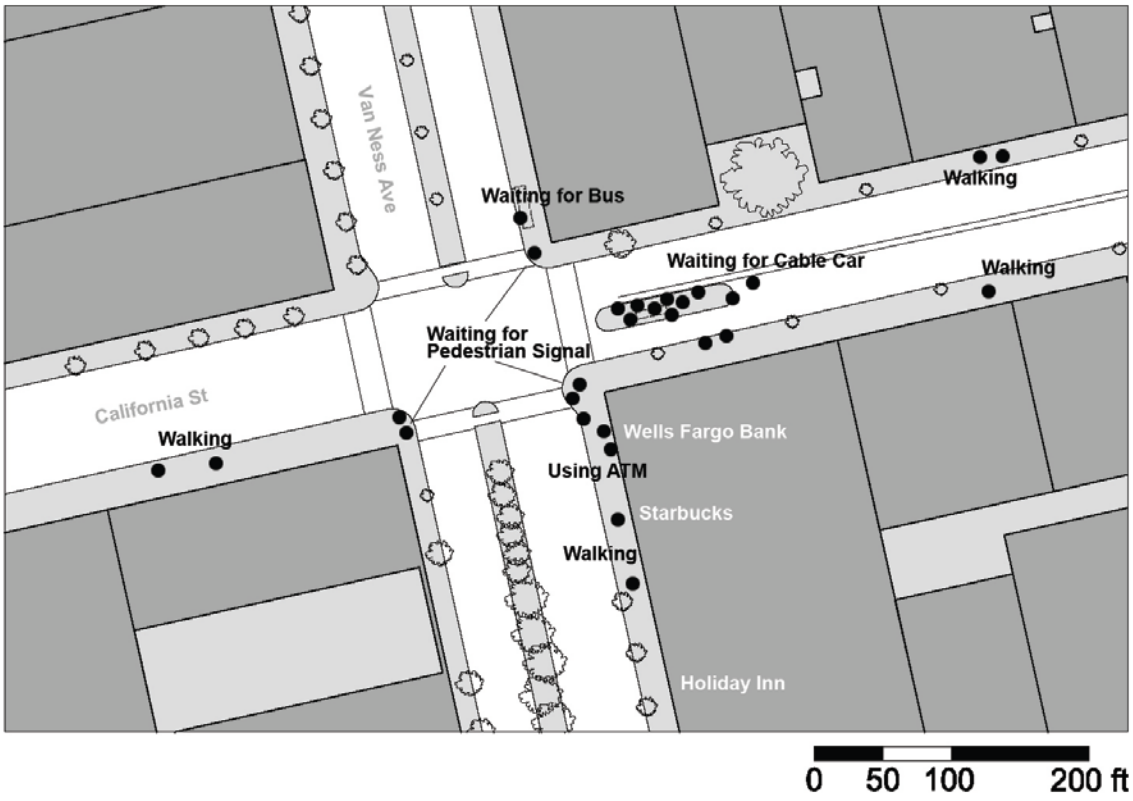


Figure 53. Activity map of Van Ness Avenue and California Street intersection and its surroundings.

Observations showed fewer people at the Van Ness Avenue and California Street intersection and in its surroundings than in Yerba Buena Lane, as illustrated in Figure 53. However, a number of pedestrians were found between Holiday Inn and the Cable Car station on California Street. Many of them are tourists but also local residents who go to the bank or Starbucks, use an ATM machine, or wait for pedestrian signal before crossing the streets.

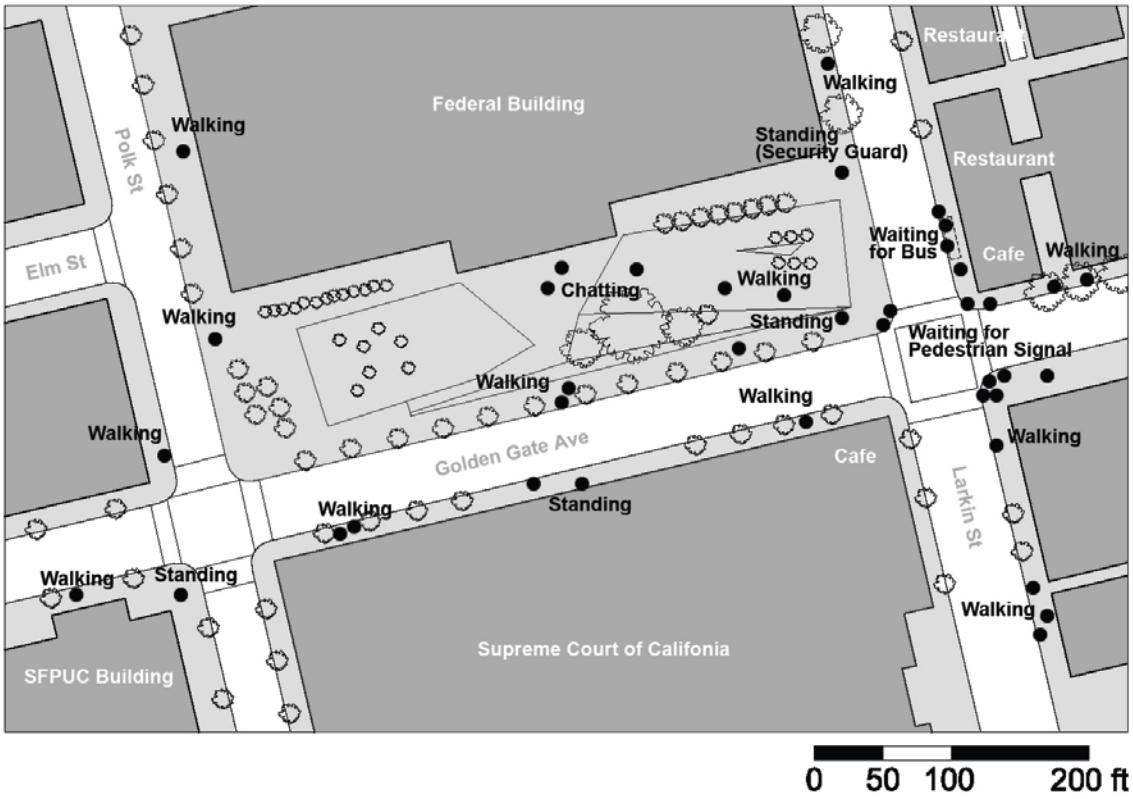


Figure 54. Activity map of P. B. Federal Building and its surroundings.

As shown in Figure 54, there exists a large open space in front of the P. B. Federal Building. While the space is not much used by the general public, except occasionally by people entering or exiting the building, more pedestrians were observed at its southeastern corner, near the Golden Gate Avenue and Larkin Street intersection. There is a constant volume of pedestrian traffic at the intersection, many of whom are walking along Golden Gate Avenue and Larkin Street, waiting for pedestrian signal to cross the streets, or waiting for bus at transit stop.

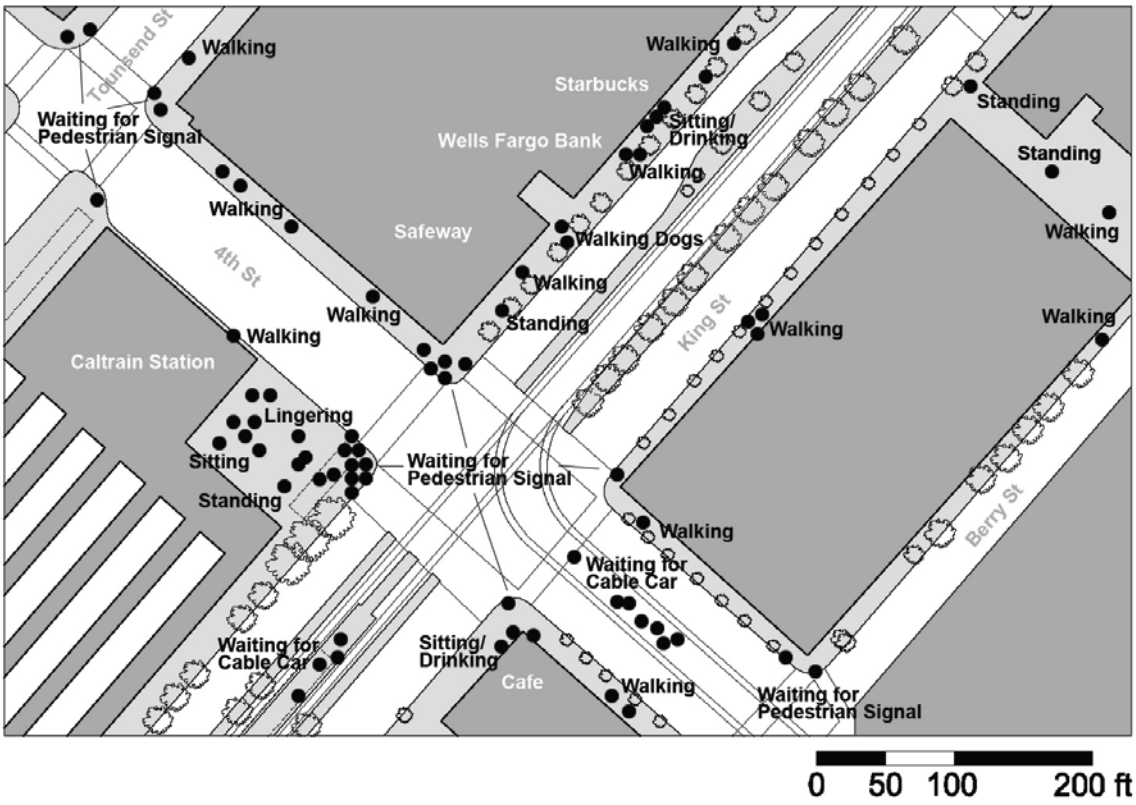


Figure 55. Activity map of 4th and King Streets intersection and its surroundings.

As shown in Figure 55, the 4th and King Streets intersection is a focal point for pedestrian activity. At the intersection, a large number many people are waiting for pedestrian signal to cross the streets. Along 4th Street, almost no activities other than walking or waiting for pedestrian signals were observed. However, along King Street, especially on the northwest side where Safeway, Wells Fargo Back, and Starbucks are lined up, many people engage in walking or sitting/drinking coffee. In the small open space at the Caltrain Station, a relatively large number of people were observed sitting on benches or lingering. During peak hours, when a train arrives at the station or when there is a baseball game held at the AT&T Park, King Street and the open space at the station become extremely crowded.

Based on these observations, locations with high pedestrian volumes were selected for the field study. As shown in Figure 56, the locations are as follows:

- Yerba Buena Lane in front of the Contemporary Jewish Museum[35]
- Southeast corner of Van Ness Avenue and California Street intersection, in front of Wells Fargo Bank and Starbucks

[35] This location exists within a privately owned area even though it is open to public. In order to prevent any awkward situations, the Yerba Buena Alliance (https://yerbabuena.org/) was contacted. A confirmation by email in June 11, 2012 was received that they approve this research activity in Yerba Buena Lane.

- Southeast corner of P. B. Federal Building's open space (northeast corner of Golden Gate Avenue and Larkin Street intersection)
- North corner of 4th and King Streets intersection in front of Safeway

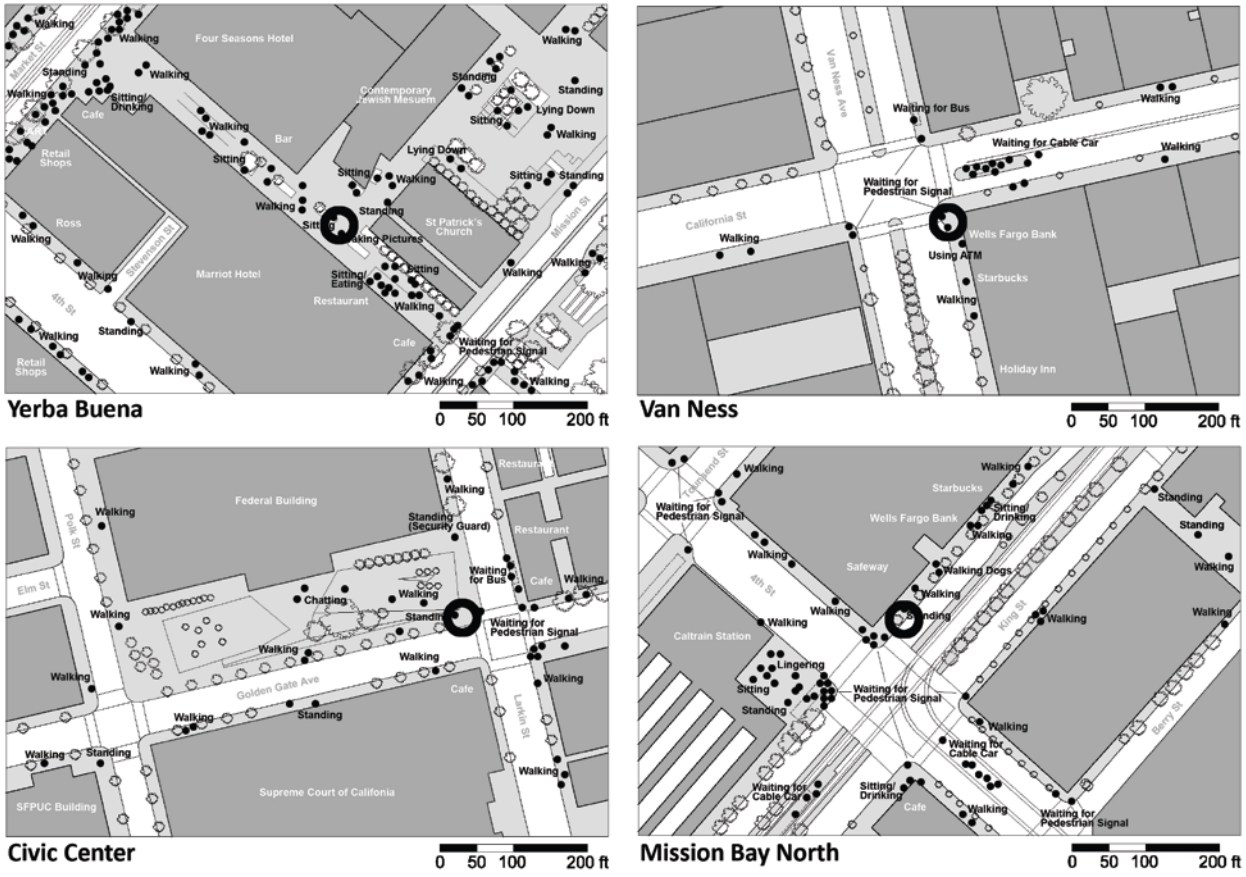


Figure 56. Selection of field study locations.

Study Procedure

The field study was carried out in 2012 at the four locations on weekdays from noon to 5 pm to catch both lunch and commuting pedestrian traffic, and from July, the windiest and second hottest month in San Francisco, to December, the least windy and coldest month, to encompass a wide range of meteorological conditions. After the daylight saving time ended on November 4th, field study was carried out only from noon to 4 pm, because it became very dark towards 4 pm, meaning that the solar radiation would near zero. Field study was not conducted on wet days for three reasons. First, it was impossible for participants to fill out a questionnaire survey sheet since it easily became wet. Second, the participation rate dropped vastly due to the bad weather condition. Third, it was practically difficult to stay outside for many hours in rain with very few participants.

The meteorological station was set up so as not to interfere with any pedestrian traffic or commercial activities in the vicinity. As shown in Figure 57, the survey administrator stood or sat approximately six to eight feet away from the station to conduct the survey. Microclimate data was set up to be automatically logged at every ten seconds. Participants were asked to stand approximately 8 to 10 feet away from the station and not in the direction where wind was blowing from in order not to block any wind or sunlight. They were given a questionnaire sheet on a clip board with a pen to fill out the questions. The participant's gender, clothing status, and time when the survey began and ended were recorded on a separate sheet. It took three minutes on average for each participant to complete the survey. During this three minute period, the equivalent wind speed was calculated based on the wind speed measured at every ten seconds. Other microclimate variables such as temperature, relative humidity, and solar radiation data used for analysis were based on the readings at the beginning of the three minute period.

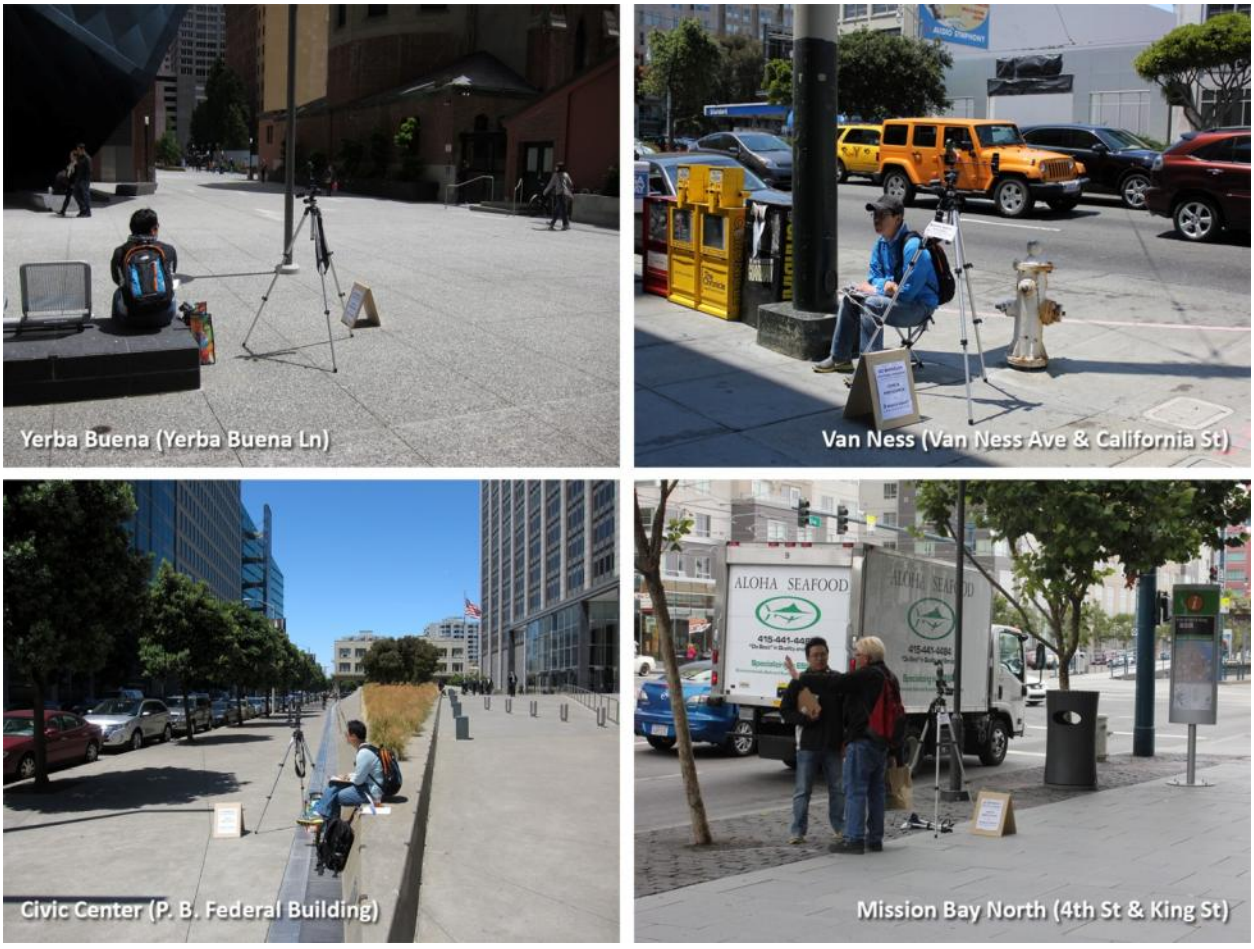


Figure 57. Field study at the four selected locations.

The original plan was to collect at least 1,000 valid samples by carrying out ten field studies per location (40 in total), assuming that 25 samples would be collected per day. However, due to the large number of days with precipitation especially in November and December, it was difficult to

meet the target. A total of 26 field studies were carried out, seven in both Yerba Buena and Civic Center and six in both Van Ness and Mission Bay North. In the end, as summarized in Table 9, 709 samples were collected out of which 701 were valid,[36] with an average of 27 valid samples per day. A total of 128 hours between July and December were spent to carry out the field study, meaning that a valid sample was collected every 11 minutes. The largest sample was collected at Yerba Buena and the smallest at Mission Bay North.

Table 9. Summary of the field study.

Location	Studied Dates	Number of Samples Collected	Number of Valid Samples	Number of Valid Samples per Day
Yerba Buena	7/5, 7/17, 8/14, 8/28, 9/25, 10/16, 11/6[a]	240	239	34
Van Ness	7/12, 7/24, 8/21, 9/11, 10/5, 10/30	144	143	24
Civic Center	7/10, 7/20, 8/17, 8/31, 9/28, 10/19, 12/7[a]	188	183	26
Mission Bay North	7/13, 8/10, 8/24, 9/14, 10/12, 11/2	137	136	23
Total		**709**	**701**	**27**

Notes: a. Days after the daylight saving time ended.

[36] It was possible to significantly reduce the number of invalid samples by keeping the questionnaire survey highly compact and easy to understand, and by standing close to participants to review the survey as they filled it out.

CHAPTER 5. URBAN FORM AND WIND

This chapter presents an answer to the first research sub-question of this research: *has the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment?* It provides results from the wind tunnel study, and discusses findings to identify urban form elements that adversely affect the wind environment. In Section 5.1, the overall changes in wind speed ratios of the four selected sites between 1985 and 2013, as well as by their location type, are compares. In Section 5.2, a series comparative analysis of wind speed ratio changes in 21 selected places within the four sites at the individual measurement location level are carried out. Lastly in Section 5.3, findings and discussions urban form conditions that make the streets and open spaces of San Francisco more wind-comfortable are summarized. Details of the wind tunnel study procedure were explained in Section 4.3.

5.1 Overall Changes in the Wind Environment

This section summarizes the wind tunnel study results. A comparative analysis of wind speed ratio changes measured at a total of 318 locations in 1985 and 2013 is presented along with discussion of significant wind speed ratio changes at various locations by their site, which are Yerba Buena, Van Ness, Civic Center, and Mission Bay North, and by their location type, which include street corner, mid-block, transit stop, bicycle lane, and open space.

Overall Wind Speed Ratio

Table 10 shows an executive summary of the wind tunnel study. It also presents the changes in the mean wind speed ratios between the two years, number of locations where the wind speed ratios increased or decreased, and the maximum increase of decrease of the wind speed ratios.

As shown in Table 10, the overall mean of wind speed ratios measured at a total of 318 locations in Yerba Buena, Van Ness, Civic Center, and Mission Bay North, was 0.279 in 1985 and has decreased by 22 percent to 0.218 in 2013. Among the 318 locations, 106 experienced an increase in the wind speed ratio while 212 experienced a decrease. This change indicates that the expected actual wind speeds under a west wind – the most dominant wind direction in the windiest months in San Francisco – at the ground level in the four sites have been significantly reduced since 1985, when the city first adopted a planning measure to reduce ground-level wind currents. It also implies that the plan has been successful in making the city's streets and open spaces more wind-comfortable.

Table 10. Wind speed ratio statistics of the four sites.[37]

Area	Number of Locations	1985			2013			Average Change (%)	Number of Increase/Decrease Locations		Maximum Increase/Decrease (%)	
		Min.	Max.	Mean	Min.	Max.	Mean		Increase	Decrease	Increase	Decrease
Yerba Buena	74	0.064	0.599	0.308	0.067	0.593	0.202	-34*	20	54	+225	-83
Van Ness	72	0.049	0.662	0.244	0.056	0.649	0.225	-8	29	43	+266	-71
Civic Center	102	0.066	0.800	0.262	0.067	0.567	0.247	-6	45	57	+154	-70
Mission Bay North	70	0.069	0.564	0.310	0.060	0.541	0.184	-41*	12	58	+347	-84
Total/ Overall	**318**	**0.049**	**0.800**	**0.279**	**0.056**	**0.649**	**0.218**	**-22***	**106**	**212**	**+347**	**-84**

* The mean wind speed ratio in 1985 and 2013 are significantly different ($p < 0.05$), based on Student's T-Test.

The mean wind speed ratios of all four sites have dropped in 2013, compared to 1985. The mean ratio of Yerba Buena measured at 74 locations was 0.308 in 1985 and 0.202 in 2013, Van Ness at 72 locations was 0.244 and 0.225, Civic Center at 102 locations was 0.262 and 0.247, and Mission Bay North at 70 locations was 0.310 and 0.184. Among the four sites, Mission Bay North has decreased by 41 percent and is followed by Yerba Buena, which had a 34 percent decrease. The biggest drop in Mission Bay North, from the highest in 1985 to the lowest in 2013, was somewhat expected since there were hardly any buildings or structures in 1985 to block the wind. Another big drop in the mean ratio is found in Yerba Buena, where every single parcel is subject to the wind planning. Although there were a number of high-rise developments since the 1990s in this site, the goal to reduce ground-level wind currents seems to have been well achieved.

The mean wind speed ratios in Van Ness and Civic Center have decreased slightly but not to an extent that is statistically significant. It is interesting to note that these two sites had the lowest ratios in 1985 but the highest in 2013, and that only 21 percent of the parcels in Van Ness and 10 percent in Civic Center have been subject to the wind planning, as previously discussed in Section 4.3.

Street Corner Locations

Table 11 presents the mean wind speed ratios at street corner locations in the four sites. Overall, the ratio has dropped from 0.249 to 0.217 by 13 percent. Yerba Buena, Civic Center, and Mission Bay North have decreased, while Van Ness experienced an increase. However, only the change in Mission Bay North, which decreased from 0.323 to 0.191, is statistically significant. Aside from Mission Bay North, the mean ratios at street corner locations in the other three sites are generally lower than their respective overall means of each site presented in Table 10.

[37] See Appendix G for a summary of raw wind speed data measured at 318 locations of the four sites in 1985 and 2013, and their graphic representation on maps.

Table 11. Wind speed ratio statistics of street corner locations.

Area	Number of Locations	1985			2013			Average Change (%)	Number of Increase/Decrease Locations		Maximum Positive/Negative Change (%)	
		Min.	Max.	Mean	Min.	Max.	Mean		Increase	Decrease	Increase	Decrease
Yerba Buena	18	0.064	0.588	0.259	0.067	0.390	0.196	-24	7	11	+143	-82
Van Ness	24	0.063	0.458	0.201	0.066	0.370	0.224	+11	15	9	+266	-71
Civic Center	33	0.080	0.483	0.246	0.067	0.487	0.235	-4	15	18	+128	-65
Mission Bay North	16	0.080	0.564	0.323	0.063	0.541	0.191	-41*	4	12	+46	-82
Total/ Overall	**91**	**0.063**	**0.588**	**0.249**	**0.063**	**0.541**	**0.217**	**-13***	**41**	**50**	**+266**	**-82**

* The mean wind speed ratio in 1985 and 2013 are significantly different ($p < 0.05$), based on Student's T-Test.

Mid-Block Locations

As shown in Table 12, the mean wind speed ratios at mid-block locations in all four sites have decreased substantially. The overall mean ratio dropped from 0.307 to 0.235 by 23 percent. Especially in Yerba Buena, the mean ratio fell the most by 40 percent. However, the mean ratios at mid-block locations in each site, both in 1985 and 2013, are generally higher than the respective site's overall mean ratios, which are shown in Table 10, indicating that the mid-block locations – essentially sidewalks – are generally windier than other parts of the site.

Table 12. Wind speed ratio statistics of mid-block locations.

Area	Number of Locations	1985			2013			Average Change (%)	Number of Increase/Decrease Locations		Maximum Positive/Negative Change (%)	
		Min.	Max.	Mean	Min.	Max.	Mean		Increase	Decrease	Increase	Decrease
Yerba Buena	22	0.082	0.549	0.308	0.067	0.593	0.184	-40*	4	18	+218	-83
Van Ness	32	0.049	0.662	0.316	0.056	0.649	0.275	-13*	10	22	+65	-61
Civic Center	43	0.066	0.800	0.281	0.067	0.508	0.241	-14*	16	27	+120	-70
Mission Bay North	32	0.069	0.553	0.335	0.081	0.474	0.228	-32*	6	26	+347	-81
Total/ Overall	**129**	**0.049**	**0.800**	**0.307**	**0.056**	**0.649**	**0.235**	**-23***	**36**	**93**	**+347**	**-83**

* The mean wind speed ratio in 1985 and 2013 are significantly different ($p < 0.05$), based on Student's T-Test.

Transit Stop Locations

The mean wind speed ratios at transit stop locations are shown in Table 13. The overall mean ratio fell from 0.281 to 0.183 by 35 percent. Although the small number of locations of this location type makes it difficult to generalize and confirm all of their statistical significance, it is apparent that the transit stop locations in all four sites have experienced a substantial decrease between 1985 and 2013. Except in Yerba Buena, the mean ratios in the other three parts are far below their respective site's overall mean ratios, implying that transit stops are generally less windy places.

Table 13. Wind speed ratio statistics of transit stop locations.

Area	**Number of Locations**	**1985**			**2013**			**Average Change (%)**	**Number of Increase/Decrease Locations**		**Maximum Positive/Negative Change (%)**	
		Min.	Max.	Mean	Min.	Max.	Mean		Increase	Decrease	Increase	Decrease
Yerba Buena	4	0.269	0.454	0.332	0.099	0.273	0.207	-38	0	4	-	-67
Van Ness	8	0.074	0.455	0.220	0.056	0.419	0.155	-30*	1	7	+37	-63
Civic Center	5	0.080	0.494	0.292	0.084	0.389	0.234	-20	1	4	+27	-37
Mission Bay North	5	0.194	0.508	0.324	0.084	0.330	0.159	-51*	0	5	-	-69
Total/ Overall	**22**	**0.074**	**0.508**	**0.281**	**0.056**	**0.419**	**0.183**	**-35***	**2**	**20**	**+37**	**-69**

* The mean wind speed ratio in 1985 and 2013 are significantly different ($p < 0.05$), based on Student's T-Test.

Bicycle Lane Locations

Table 14 shows that the overall mean wind speed ratio at bicycle lane locations in the four areas has dropped from 0.166 to 0.144 by 13 percent. Although the mean ratio in Yerba Buena has increased by 37 percent, all mean ratios of the four sites in 1985 and 2013 remain below their respective site's mean ratios, indicating that bicycle lanes are less windy.

Table 14. Wind speed ratio statistics of bicycle lane locations.

Area	Number of Locations	1985			2013			Average Change (%)	Number of Increase/Decrease Locations		Maximum Positive/Negative Change (%)	
		Min.	Max.	Mean	Min.	Max.	Mean		Increase	Decrease	Increase	Decrease
Yerba Buena	8	0.106	0.234	0.145	0.085	0.380	0.199	+37	5	3	+225	-35
Van Ness	8	0.063	0.201	0.105	0.063	0.192	0.100	-5	3	5	+40	-26
Civic Center	6	0.094	0.410	0.193	0.067	0.364	0.176	-9	3	3	+62	-49
Mission Bay North	10	0.086	0.450	0.216	0.070	0.225	0.117	-46*	2	8	+10	-78
Total/ Overall	**32**	**0.063**	**0.450**	**0.166**	**0.063**	**0.038**	**0.144**	**-13**	**13**	**19**	**+225**	**-78**

* The average wind speed ratio in 1985 and 2013 are significantly different ($p < 0.05$), based on Student's T-Test.

Open Space Locations

The mean wind speed ratios of open space locations show varied results as presented in Table 15. The overall mean ratio has decreased from 0.341 to 0.240 by 30 percent. While the mean ratio in Yerba Buena and Mission Bay North substantially dropped, that in Civic Center rose significantly. Also, the mean ratios in Yerba Buena and Civic Center, as well as the overall mean ratio, in both 1985 and 2013, are higher than their respective site's overall means, regardless of whether they increased or decreased. That in Mission Bay North in 2013 has also significantly decreased.

Table 15. Wind speed ratio statistics of open space locations.

Area	Number of Locations	1985			2013			Average Change (%)	Number of Increase/Decrease Locations		Maximum Positive/Negative Change (%)	
		Min.	Max.	Mean	Min.	Max.	Mean		Increase	Decrease	Increase	Decrease
Yerba Buena	22	0.067	0.599	0.406	0.085	0.554	0.233	-43*	4	18	+195	-83
Van Ness	0	-			-			-	-	-	-	-
Civic Center	15	0.066	0.550	0.258	0.070	0.567	0.324	+26	10	5	+154	-45
Mission Bay North	7	0.138	0.384	0.311	0.060	0.140	0.084	-73*	0	7	-	-84
Total/ Overall	**44**	**0.066**	**0.599**	**0.341**	**0.060**	**0.567**	**0.240**	**-30***	**14**	**30**	**+105**	**-84**

* The mean wind speed ratio in 1985 and 2013 are significantly different ($p < 0.05$), based on Student's T-Test.

5.2 Changes in the Wind Environment by Site

As presented in the previous section, a series of comparative examinations of the mean wind speed ratios by site, location type, and year, effectively summarize the changes between 1985 and 2013. In addition, it is also crucial to examine the wind speed ratio changes at individual measurement locations for a better understanding of the change. The following part of this section presents a series of comparative analyses at the location level by grouping a number of adjacent locations 21 several places in the four sites that are along a street or in an open space that are of specific interest. Some measurement locations may be included in more than one place.

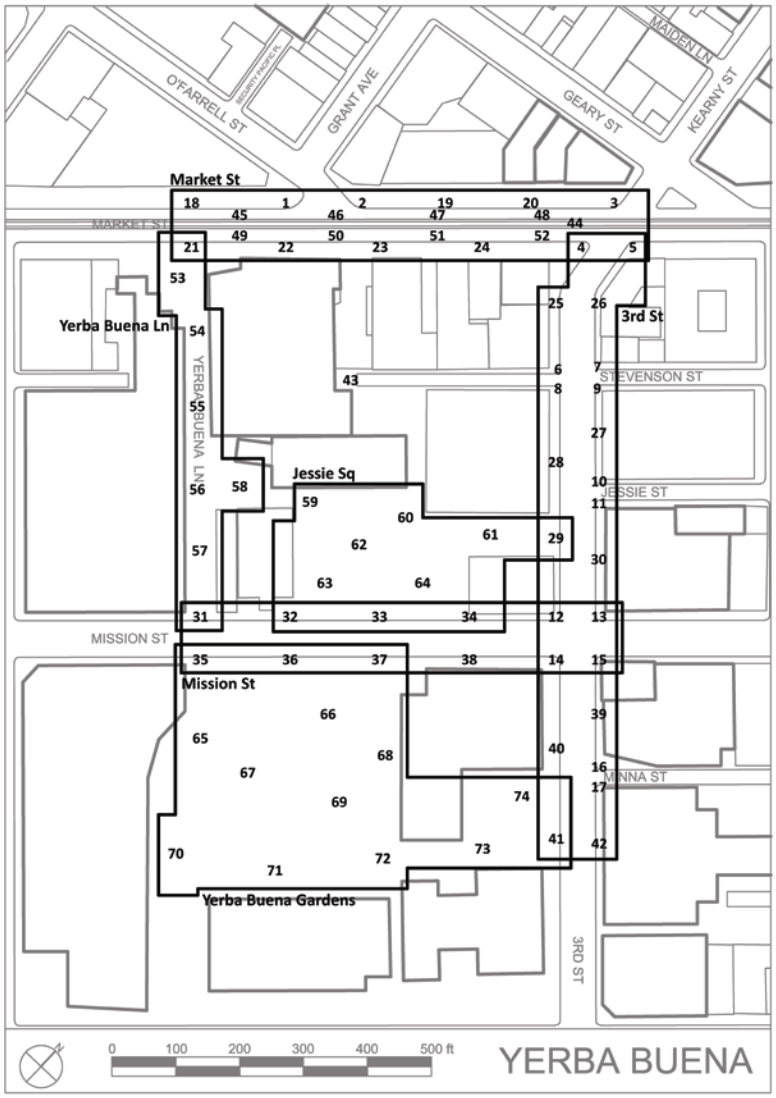


Figure 58. Selection of places in Yerba Buena.

Yerba Buena

As shown in Figure 58, 73 measurement locations in Yerba Buena were grouped into six places for a further comparison of the wind speed ratios. Three streets, including Market, Mission, and 3rd streets, and three open spaces, including Yerba Buena Lane, Jessie Square, and Yerba Buena Gardens, have been chosen.

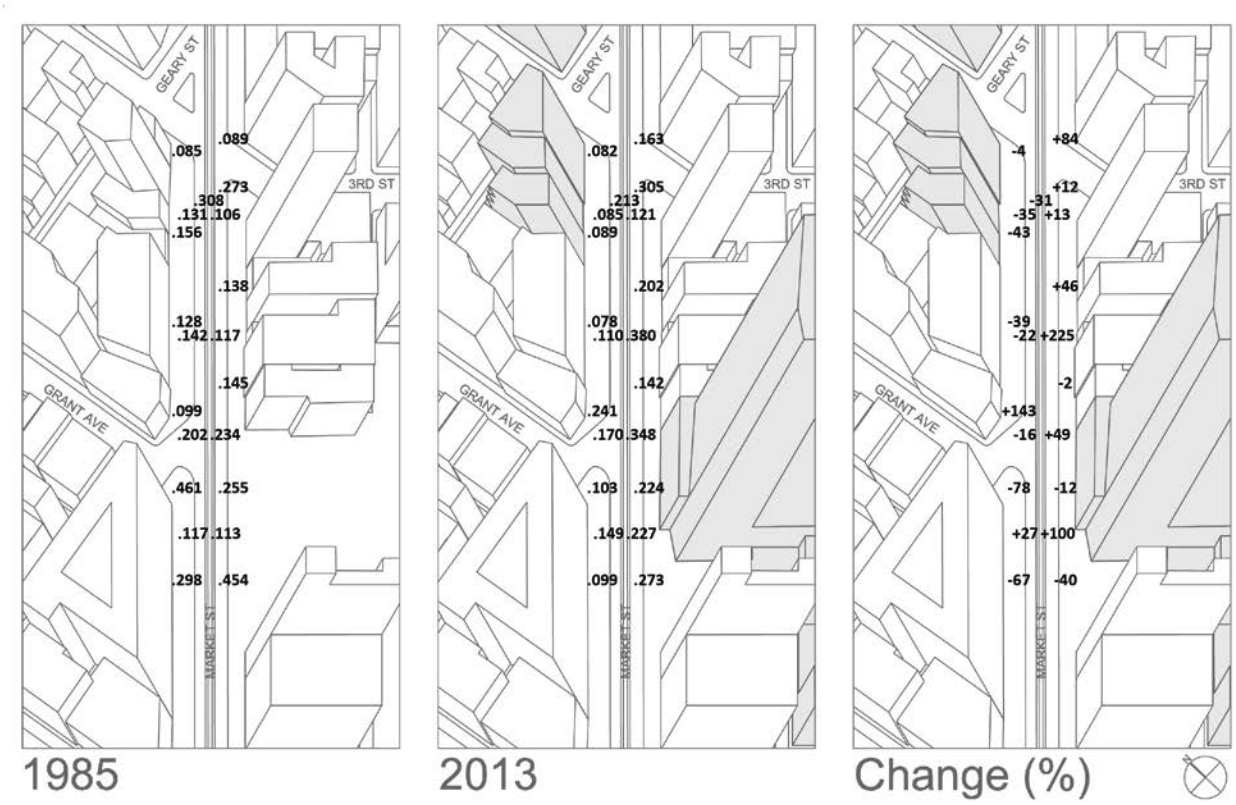


Figure 59. Wind speed ratios in 1985 and 2013, and changes in Market Street.

Figure 59 shows wind speed ratios at locations on public sidewalks, bicycle lanes, and transit stops along Market Street. In 1985, this place was generally well-sheltered from the west wind. Wind speed ratios at most locations on sidewalks and roads remain below 0.250. Higher ratios are observed at the Market Street and O'Farrell Street intersection. The west wind that runs along O'Farrell Street is induced to the large open space located in the south of the intersection, which was vacated in 1985 for new construction, and leaves several measurement locations with ratios that exceed 0.450. In 2013, the west wind that runs along O'Farrell Street enters Market Street, leaving several locations between O'Farrell Street and Geary Street, especially on bicycle lanes, with higher ratios that exceed 0.340 and that have increased up to 225 percent. However, the ratios at most locations remain below 0.250.

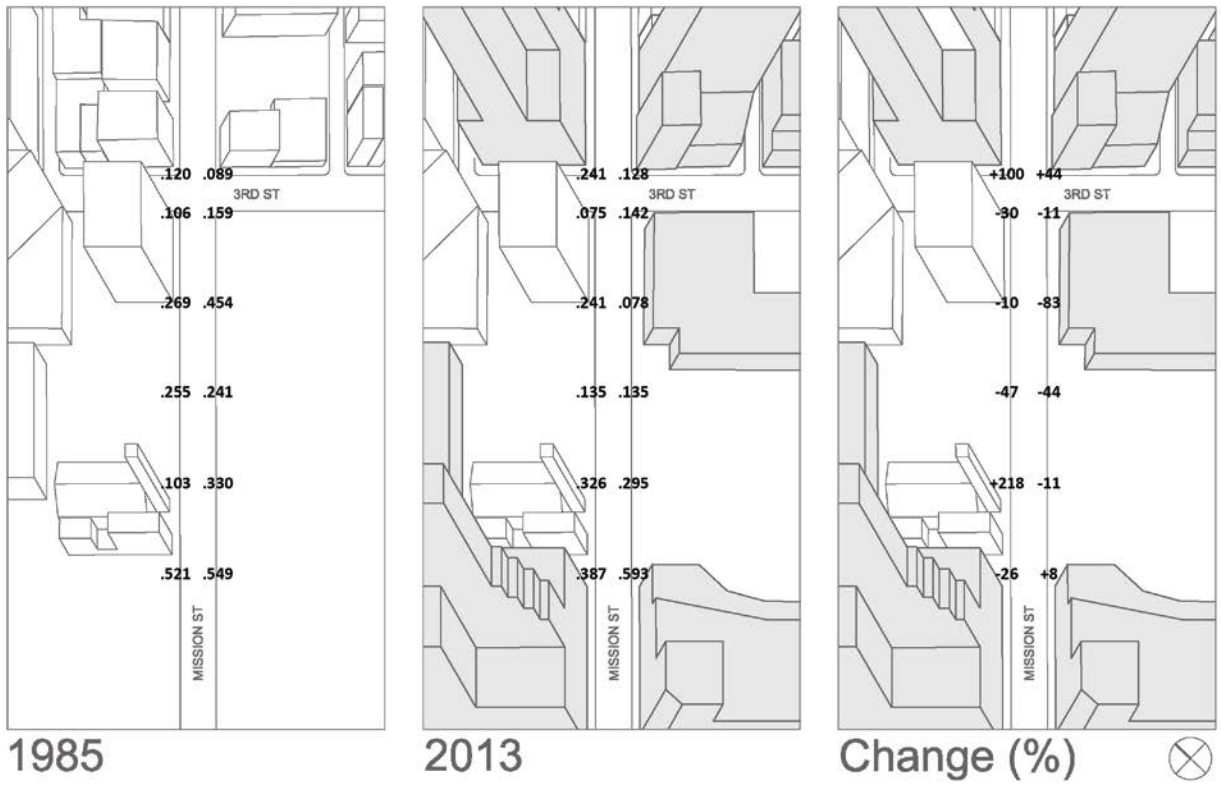


Figure 60. Wind speed ratios in 1985 and 2013, and changes in Mission Street.

Figure 60 shows Mission Street, on which the measurement locations are all on sidewalks. In 1985, this place was relatively windy. The scarcity of buildings did not generate much wind friction, letting wind speed ratios exceed 0.450 at several locations. In 2013, new buildings significantly reduced the wind speed ratios, except at one location in front of St. Patrick's Church, where the ratio has increased by 218 percent. Two new high-rise buildings in the east of 3rd Street have substantially increased the ratios at their street corners.

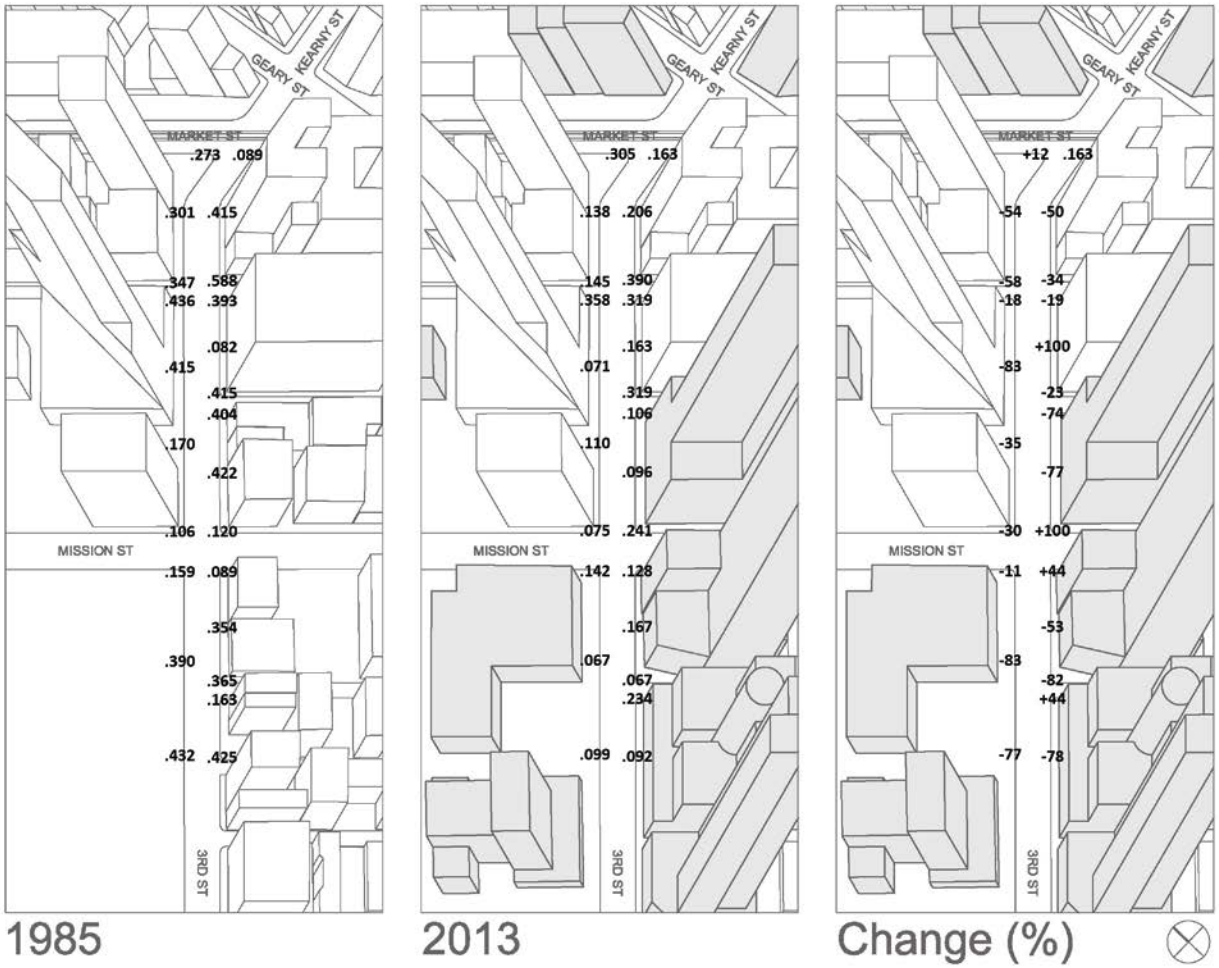


Figure 61. Wind speed ratios in 1985 and 2013, and changes in 3rd Street.

Measurement locations on 3rd Street, as shown in Figure 61, are all street corners or mid-block points. In 1985, a number of locations in the north of Mission Street, especially at street corners, recorded higher wind speed ratios, many of which exceed 0.400. Several locations in the south of Mission also showed ratios over 0.350. In 2013, the ratios dropped in general, only a few exceeding 0.300. Especially in the south of Market, new buildings on both sides of 3rd Street significantly reduced the ratios. On the other hand, locations on Market Street and Mission Street have increased between 1985 and 2013.

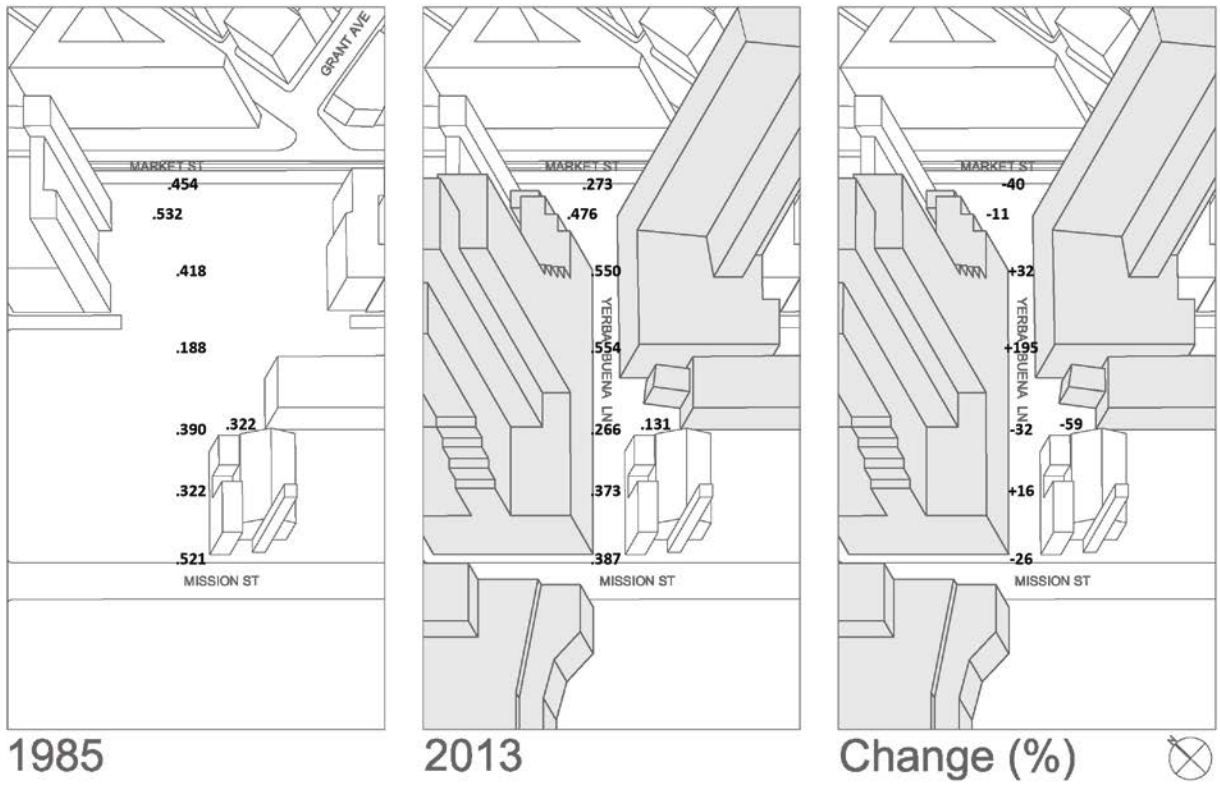


Figure 62. Wind speed ratios in 1985 and 2013, and changes in Yerba Buena Lane.

As presented in Figure 62, Yerba Buena Lane in 1985, when it actually did not exist, was a vacant space with a very high wind level. Wind speed ratios at most measurement locations exceeded 0.320. However in 2013, after the Marriot Marquis Hotel and the Four Seasons Hotel were built, the ratios changed significantly. Yerba Buena Lane is now a narrow open space that operates as a channel between the two high-rise buildings. Especially in the northern part of this place, the ratio at one location has increased by 195 percent, and there are several locations where the ratio exceeds 0.550. Usually, the west wind that runs along Market Street is induced into Yerba Buena Lane's narrow channel and is accelerated. While a small plaza in front of the Contemporary Jewish Museum is less windy, the southern part of Yerba Buena Lane between Marriot and St. Patrick's Church also has a relatively high wind speed level.

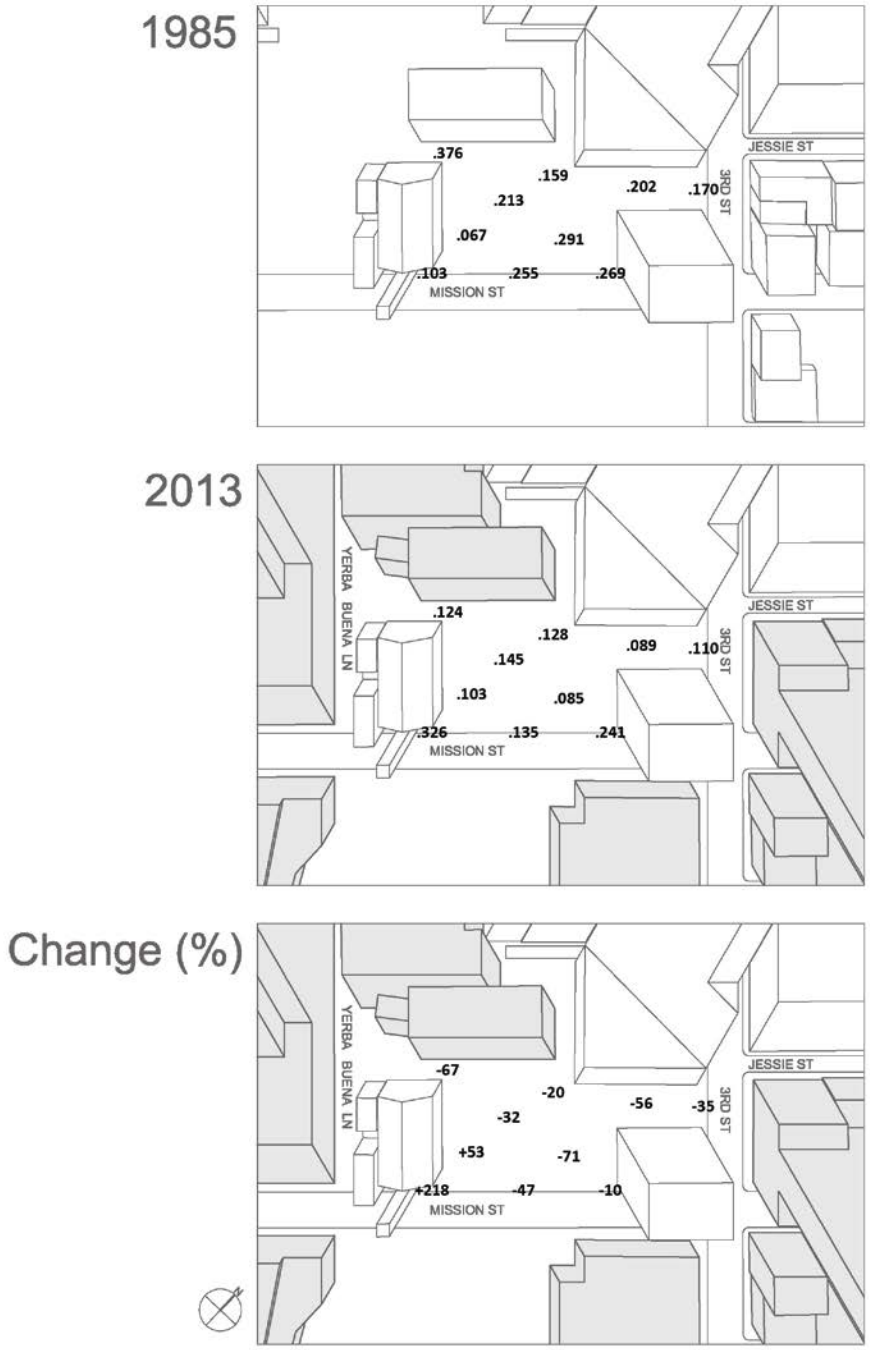


Figure 63. Wind speed ratios in 1985 and 2013, and changes in Jessie Square.

Wind speed ratios and their changes in Jessie Square are illustrated in Figure 63. In 1985, the place was sheltered by several high-rise buildings in the north and west, keeping the ratios mostly below 0.300, except at one location where wind is accelerated by the narrow strip between St. Patrick's Church and Jessie Power Station. By 2013, the ratios have significantly decreased at most points where they remain below 0.150, making Jessie Square a calm place

from wind. A substantial increase in wind speed ratio is observed at two points in the southeast of St. Patrick's Church.

As shown in Figure 64, Yerba Buena Gardens is where wind speed ratios dropped the most between 1985 and 2013. In 1985, the place had relatively high wind speed ratios that near 0.600 at many measurement locations. However in 2013, the ratios fell significantly at almost all locations by up to 83 percent. Except one at the northwestern corner and several in the middle, most locations show ratios below 0.150. It seems that the buildings in Yerba Buena Gardens contribute to sheltering the space from excessive winds.

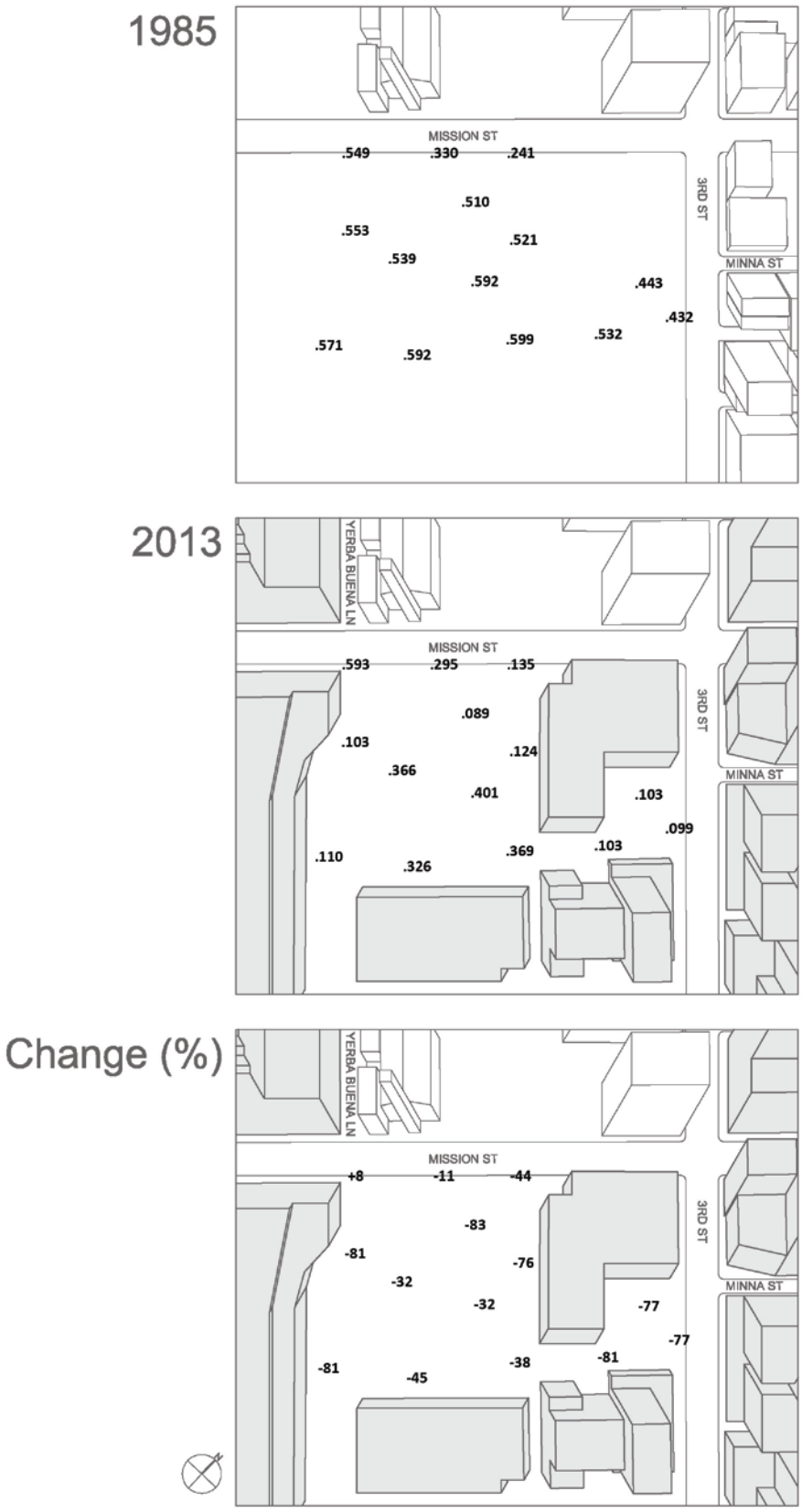


Figure 64. Wind speed ratios in 1985 and 2013, and changes in Yerba Buena Gardens.

Van Ness

As shown in Figure 65, 72 measurement locations in Van Ness were grouped into five places for a further comparison of wind speed ratios. They are Sacramento Street, California Street, Pine Street, Van Ness Avenue, and Polk Street.

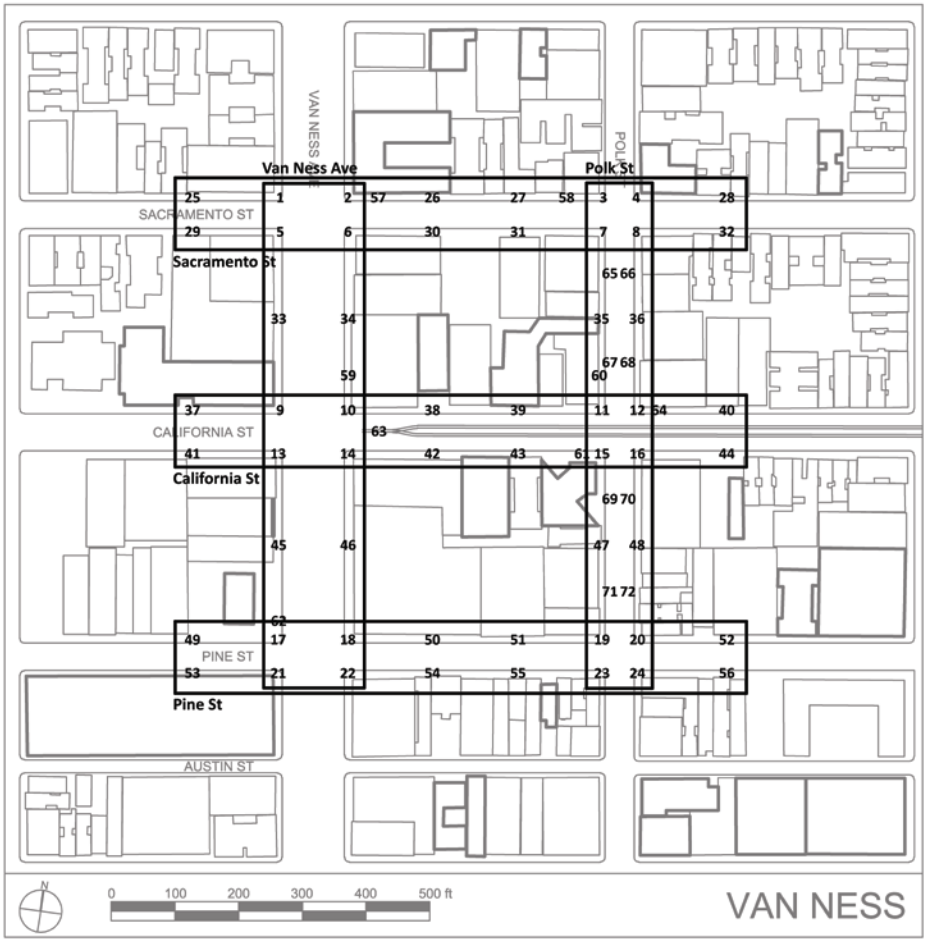


Figure 65. Selection of places in Van Ness.

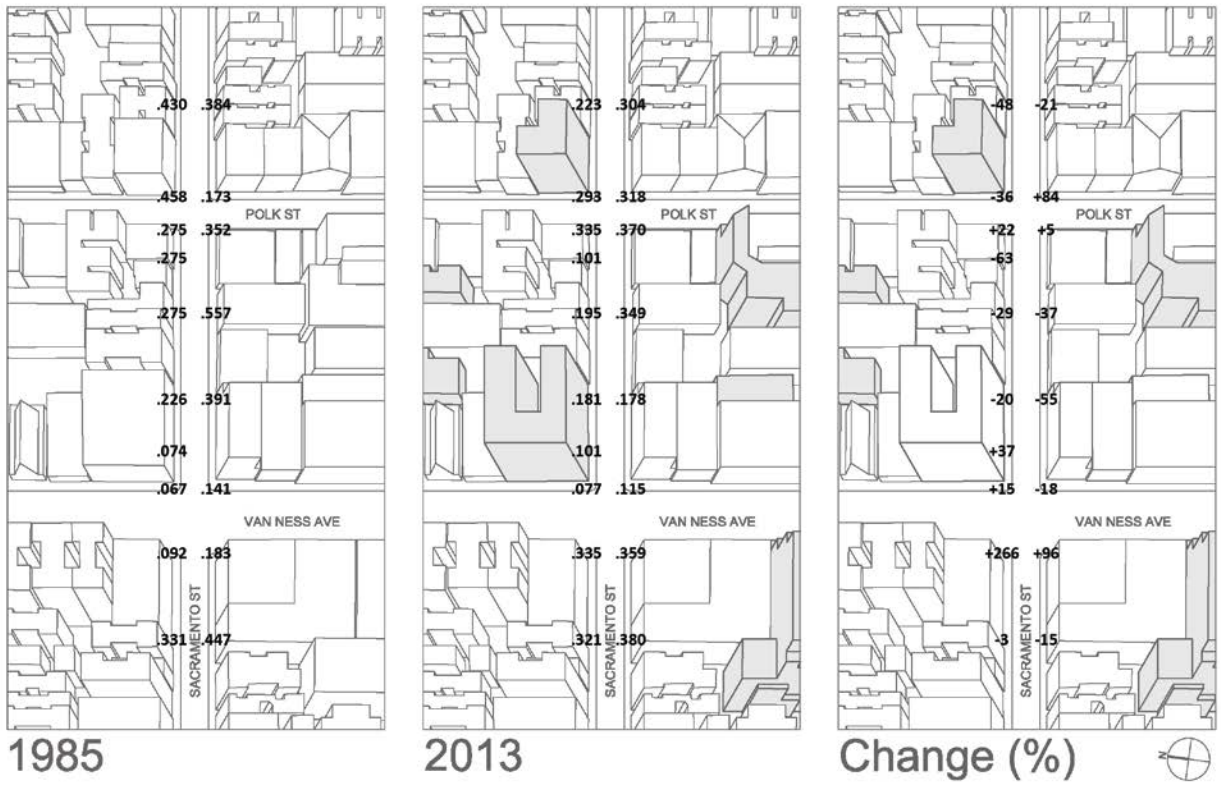


Figure 66. Wind speed ratios in 1985 and 2013, and changes in Sacramento Street.

Figure 66 presents the wind speed ratios and their changes in Sacramento Street. Measurement locations in this place are street corners, mid-block points, or transit stops. In 1985, a wide range of ratios between 0.067 and 0.557 is observed. Locations at the Sacramento Street and Van Ness Avenue intersection have the lowest ratios under 0.200. Those located in the west of Van Ness Avenue, on the southern corner of Sacramento between Van Ness Avenue and Polk Street, and in the east of Polk Street show the highest ratios, many of which exceed 0.400. In 2013, the range is between 0.077 and 0.380. While the ratios at most locations are lower than in 1985, many street corner locations have become windier, especially the ratios at the northwestern and southwestern corners of the Sacramento Street and Van Ness Avenue intersection have increased by up to 266 percent.

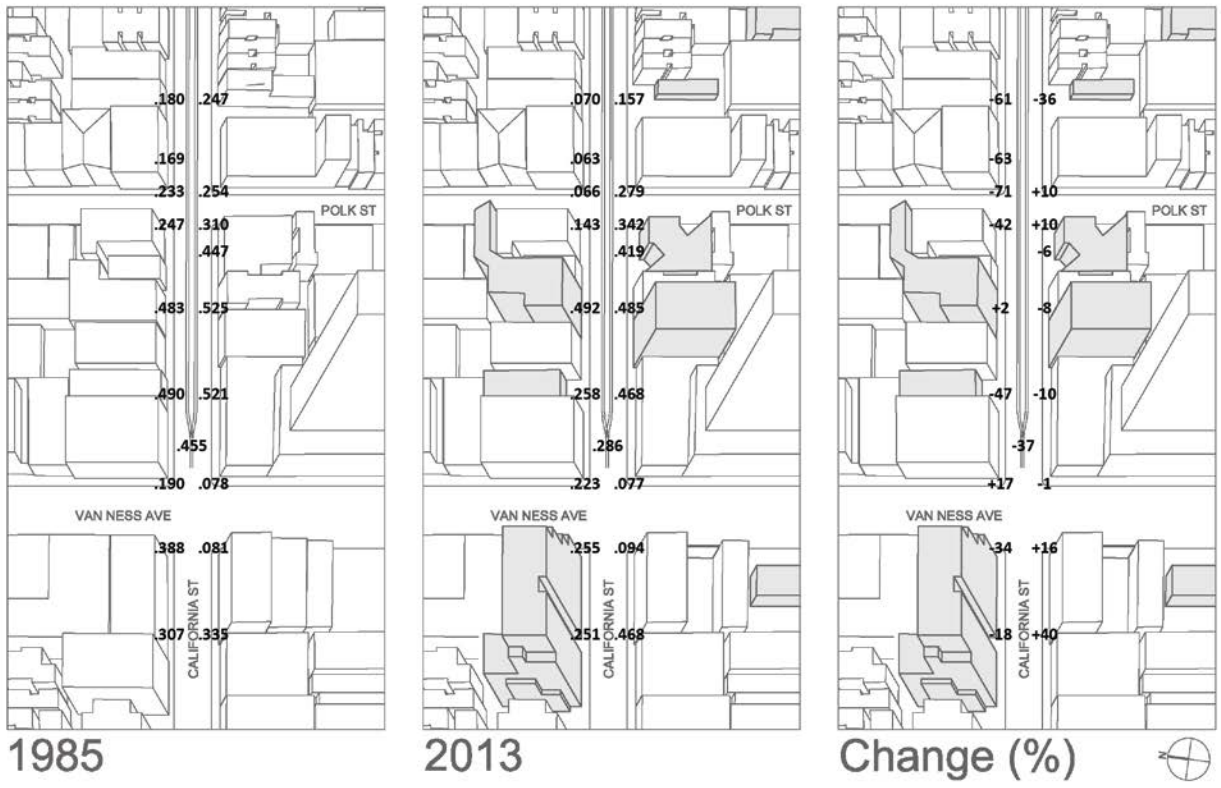


Figure 67. Wind speed ratios in 1985 and 2013, and changes in California Street

Located only one block south of Sacramento Street, California Street also shows a wide range of wind speed ratios between 0.078 and 0.521 in 1985, as presented in Figure 67. However, except several locations at street intersections, where the ratios remain generally low, the west wind that runs along California Street is being accelerated by continuous street walls on both sides of the street, leaving many mid-block points with the highest ratios especially between Van Ness Avenue and Polk Street. In 2013, a new development with an uneven southern façade located in the northwestern corner of the California Street and Van Ness Avenue intersection has changed the wind environment in California Street. Not only the ratios at measurement locations directly in front of the building but also at those between Van Ness Avenue and Polk Street, which had the highest wind speed ratios in 1985, have substantially decreased.

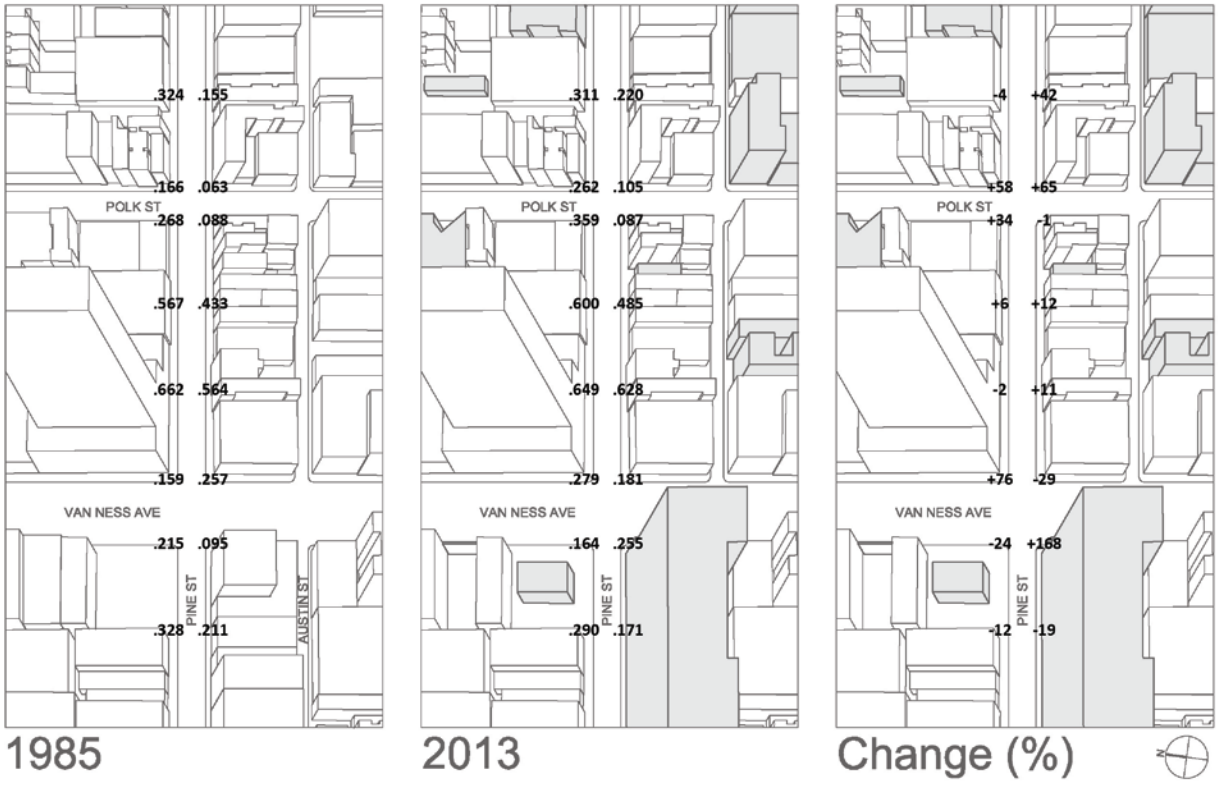


Figure 68. Wind speed ratios in 1985 and 2013, and changes in Pine Street

Figure 68 shows Pine Street, which has the highest range of wind speed ratios in Van Ness in both years. In 1985, the west wind that runs along the street is accelerated as it passes the 25-story Holiday Inn Golden Gateway located at the northeastern corner of the Pine Street and Van Ness Avenue intersection. The ratios rise up to 0.662 and gradually slow down at Polk Street. In 2013, the 13-story San Francisco Towers built in 1997 at the southwestern corner of the Pine Street and Van Ness Avenue intersection has even more pushed up the ratios at most locations along Pine Street.

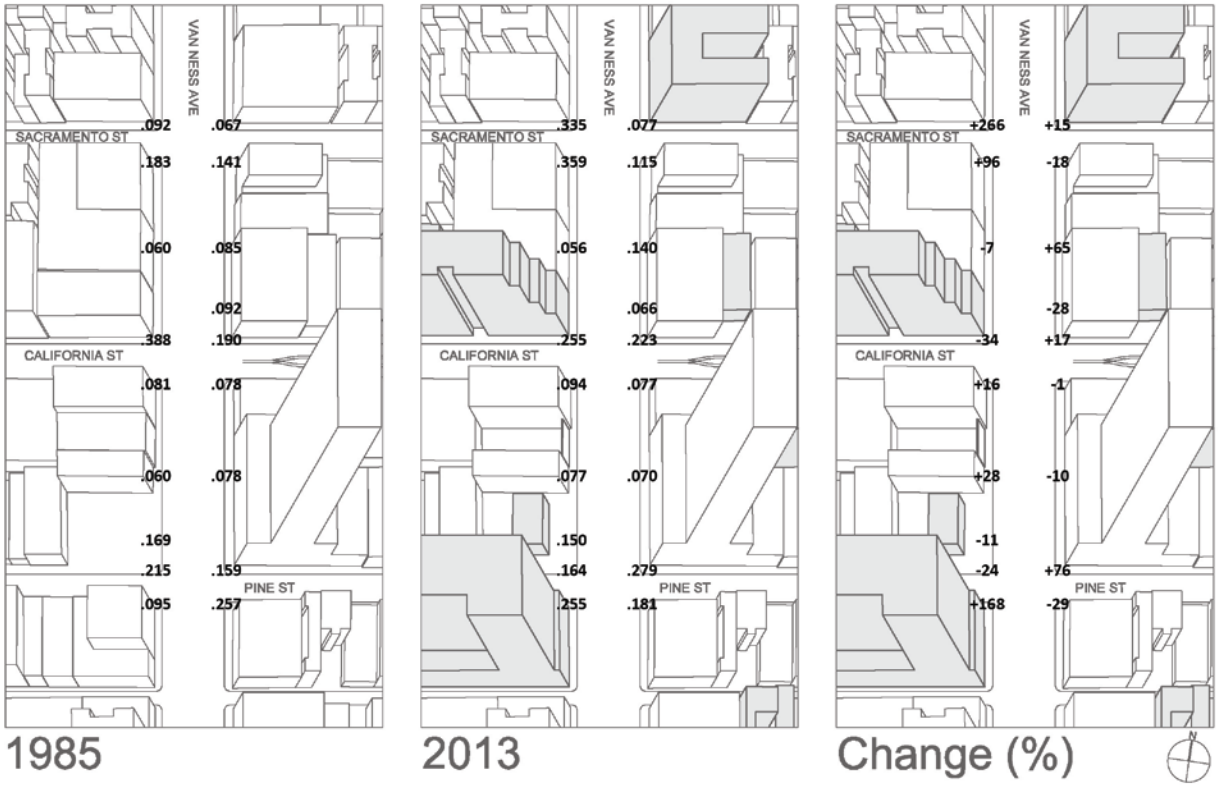


Figure 69. Wind speed ratios in 1985 and 2013, and changes in Van Ness Avenue.

Figure 69 shows Van Ness Avenue, the major thoroughfare in this site. In 1985, with the exception of one location at the northwestern corner of the Van Ness Avenue and California Street intersection that records 0.388, all measurement locations experience relatively low wind speed ratios not exceeding 0.260, and many of them remain below 0.100. In 2013, while many locations in this place experience higher wind speed ratio than in 1985, such increase is more concentrated at street corner locations, where the ratios have increased by up to 266 percent. Ratios at some mid-block point locations have increased but mostly stay below 0.170.

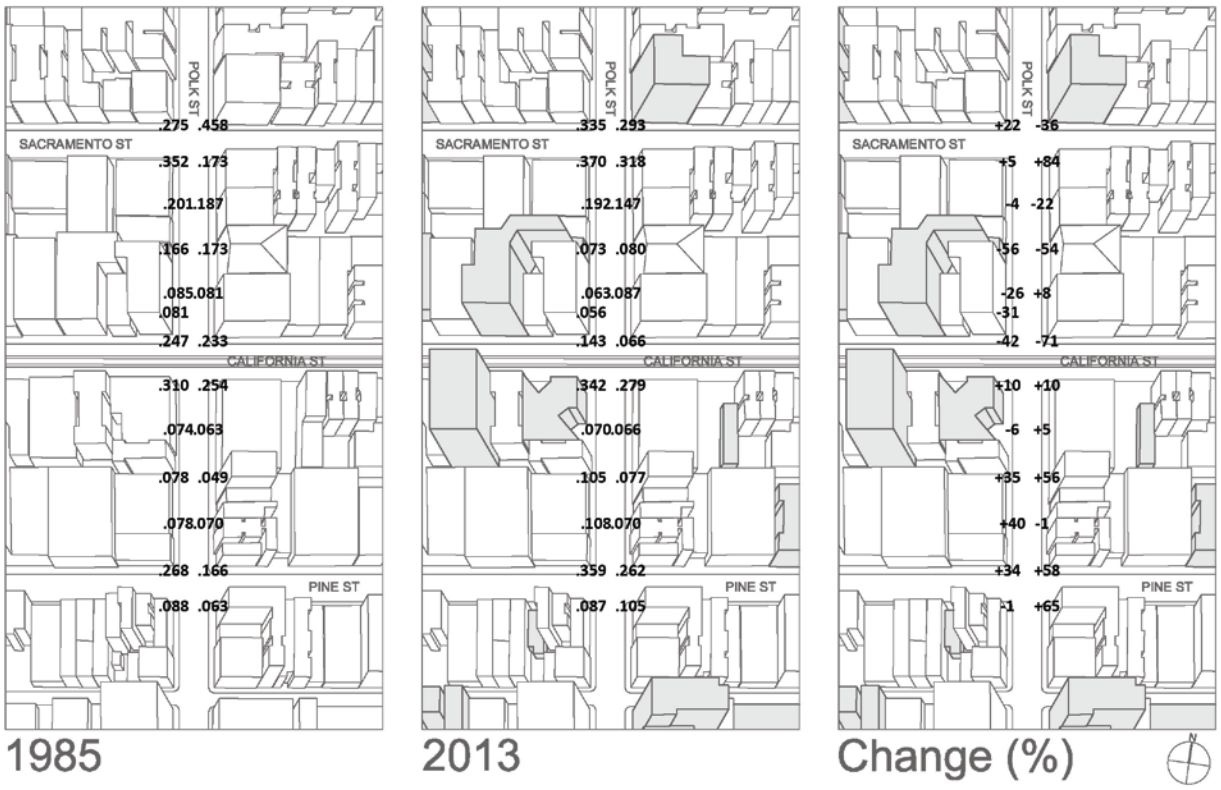


Figure 70. Wind speed ratios in 1985 and 2013, and changes in Polk Street.

Figure 70 presents Polk Street, one of the most representative multi-modal streets in San Francisco today. In 1985, there existed a significant difference in the wind speed ratios between measurement locations at street corners, which are generally higher, and those at mid-block points, bicycle lanes, and transit stops, which do not exceed 0.200 in general. In 2013, such a difference is still observed. However, many of the street corner locations are experiencing higher ratios than in 1985, while ratios at all other measurement locations remain below 0.200, mostly under 0.100.

Civic Center

As shown in Figure 71, 98 measurement locations in Civic Center were grouped into six places for a further comparison of wind speed ratios. The places are Turk Street, Golden Gate Avenue and P. B. Federal Building, McAllister Street, Polk Street, Larkin Street, and Civic Center Plaza.

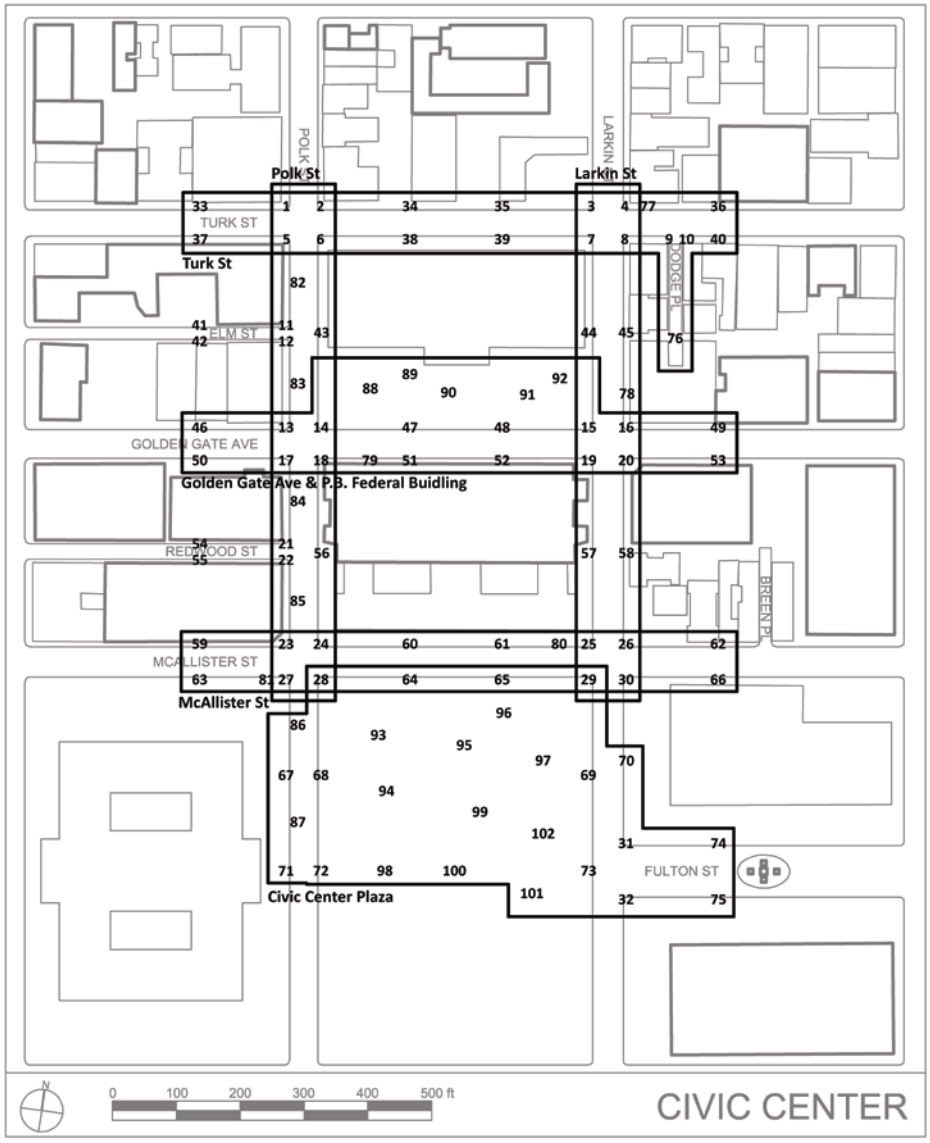


Figure 71. Selection of places in Civic Center.

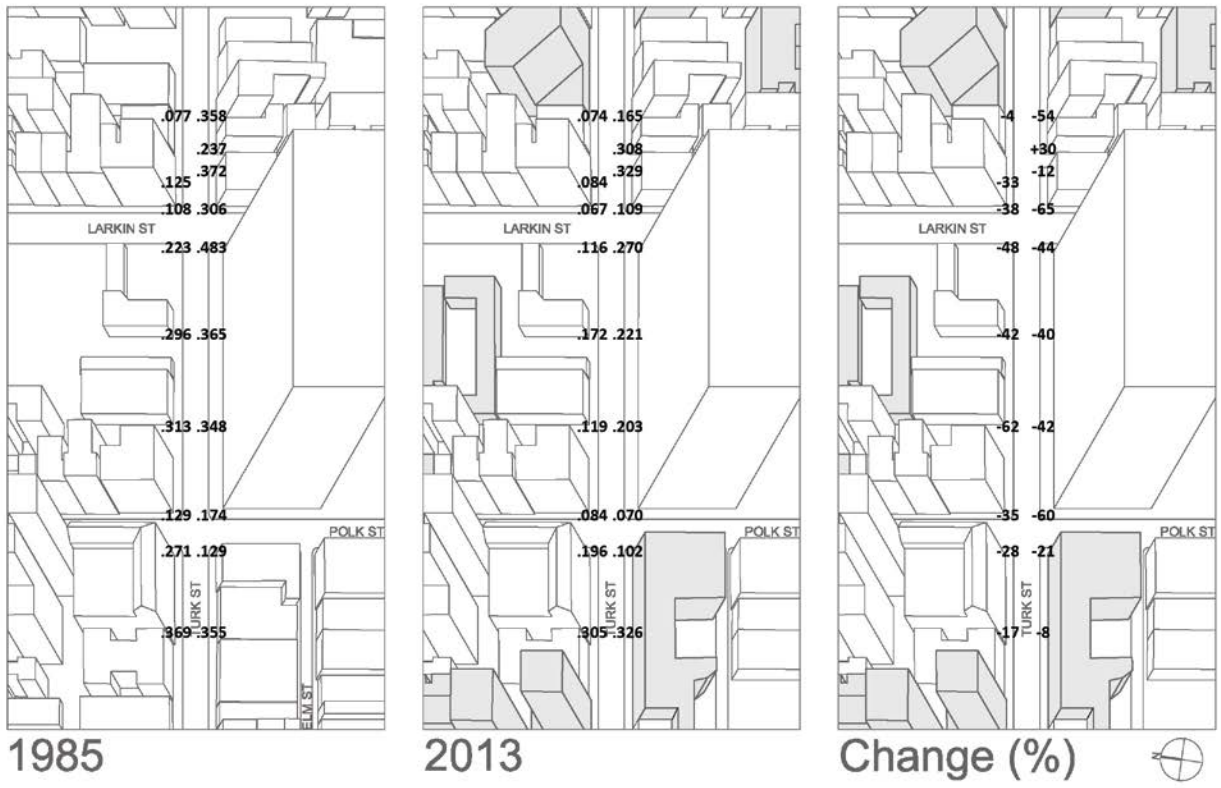


Figure 72. Wind speed ratios in 1985 and 2013, and changes in Turk Street.

As shown in Figure 72, the wind speed ratios in Turk Street in 1985 range between 0.077 and 0.483. While the measurement locations with lower ratios are mostly located at street intersections or in the east of Larkin Street, those with higher ratios are mostly located close to or in the east of the 22-story P. B. Federal Building. The building's typical simple box-shape that has flat façades on all sides is accelerating the west wind as it runs along Turk Street. In 2013, the ratios at all locations, except one at the Turk Street and Dodge Place intersection, are lower than in 1985. Those with the highest ratios that exceed 0.290 in 1985 are experiencing ratios below 0.270 in 2013. Also, several new developments in the west of Polk Street seem to have slowed down the wind movement along Turk Street.

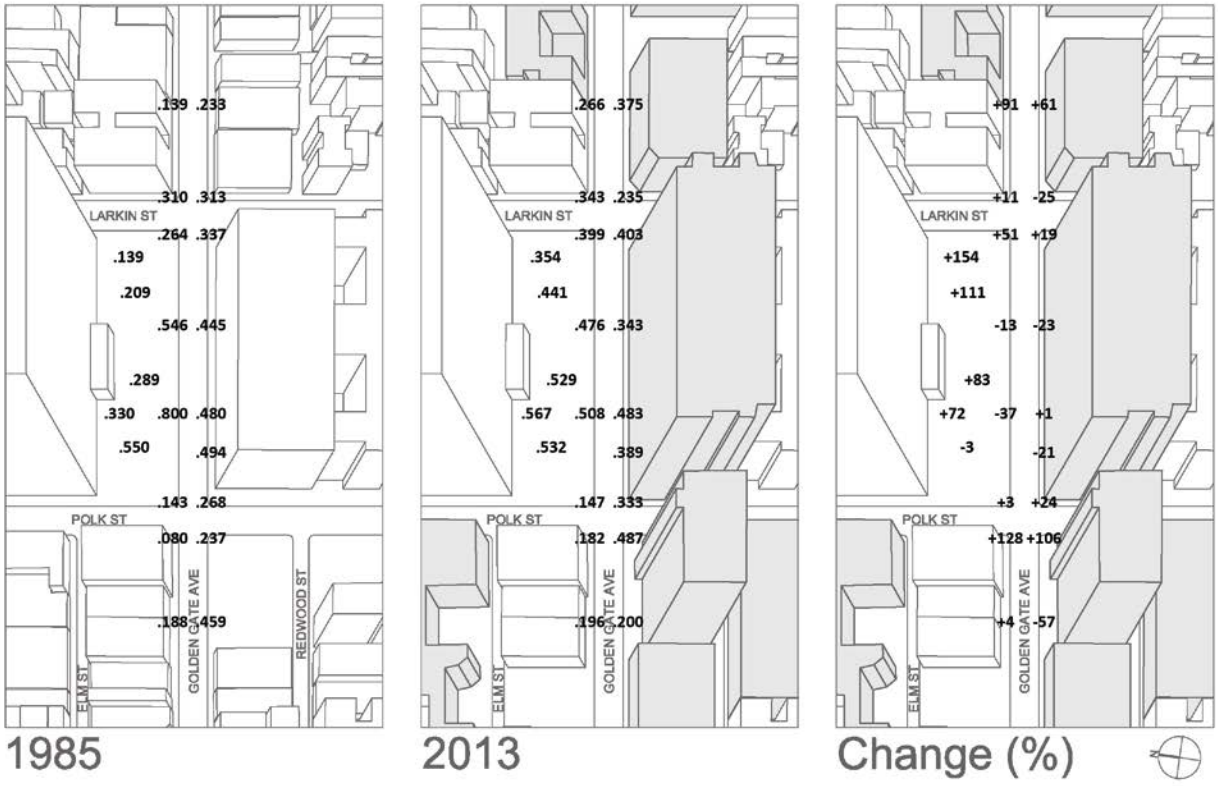


Figure 73. Wind speed ratios in 1985 and 2013, and changes in Golden Gate Avenue.

Figure 73 presents wind speed ratios and their changes in Golden Gate Avenue and an open space located in front of P. B. Federal Buildings. This place had been studied by Bosselmann et al. (1988) in their research on people's perception of comfort in outdoor spaces. In 1985, the ratios range between 0.080 and 0.800. Locations with the highest ratios, many of which exceed 0.450, are mostly concentrated between Polk Street and Larkin Street and in the open space in front of P. B. Federal Building. In 2013, after several new buildings were built, including the State of California building that was heightened to 15 stories and the 13-story SFPUC building, most locations in the east of Polk Street are experiencing higher wind speed ratios.

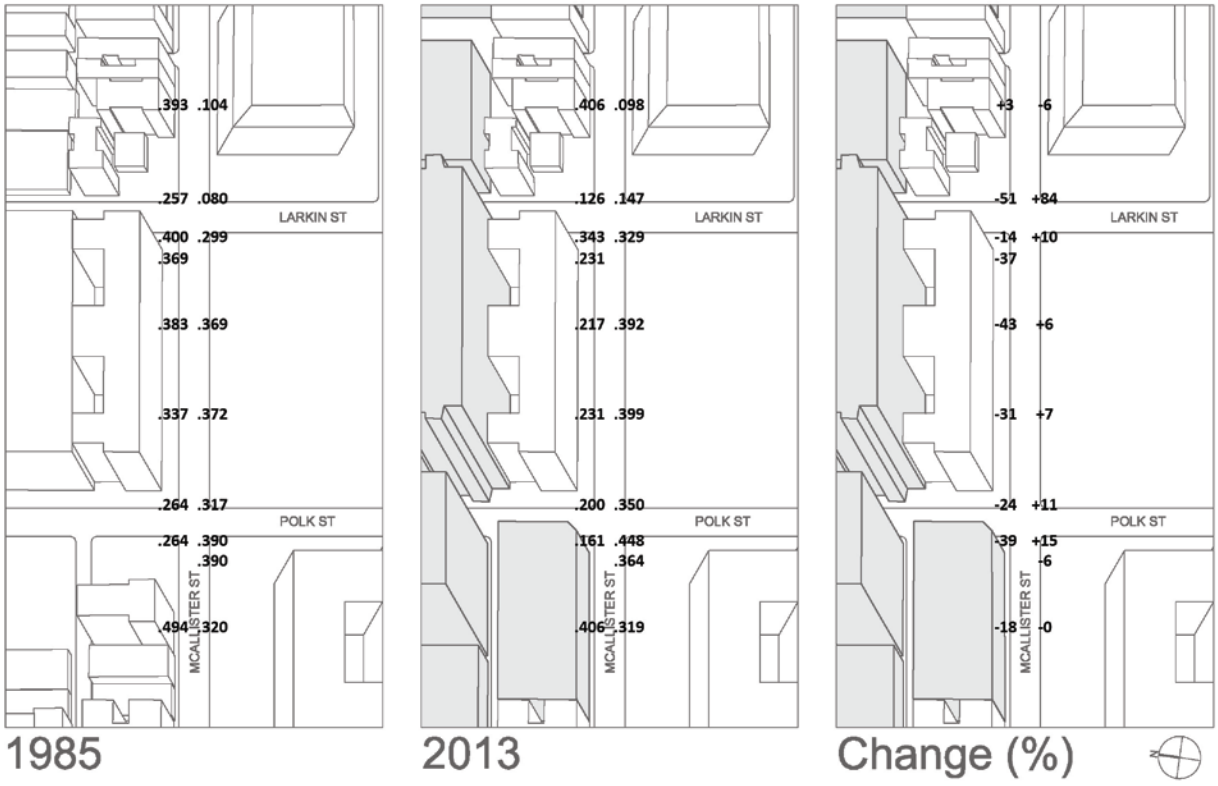


Figure 74. Wind speed ratios in 1985 and 2013, and changes in McAllister Street.

As shown in Figure 74, McAllister Street in 1985 experiences relatively high wind speed ratios at most locations that exceed 0.360. In 2013, after several buildings were built north of the street, the ratios have generally decreased except at a few locations at the southern corners of the two street intersections.

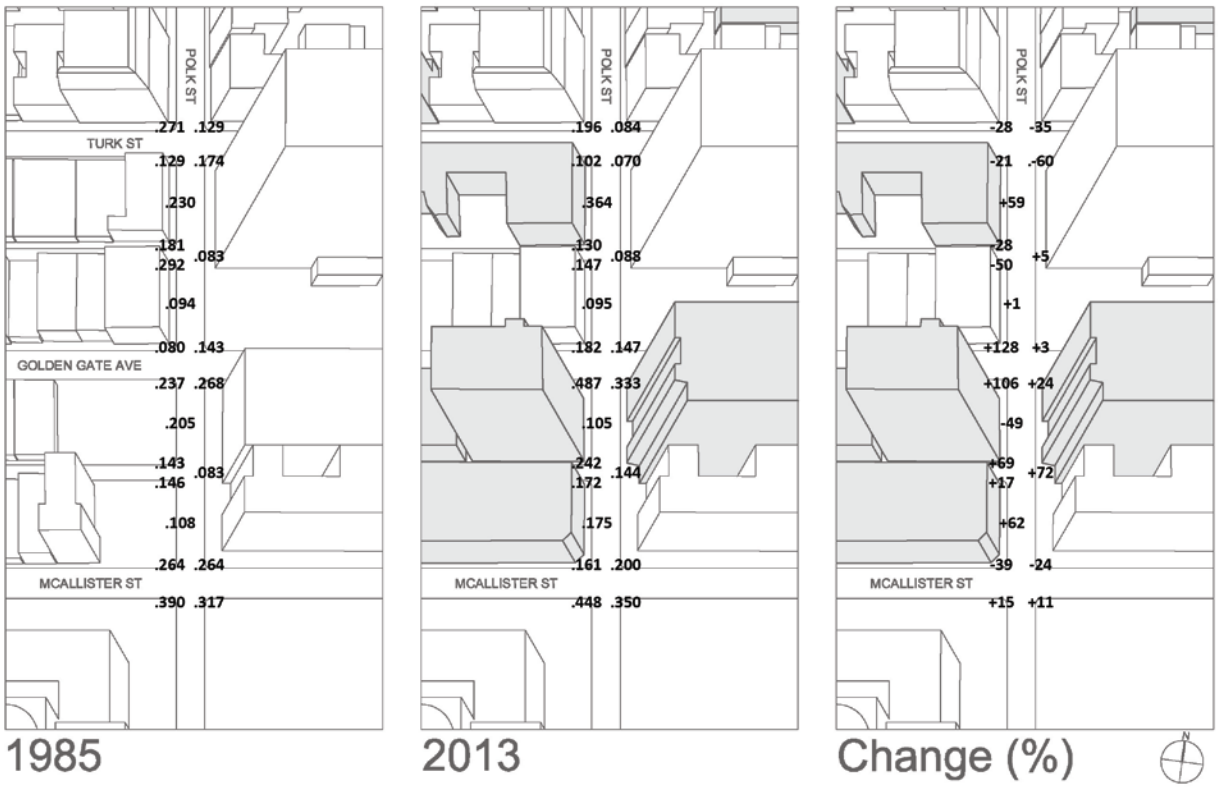


Figure 75. Wind speed ratios in 1985 and 2013, and changes in Polk Street.

As illustrated in Figure 75, Polk Street between Turk Street and McAllister Street in 1985 shows relatively low wind speed ratios, below 0.300, except at the two most southern measurement locations. However in 2013, the construction of several new buildings, mostly concentrated between Golden Gate Avenue and McAllister Street, has increased the ratios in this part by up to 120 percent. While most locations on mid-block points and bicycle lanes experience ratios below 0.250, those at several street corners experience ratios up to 0.487.

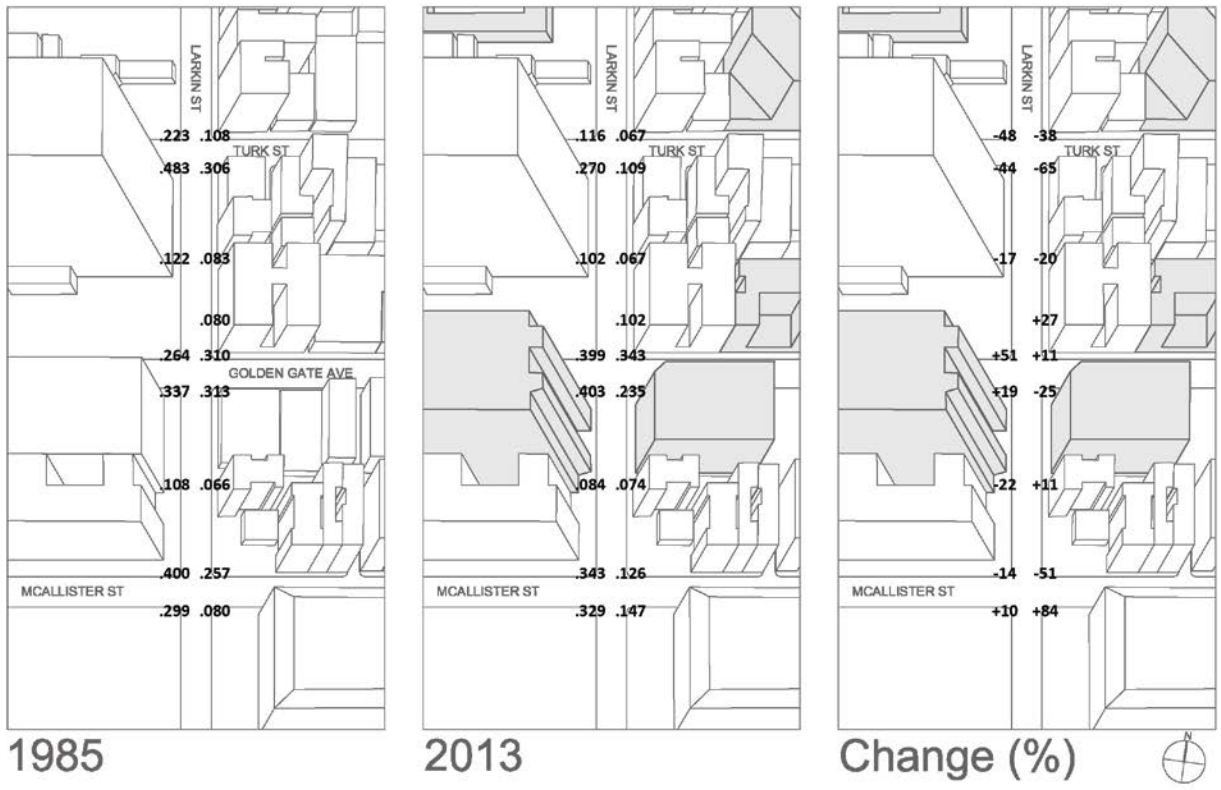


Figure 76. Wind speed ratios in 1985 and 2013, and changes in Larkin Street.

Figure 76 shows Larkin Street, where a clear difference is observed in wind speed ratios between the measurement locations at street corners and mid-block points in both years. In 1985, while the ratios at all mid-block points and transit stops remain below 0.130, those at street corners are generally higher, some of which reaching 0.483. By 2013, the biggest increases in the ratios have taken place at street corner locations especially at the two southern intersections, where the ratios soared up to 84 percent. Several new buildings such as the State of California Building and the SFPUC Building located on the west seem to have influenced the wind environment.

Figure 77 shows Civic Center Plaza, one of the largest public open spaces in San Francisco. A wide range of wind speed ratios are observed in this place. In 1985, the ratios range from 0.077 to 0.480. Measurement locations with lower ratios are mostly located towards the west, while those with higher ratios are found towards the east and north. Such an overall trend is similarly observed in 2013. Many locations in the eastern and northern parts of the place have also experienced a substantial increase in the wind speed ratios up to 92 percent. Several new buildings such as the State of California Building and the SFPUC Building located on the west seem to have influenced the wind environment in this part of the Plaza.

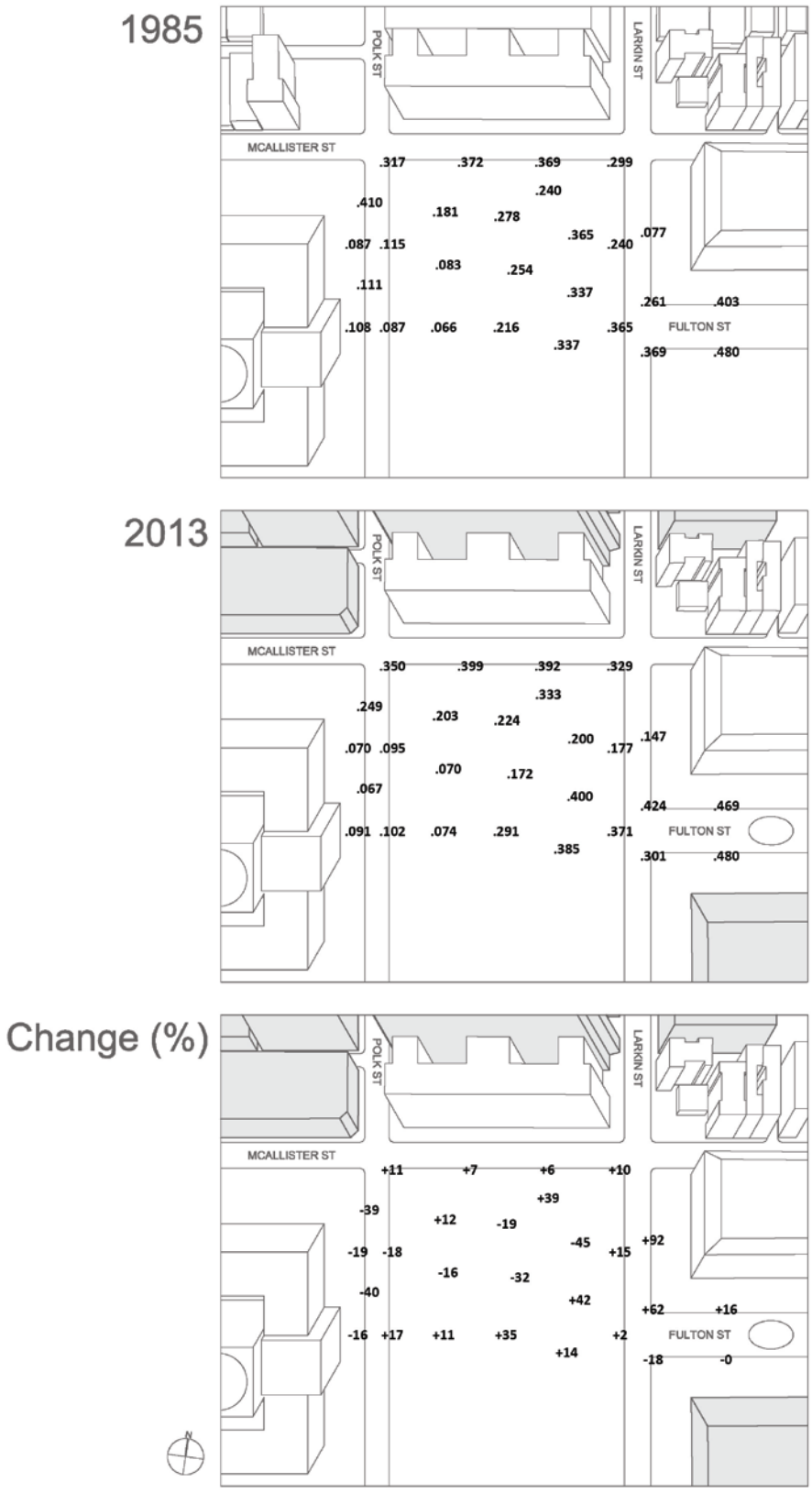


Figure 77. Wind speed ratios in 1985 and 2013, and changes in Civic Center Plaza.

Mission Bay North

As shown in Figure 78, 70 measurement locations in Mission Bay North were grouped into four places for a further comparison of the wind speed ratios. They are all streets, which are Townsend Street, King Street, Berry Street, and 4th Street.

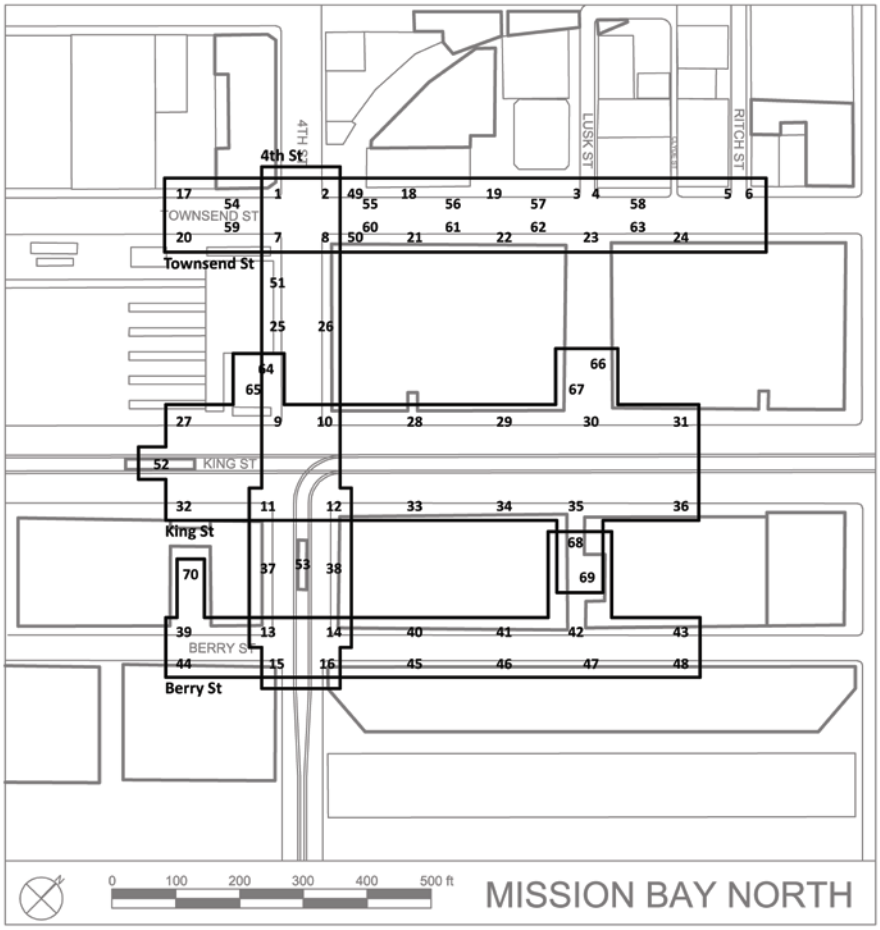


Figure 78. Selection of places in Mission Bay North.

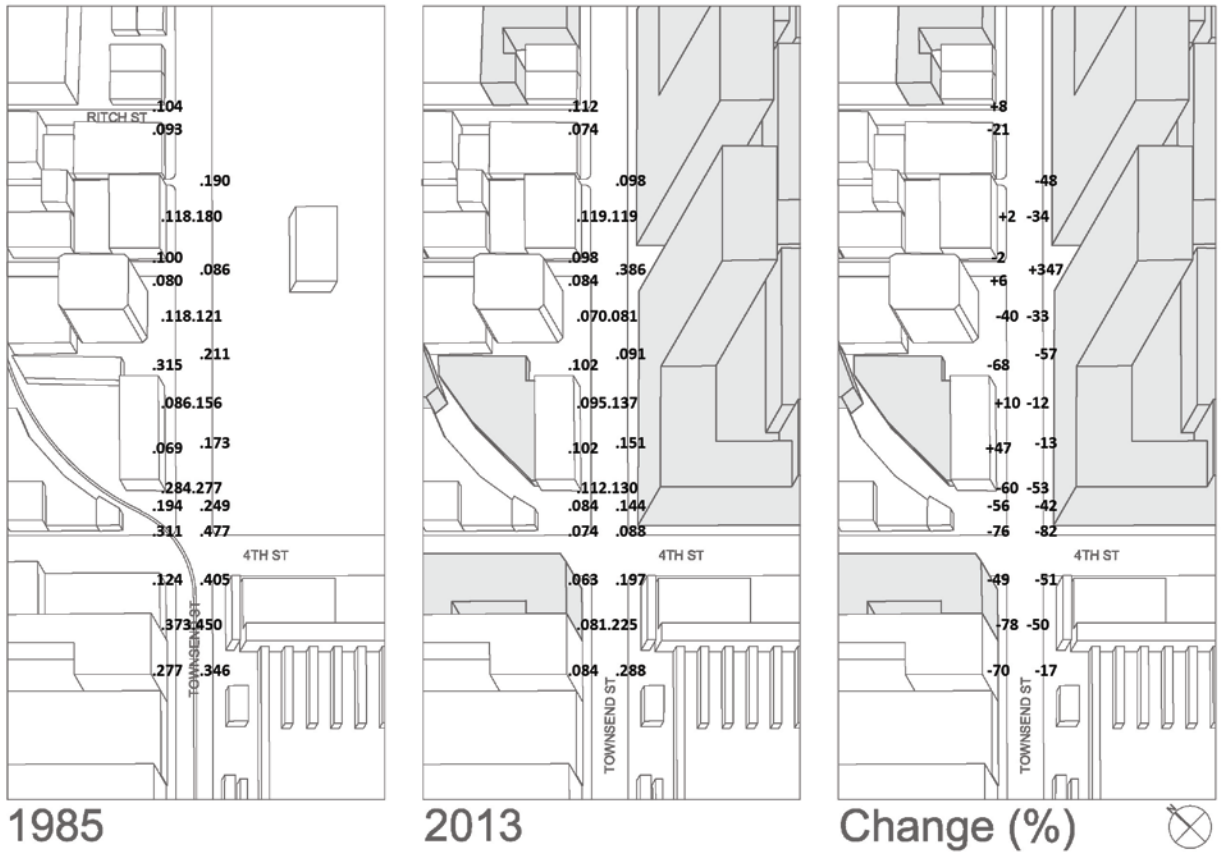


Figure 79. Wind speed ratios in 1985 and 2013, and changes in Townsend Street.

Figure 79 shows the wind speed ratios and their changes in Townsend Street, a multi-modal street that carries buses and bicycles in addition to automobiles and pedestrians. In 1985, wind speed ratios at measurement locations on sidewalks, such as street corners, mid-block points, and transit stops, show a relatively wide range between 0.080 and 0.477. Those on bicycle lanes show a similar variety as well, ranging from 0.118 to 0.450. Especially, measurement locations near the Townsend Street and 4th Street intersection experience the highest ratios that go up to 0.477. In 2013, except at one location which shows the highest ratio of 0.386 and has increased the most by 347 percent between two new high-rise residential buildings, all measurement points remain below 0.290.

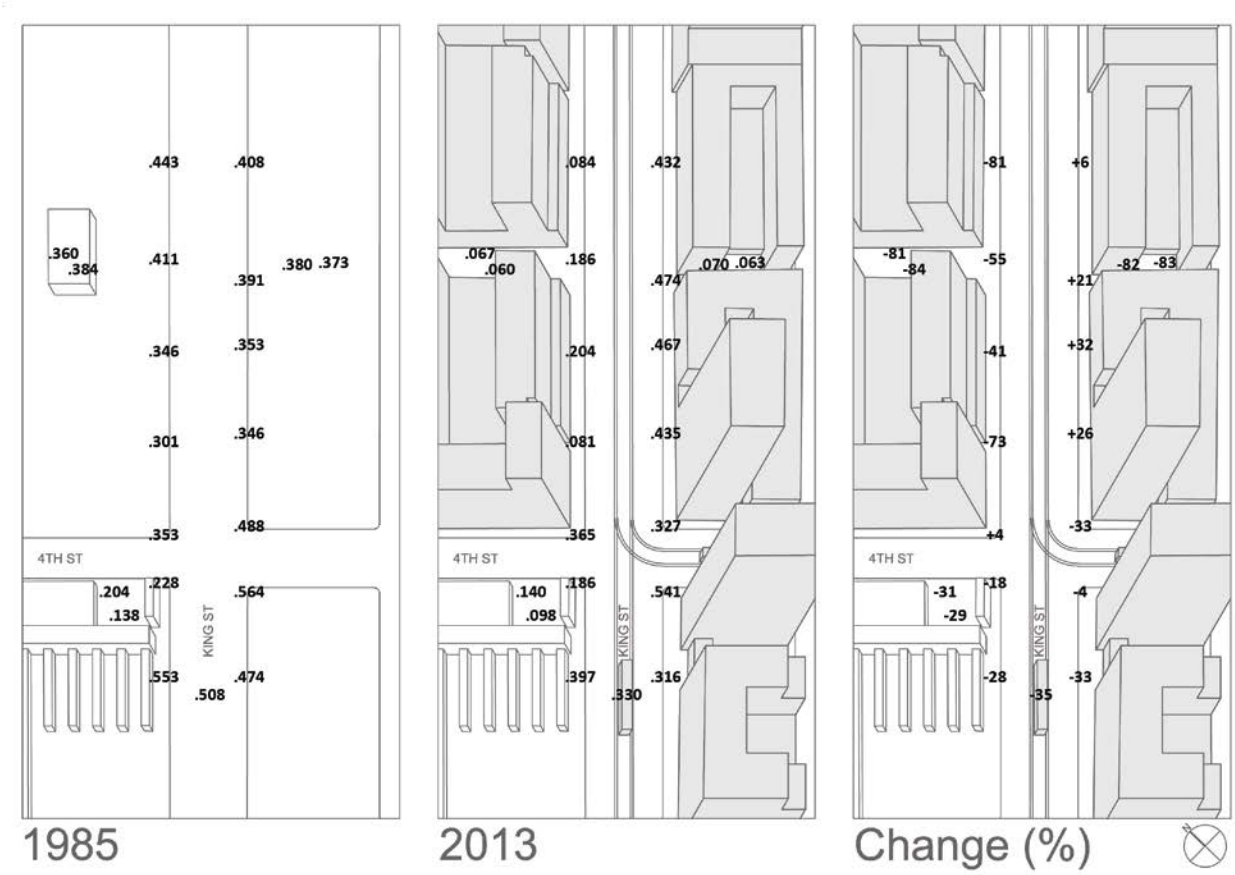


Figure 80. Wind speed ratios in 1985 and 2013, and changes in King Street.

Figure 80 shows the wind conditions and their changes in King Street and two open spaces directly linked to the street. In 1985, all measurement locations, except for two that are located in the direct front of the Caltrain Station sheltered by the station building, experience relatively high wind speed ratios that range between 0.301 and 0.564, as this place did not have many buildings that would block the west wind. However in 2013, the new developments on both sides of King Street have decreased the wind speed ratios in general. Especially, the ratios in small open spaces between the high-rise residential towers have decreased by up to 84 percent. On the other hand, several locations on the southeastern side of King Street experience higher wind speed ratios that reach up to 0.474. Also, the King Street and 4th Street intersection still remains a spot with higher ratios.

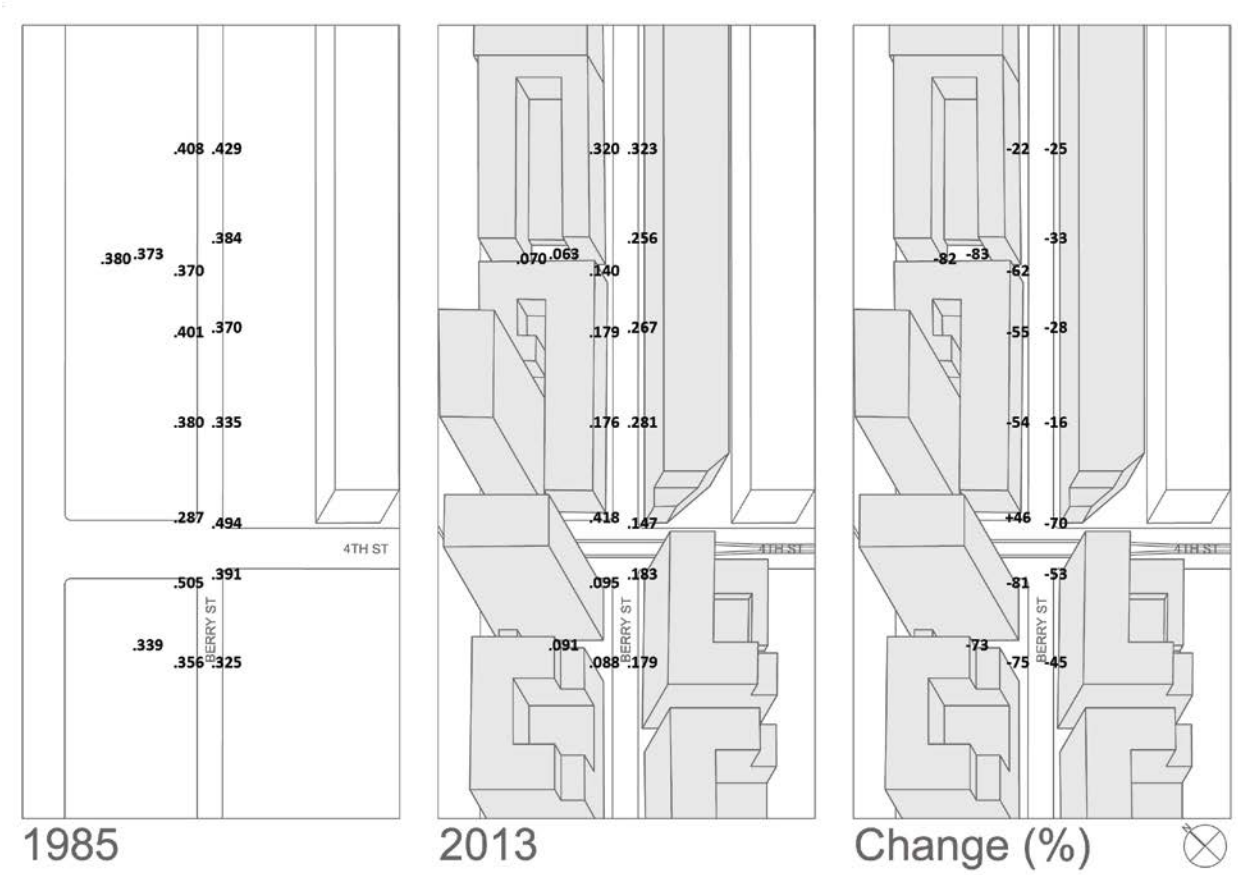


Figure 81. Wind speed ratios in 1985 and 2013, and changes in Berry Street.

Berry Street is shown in Figure 81. In 1985, as a flat vacant land with only one building near the street, this place shows high wind speed ratios throughout that range between 0.325 and 0.505. However in 2013, after arrays of high-rise residential towers were built in the 2000s, the ratios along Berry Street have been decreased substantially. Apart from one location at the Berry Street and 4th Street intersection, all locations experience ratios that remain below 0.290, and those in small open spaces between the buildings below 0.100.

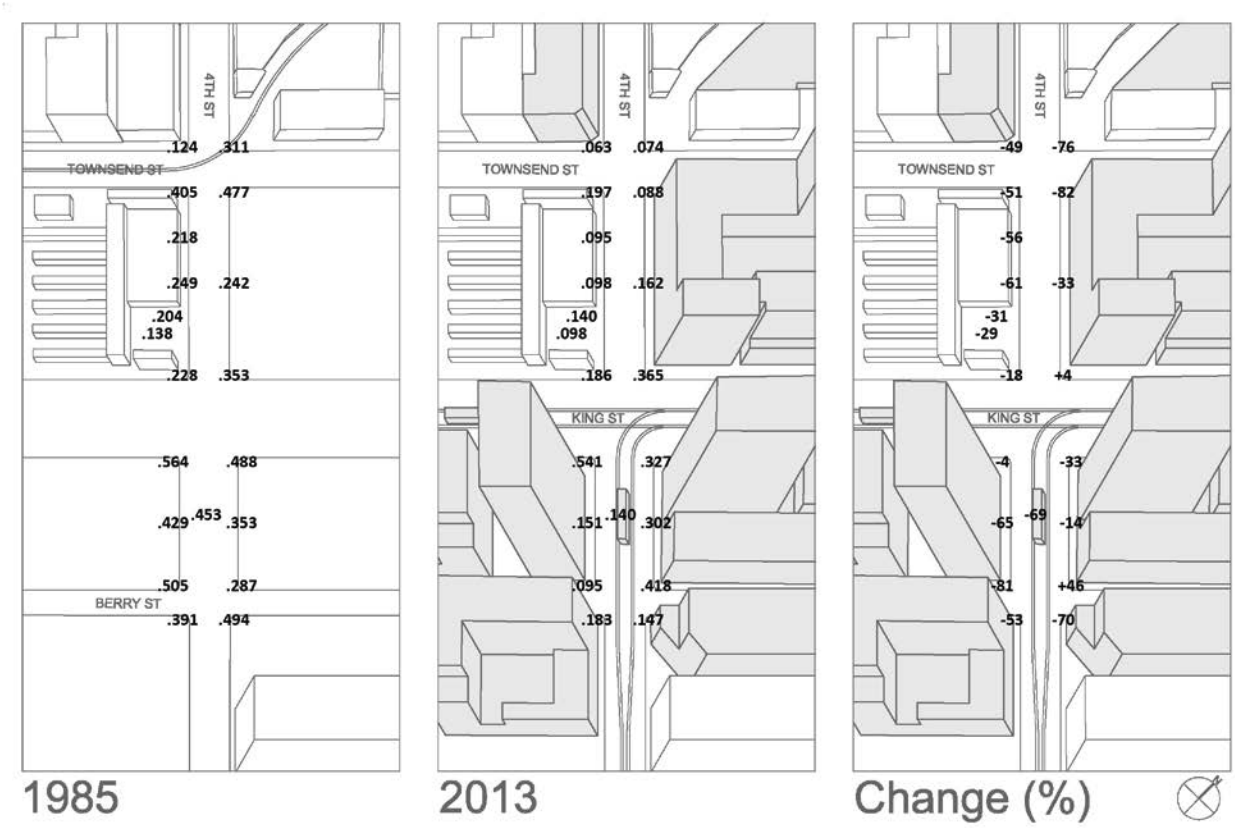


Figure 82. Wind speed ratios in 1985 and 2013, and changes in 4th Street.

As presented in Figure 82, 4th Street also has gone through a substantial change between 1985 and 2013. The wind speed ratios in 1985 were very high especially at measurement locations in the south of King Street which soared up to 0.564, while many of those near the Caltrain Station stayed below 0.250. In 2013, except the three locations at the 4th Street and King Street intersection and two in the direct south, all measurement locations enjoy ratios that do not exceed 0.200.

5.3 Urban Form and Wind

This section summarizes the results from the wind tunnel study presented in the previous sections of this chapter. To identify urban form elements that adversely affect the wind environment, it also further examines nine among the 21 places examines in the previous section that experience high wind speed ratios in 2013 with respect to their urban form conditions in order. At the end, findings on how the changes in urban form have deteriorated the wind environment are provided, and guidelines on controlling urban form so that they can be mitigated from excessive wind at the pedestrian level are suggested.

Comparison of Wind Speed Ratios between 1985 and 2013

As discussed in Section 5.1, the mean of wind speed ratios measured at 318 locations in Yerba Buena, Van Ness, Civic Center, and Mission Bay North, was 0.279 in 1985 and decreased by 22 percent to 0.218 in 2013. Among the 318 measurement locations, 106 locations experienced increase and 212 experienced decrease in the wind speed ratios.

Among the four sites, Yerba Buena had the biggest mean decrease rate of 34 percent and was followed by Mission Bay North which had a 22 percent drop. The mean decrease rate of Van Ness and Civic Center were 8 percent and 6 percent respectively, both of which are not statistically insignificant. As shown in Figure 83, Yerba Buena had the highest mean wind speed ratio at 0.308 in 1985 and was followed by Mission Bay North at 0.279, Civic Center at 0.262, and Van Ness at 0.244. In 2013, Civic Center showed the highest mean ratio at 0.247, and is followed by Van Ness at 0.225, Yerba Buena at 0.202, and Mission Bay North at 0.184.

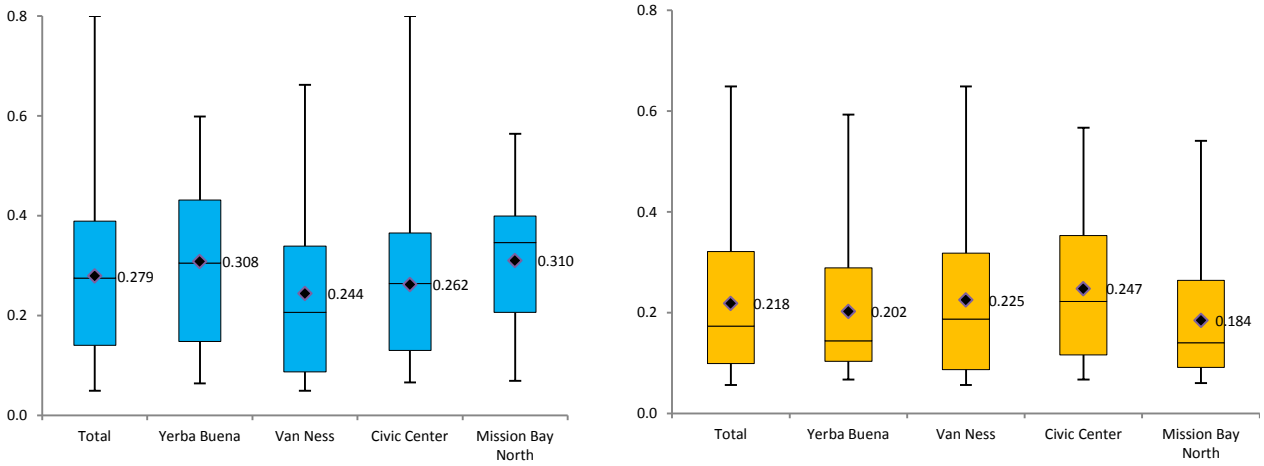


Figure 83. Wind speed ratio ranges of the four sites in 1985 (left) and 2013 (right).

Among the five locations types, which are street corner, mid-block point, transit stop, bicycle lane, and open space, wind speed ratios at transit stops in the four sites experienced the biggest drop by 35 percent on average. They are followed by open space locations, which dropped by 30 percent, and mid-block point locations, which fell by 23 percent. Ratios at street corners and bicycle lanes decreased by 13 percent. On the other hand, based on the result in 2013, measurement locations at open spaces show the highest mean ratio at 0.240, as shown in Figure 84. They are followed by mid-block points at 0.235 and street corners at 0.217. The mean wind speed ratios were the lowest at transit stops at 0.183 and bicycle lanes at 0.144.

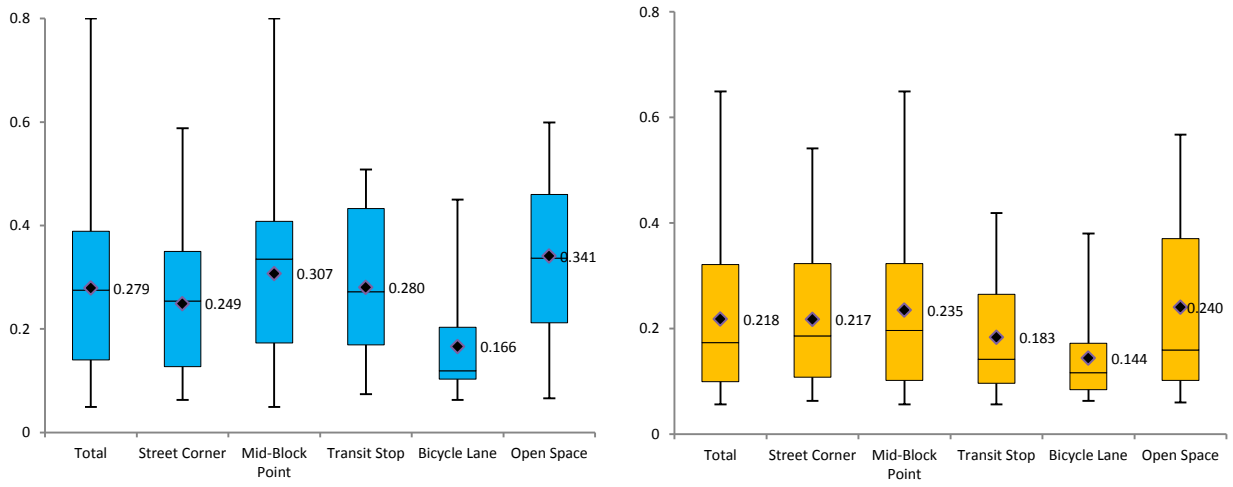


Figure 84. Wind speed ratio ranges of the five location types in 1985 (left) and 2013 (right)

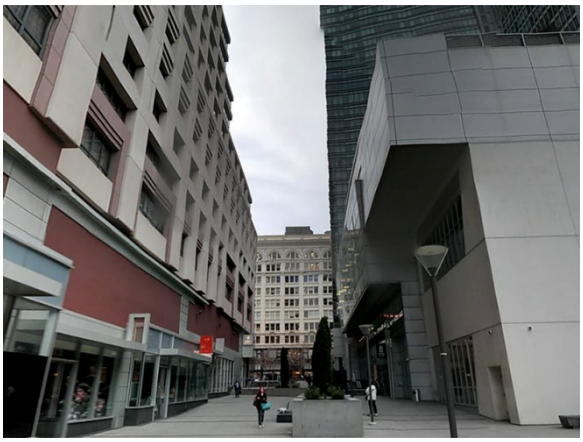
These numbers indicate that public streets and open spaces in the four selected sites are generally experiencing lower levels of wind speed ratios in 2013 than in 1985, meaning that the city has become more wind-comfortable since its implementation of wind planning in 1985. In this sense, it can be concluded that the plan has changed San Francisco's urban form so as to provide a more wind-comfortable environment.

Windy Places and their Urban Form

However, there still exist a number of places in the sites where the wind speed ratios are generally high or have increased since 1985 despite the implementation of the wind planning measures. These places are not just individual measurement locations that show higher ratios than the surrounding ones but concentrations of locations with high ratios. It is important to study the urban form conditions of these windy places and understand how the conditions are affecting the wind speed ratios. While the existing plan of San Francisco relies only on wind speed criteria to secure a wind-comfortable environment, it would be effective to provide specific guidelines on urban forms based on this exercise, so that planners, urban designers, architects, and developers would benefit from it.

Eight places among the 21 places were selected that were comparatively examined in detail in the previous section. The eight places are those with concentrations of several measurement locations, where the wind speed ratios exceed 0.350 in 2013. 0.350 corresponds to the 80th percentile of the overall wind speed ratio distribution measured at 318 locations in 2013. The eight places are Yerba Buena Lane and Yerba Buena Gardens in Yerba Buena; California and Pine Streets in Van Ness; Golden Gate Avenue and P. B. Federal Building, and McAllister Street and Fulton Street in Civic Center Plaza in Civic Center; and King Street in Mission Bay North. The following part summarizes the wind speed ratio ranges in each place, and examines their urban form conditions with a specific focus on their vertical street section and its dimensions.

Yerba Buena Lane experiences a concentration of wind speed ratios that range between 0.373 and 0.554, especially in its northern half which is a 40-foot wide passage between the 42-story Four Seasons Hotel and 38-story Marriot Marquis Hotel. Running northwest-southwest, Yerba Buena Lane is not directly exposed to the west wind. The wind has to make a 45-degree right turn to enter this place. However, as shown in Figure 85, the 44-story and 33-story façades of the two buildings that directly meet the ground of Yerba Buena Lane are inducing faster winds at higher altitudes to slide down to the pedestrian environment, generating adverse wind conditions at the ground level.



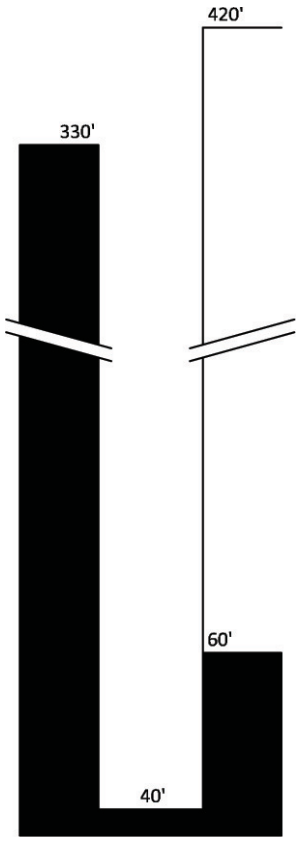


Figure 85. Google Street View and sectional diagram of Yerba Buena Lane, facing northwest.

Yerba Buena Gardens is a large-scale open space surrounded by high-rise buildings in its north and east, as shown in Figure 86. While the wind speed ratios in the eastern and northwestern parts of this place range between 0.366 and 0.593. The west wind is let into Yerba Buena Gardens without much obstruction since there are no buildings on its northern edge while the building heights on the western, southern, and eastern peripheries are generally low. Fortunately, rows of 40-foot tall trees are located near the buildings, formulating shelters that protect people from excessive winds.

Figure 86. Google Street View and sectional diagram of Yerba Buena Gardens, facing northwest.

As shown in Figure 87, the 80-foot wide California Street runs east-west, being directly exposed to the west wind. Buildings on both sides create a continuous street wall, along which the building heights range between 30 feet and 70 feet. Between Van Ness Avenue and Polk Street, the wind speed ratios range between 0.419 and 0.492. The 25-story Holiday Inn Golden Gateway Hotel located in the south of the street is also contributing to the acceleration of wind speed in this place.

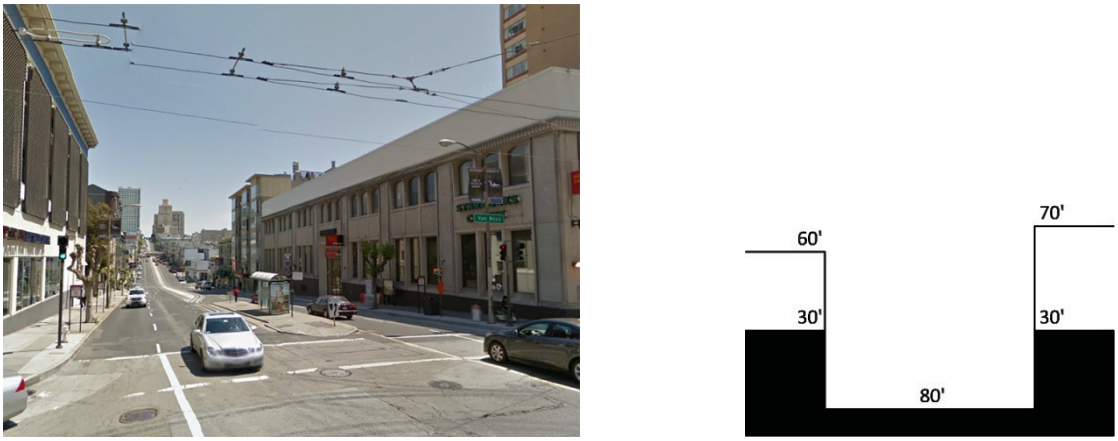


Figure 87. Google Street View and sectional diagram of California Street, facing east.

Pine Street, especially between Van Ness Avenue and Polk Street, carries a concentration of locations with high wind speed ratios that range between 0.359 and 0.649. As shown in Figure 88, the usual building heights on each side of the street are between 20 and 40 feet. However, the 25-story Holiday Inn Golden Gateway Hotel's southern façade directly meets the ground without any changes in the surface, generating faster winds at the pedestrian level and accelerating the west wind, which is directly let in to this place.

Figure 88. Google Street View and sectional diagram of Pine Street, facing east.

Figure 89 shows Golden Gate Avenue and P. B. Federal Building, where a 174-foot wide open space is surrounded by high-rise buildings in its direct north and south. This place is exposed to the west wind and experiences a high wind speed ratio level that ranges between 0.375 and 0.567. Along the two buildings' façades, the wind is induced downward and directly hits the ground level without any changes on the surface, letting faster winds at higher altitudes easily enter the pedestrian environment.

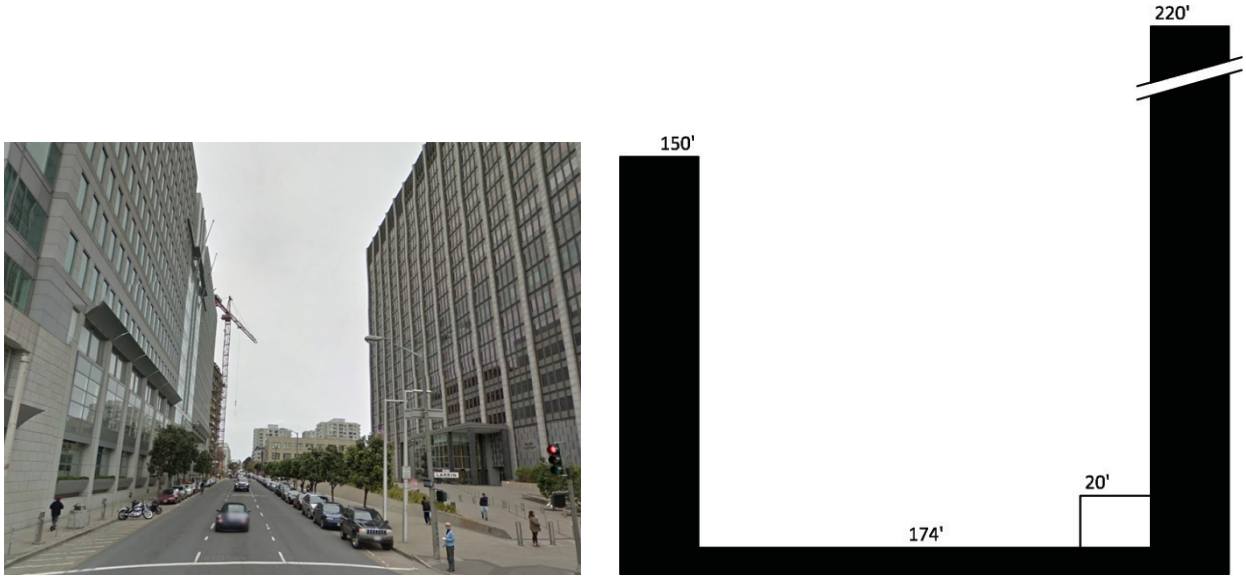


Figure 89. Google Street View and sectional diagram of Golden Gate Avenue and P. B. Federal Building, facing west.

McAllister Street, as shown in Figure 90, is the northern border of the Civic Center Plaza, a large-scale open space where the west wind is directly let in. Also, the seven-story Supreme Court Building on the north side of the street creates a continuous street wall, as introduced in Section 2.6, along which the wind is accelerated. Wind speed ratios range between 0.364 and 0.406 in this place.

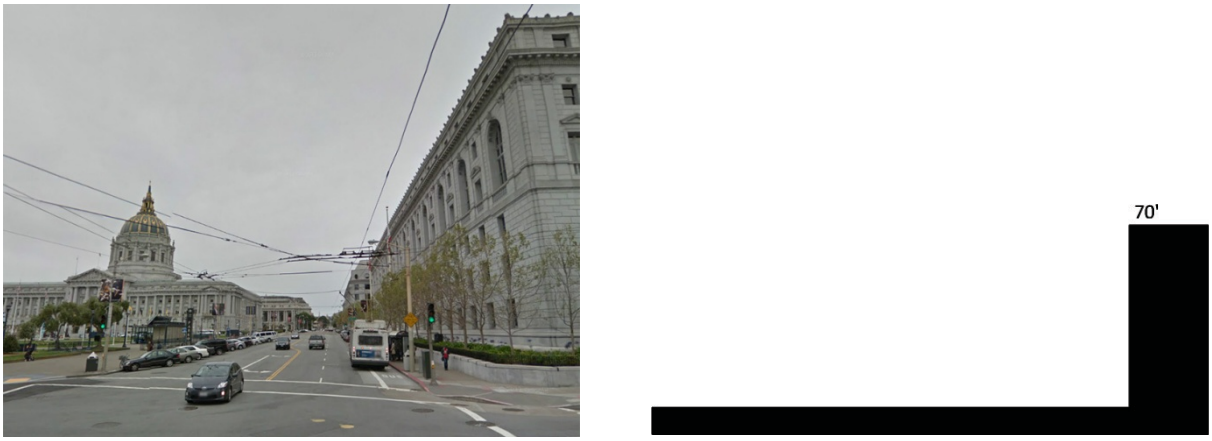


Figure 90. Google Street View and sectional diagram of McAllister Street and Civic Center Plaza, facing west.

Fulton Street, located in the direct east of the Civic Center Plaza, is a major passage through which the west wind that arrives at the plaza travels. As shown in Figure 91, the 144-foot wide street surrounded by six-story buildings in its direct north and south carries the west wind, making many locations in this place have higher wind speed ratios that range between 0.371 and 0.480.

Figure 91. Google Street View and sectional diagram of Fulton Street and Civic Center Plaza, facing west.

Figure 92 presents King Street, a 160-foot wide thoroughfare that runs southwest-northeast. This street is both directly and indirectly exposed to the west wind, as it is fairly wide and there are not any obstacles in the west of 4th Street. However, the wind still has to make a 45-degree left turn to enter this place. On both sides of the street, continuous street walls are created that rise up to 17 stories. Such heights increase the wind speed ratios, especially along the southeastern edge of the street where the ratios range between 0.432 and 0.541.

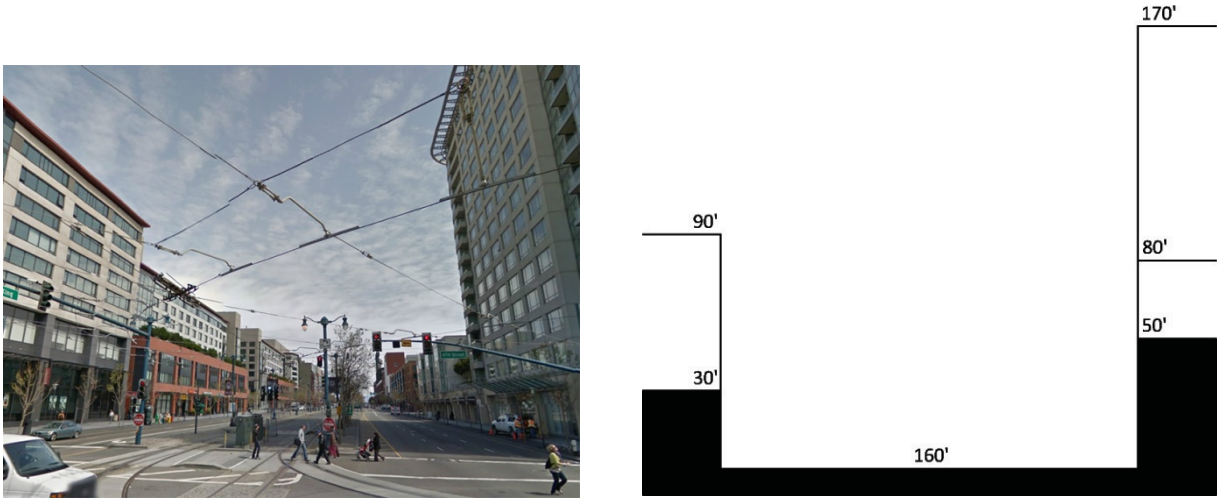


Figure 92. Google Street View and sectional diagram of King Street, facing northeast.

Urban Form and Wind

In summary, it was found that the following urban form conditions are commonly found in the eight places, contributing to the increase in wind speed ratio: direct exposure of street orientation to the prevailing (west) wind; high-rise building façades that directly meet the ground without any changes on the surface such as setbacks; and continuous street wall.

Except for Yerba Buena Lane, all places are directly exposed to the prevailing wind from the west. California Street and Pine Street in Van Ness and Golden Gate Avenue, McAllister Street, and Fulton Street in Civic Center all run east-west, letting in the west wind into the street without much obstruction. King Street in Mission Bay North is partially exposed to the west wind. On the other hand, streets that run north-south such as 3rd Street in Yerba Buena, Van Ness Avenue and Polk Street in Van Ness, Polk Street and Larkin Street in Civic Center, and 4th Street in Mission Bay North commonly enjoy low wind speed ratios. Locations with high ratios on these streets are mostly concentrated at street intersections where they meet east-west streets. Yerba Buena Gardens and Civic Center Plaza, both of which are large-scale open spaces with low-rise buildings in the surrounding, are also directly exposed to the west wind.

According to Davenport's vertical profile of the boundary wind layer, as discussed in Section 2.4, wind speed increases as the altitude rises. For example, the average wind speed at on the 30th floor would be much faster than that on the ground level. Especially when a façade of a high-rise

building does not have any setbacks on its surface, the faster wind from a higher altitude would swiftly slide down the building's façade directly to the pedestrian environment at the ground level without any obstruction. If the building is wide or flat, more wind over the rooftops is diverted downward into the street. In this sense, the high wind speed ratios in Yerba Buena Lane, Pine Street, Golden Gate Avenue, and King Street are all generated by high-rise building façades that meet the ground directly. As mentioned earlier, Yerba Buena Lane and Golden Gate Avenue are both sandwiched between two high-rise buildings on both sides that reach up to 42 stories. Pine Street and King Streets directly meet a 24-story and 17-story façade respectively. In addition, it is interesting to note that wind speed ratios in Pine Street and Golden Gate Avenue are higher than those in streets one block north or south that also run east-west.

Another common condition is the continuous street walls. As initially discussed in Section 2.6, a continuous street wall in this research is defined as a continuum of street buildings that have façades with an identical physical pattern throughout or in a certain part of a street. Yerba Buena Lane, Golden Gate Avenue, McAllister Street, Fulton Street, and King Street examined in this section are all aligned by a single building that has a relatively smooth façade on at least one side of the street. It is also noteworthy that the north side of Pine Street, where there are only three buildings along the block, and the south side of Turk Street, where the P. B. Federal Building fills up the entire block whereas the north side has many smaller buildings, are experiencing higher wind speed ratios.

With regard to the three urban form conditions that create a windier urban environment, the following can be suggested to mitigate the adverse effects of wind in cities. First, streets should be laid out in a way that deflects the prevailing wind. In this way, buildings can deflect the wind and so that the fierce winds do not enter public streets or neighborhood spaces. Accordingly in San Francisco, the South of Market grid is better than the North of Market grid from the wind perspective. The diagonal street grid in the Treasure Island Redevelopment Plan mentioned in Section 3.6 is a good alternative approach.

Second, at the individual building level, various design measures to mitigate the adverse effect of fast winds that run along a smooth building façade should be applied. These measures include adopting podium structures in the lower part of the building and installing canopies directly above the pedestrian level that would block the winds coming down from higher altitudes along the building façades. Making building tops shaped liked a wedding cake (stepped back going upward) could also be useful.

Third, street buildings should be more diverse with regard to their façade design, creating a more heterogeneous street wall. Many smaller buildings than one larger building and fragmented building masses than simple forms can be preferred in decreasing the wind speeds.

CHAPTER 6. WIND AND COMFORT[38]

This chapter provides a part of the results from the field study. More specifically, it seeks to present an answer to the second research sub-question of this research: a*re the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco?* Section 6.1 examines the relationship between wind speed and people's perceived comfort, and Section 6.2 investigates the effectiveness of wind speed criteria in determining outdoor comfort. Section 6.3 summarizes the answers of open-ended questions that bring additional information using a qualitative method. Details of the field study procedure were explained in Section 4.4.

6.1 Wind and Comfort

This section explorers the relationship between wind and comfort, more specifically between equivalent wind speed and four comfort measures: thermal sensation, wind sensation, wind preference, and overall comfort. After summarizing the descriptive statistics of the variables collected from the field survey, analysis is carried out in two ways. First, the simple relationship between wind and comfort is examined. Second, the more complex relationship between the two that generates the net effect of wind on comfort by taking into consideration additional variables that would affect comfort is investigated.

Descriptive Statistics

Table 16 summarizes the descriptive statistics of the variables collected from the field survey and used in this analysis. For categorical or ordinal variables, the table summarizes frequency of their categories. More men (58%) than women (42%) participated in the field study. The majority of the participants visit the places where the field studies were executed four or more times per week (41%) on their way to somewhere (56%). Respondents from each of the four studied places were relatively evenly distributed, Yerba Buena Lane being the one with the most participants (34%). With regard to thermal history and status, the mean metabolic rate of survey participants was 1.7 *met*,[39] the mean time spent outside in the last 1 hour was 26 minutes, and mean clothing level was 0.86 *clo*.[40] During the field study, on average the equivalent wind speed was 11.7 mph, temperature was 63.3 °F, the amount of solar radiation was 238 W/m^2, and the relative humidity was 69.8 percent on average. With respect to the survey participants' perceived outdoor thermal comfort, most of them chose "slightly cool" (37%) among the seven scales of thermal sensation, "moderate wind" (46%) among the five scales of wind sensation, "neutral" (46%) as their wind preference, and agreed (79%) that they were feeling thermally comfortable overall.

[38] See Appendix H for all outputs of statistical modeling in this chapter.
[39] As presented in Section 4.4, *met* is a unit that represents energy generated inside the body due to various activities (1 *met* = 58.2 W/m^2). For example, the *met* value of a person walking at a speed of 2.0 mph is 2.0.
[40] As presented in Section 4.4, *clo* is a unit that represents thermal insulation provided by garments and clothing ensembles (1 *clo* = 0.155 m^2·°C/W). For example, the *clo* value of a man wearing a typical suit is 1.0

Table 16. Descriptive statistics and frequencies of variables.

Variable			Unit	Descriptive Statistics or Frequency	Variable Name
Independent Variable	Individual	Gender	-	Female: 295 (42%) Male: 406 (58%)	SEXID (Female=1)[a]
		Visit frequency	-	4+/week: 287 (41%) 1-3/week: 127 (18%) 1-3/month: 143 (20%) Rarely/first time: 144 (21%)	OFTEN1 (4+/week=1)[a] OFTEN2 (1-3/week=1)[a] OFTEN3 (1-3/month=1)[a]
		Visit purpose	-	Wait for someone: 16 (2%) Rest or linger: 35 (5%) Have lunch/coffee: 98 (14%) On way to somewhere: 391 (56%) Others: 161 (23%)	PURPS1 (wait =1)[a] PURPS2 (rest/linger=1)[a] PURPS3 (lunch =1)[a] PURSP4 (on way=1) [a]
	Location	Location	-	Yerba Buena: 239 (34%) Van Ness: 161 (23%) Civic Center: 183 (26%) Mission Bay North: 118 (17%)	LOCYB (Yerba Buena=1)[a] LOCVN (Van Ness=1)[a] LOCCC (Civic Center=1)[a]
	Thermal history and status	Metabolic rate	met	Min: 0.6; Max 4.5; Mean: 1.7; Std Dev: 0.5	MET
		Time spent outside in the last 1 hour	minute	Min: 0; Max: 60; Mean: 26; Std Dev: 20	OUT_MIN
		Clothing insulation	clo	Min: 0.30; Max: 1.64; Mean: 0.86; Std Dev: 0.24	CLO
	Microclimatic Condition	Equivalent wind speed	mph	Min: 1.9; Max: 29.2; Mean: 11.7; Std Dev: 4.4	EW_SPD
		Temperature	°F	Min: 54.2; Max: 75.8; Mean: 63.3; Std Dev: 4.3	TEMP
		Solar radiation	W/m^2	Min: 6; Max: 949; Mean: 238; Std Dev: 249	SOLAR
		Humidity	%	Min: 46.2; Max: 94.4; Mean: 69.8; Std Dev: 11.1	R_HUMID
Dependent Variable	Comfort	Thermal sensation	-	Cold: 43 (6%) Cool: 100 (14%) Slightly cool: 259 (37%) Neutral: 163 (23%) Slightly warm: 86 (13%) Warm: 41 (6%) Hot: 9 (1%)	FEEL (cold=1, cool=2, slightly cool=3, neutral=4, slightly warm=5, hot=6)
		Wind sensation	-	No wind: 9 (1%) Slight wind: 200 (29%) Moderate wind: 324 (46%) Strong wind: 153 (22%) Very strong wind: 15 (2%)	W_FEEL (no wind=1, slight wind=2, moderate wind=3, strong wind=4, very strong wind=5)
		Wind preference	-	More wind: 26 (4%) Neutral: 320 (46%) Less wind: 355 (51%)	W_PREF (more wind=1, neutral=2, less wind=3)
		Overall comfort	-	Yes: 554 (79%) No: 147 (21%)	COMFD (yes=1, no=0)

Notes: a. Dummy variables were used for categorical variables.

Simple Relationship between Wind and Comfort

This part examines whether a direct relationships exists between the equivalent wind speed and the comfort measures, which are thermal sensation, wind sensation, wind preference, and overall comfort. First, to see whether a relationship exists, the distribution of equivalent wind speeds by each category of the four comfort measures is compared. Second, an analysis of variance (ANOVA) is carried out to test whether the relationship is significant, in other words, whether there exist differences between each category's mean equivalent wind speed. ANOVA is a statistical test used when testing whether significant differences exist in the means of a normally distributed dependent variable broken down by the categories of an independent variable. When the F value, generate by ANOVA, is larger than 1, it is accepted that there exist significant differences. For this analysis, the equivalent wind speed is temporarily assumed to be the dependent variable for convenience.

Figure 93 shows the relationship between each category of the seven-point scale thermal sensation and equivalent wind speed. The overall trend revealed is that the warmer or hotter the perceived thermal sensation is the higher the equivalent wind speeds. One exception is the mean equivalent wind speed for those who responded "hot." It shows a higher value than that for "warm," which seems to be due to the very small sample size. However, an overall trend exist that faster winds make people feel cooler or colder, while slower winds make people feel warmer or hotter. The F value generated by ANOVA is 16.65 and the significance level is 0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

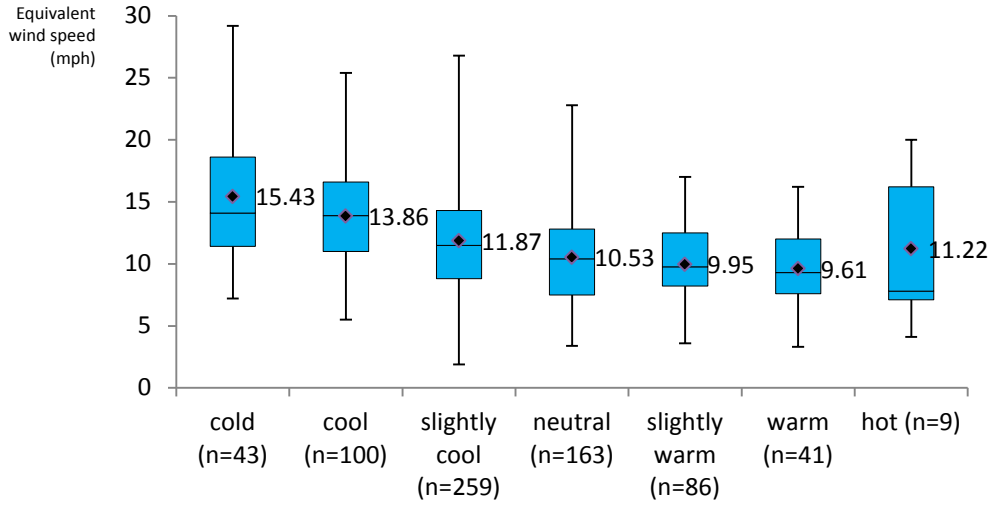


Figure 93. Distribution of equivalent wind speed (mph) by thermal sensation (N=701).

Figure 94 shows the relationship between each category of the five-point scale wind sensation and equivalent wind speed. It presents an overall trend that the stronger the perceived wind sensation is the higher the equivalent wind speeds. In other words, faster winds make people feel that the wind is strong. The F value generated by ANOVA is 66.70 and the significance level is

0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

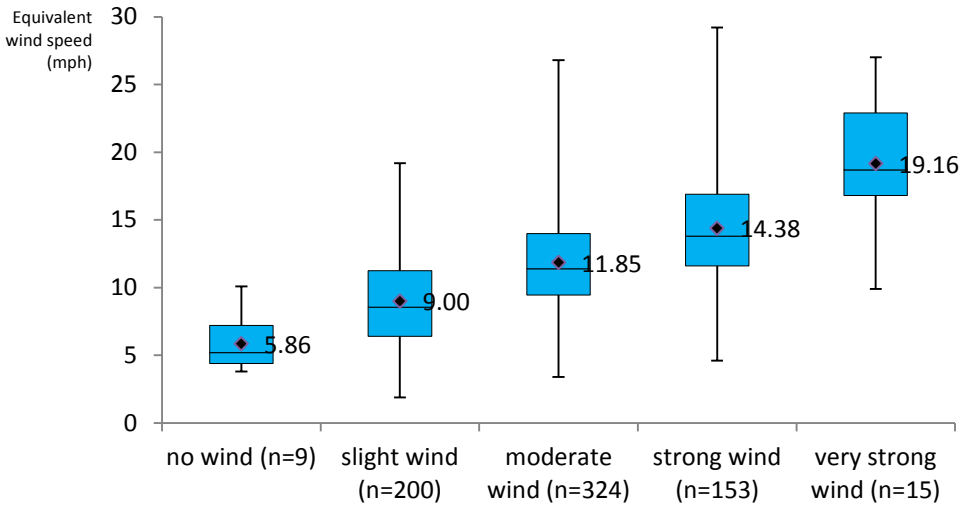


Figure 94. Distribution of equivalent wind speed (mph) by wind sensation (N=701).

Figure 95 shows the relationship between each category of the three-point scale wind preference and equivalent wind speed. It presents an overall trend that the more people want less wind the higher the equivalent wind speeds. In other words, faster winds make people want less wind, while slower winds make people in need of wind. The F value generated by ANOVA is 30.65 and the significance level is 0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

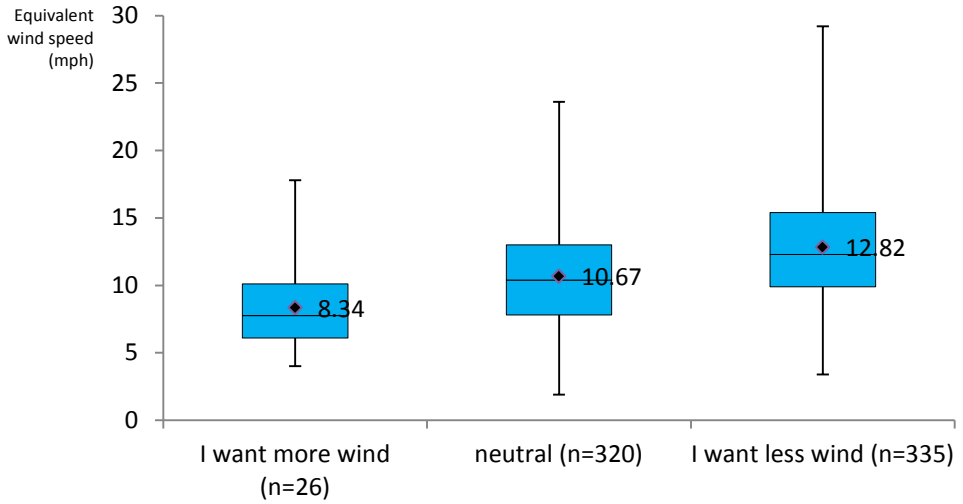


Figure 95. Distribution of equivalent wind speed (mph) by wind preference (N=701).

Figure 96 shows the relationship between each category of the binary overall comfort and equivalent wind speed. It presents an overall trend that faster winds make people uncomfortable, while slower winds make people comfortable. The F value generated by ANOVA is 69.75 and the significance level is 0.000, indicating that the difference in the mean equivalent wind speed is significant.

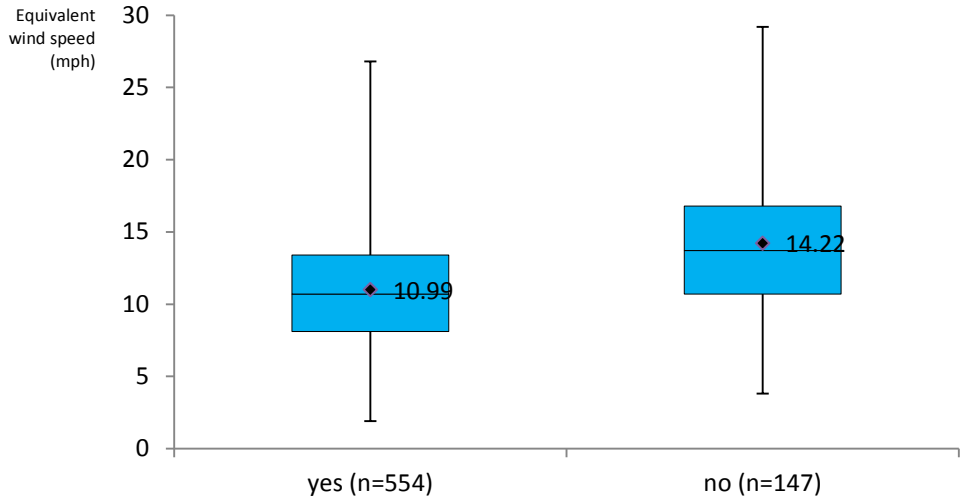


Figure 96. Distribution of equivalent wind speed (mph) by overall comfort (N=701).

In sum, there exist significant differences between the mean equivalent wind speeds of all categories within each comfort measure, meaning that there are significant relationships between wind and comfort.

The Net Effect of Wind on Comfort

This part examines the relationship between wind and comfort taking into consideration other variables that would affect outdoor thermal comfort, as summarized in Table 16. This process also makes it possible to find the net effect of wind – more specifically, the equivalent wind speed – on people's perception of comfort.

An ordinal logistic regression model is used for estimating the relationship between the variables and thermal sensation, wind sensation, and wind preference. Ordinal (or ordered) logistic regression is a statistical model that estimates the relationship between one or more independent variables and an ordinal, not continuous, dependent variable. As for overall comfort, a simple logistic regression is used that estimates the relationship between one or more independent variables and a binary dependent variable.

Table 17 shows that SEXID, OFTEN1, LOCVN, LOCCC, MET, OUT_MIN, EW_SPD, TEMP, and SOLAR are the variables that are significant at 0.05, 0.01, or 0.001 level when estimating

thermal sensation (FEEL) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

Table 17. Estimation of thermal sensation using ordinal logistic regression.

Variable	**FEEL**		
	Coefficient	Standard Error	Z
SEXID	-0.494	0.146	-3.37***
OFTEN1	0.434	0.203	2.13*
OFTEN2	0.314	0.233.	1.34
OFTEN3	0.428	0.224	1.91
PURPS1	0.484	0.363	1.33
PURPS2	-0.097	0.491	-0.20
PURPS3	0.031	0.246	0.13
PURPS4	0.164	0.177	0.93
LOCYB	-0.385	0.234	-1.64
LOCVN	0.611	0.266	2.30*
LOCCC	0.666	0.245	2.71**
MET	0.360	0.162	2.21*
OUT_MIN	0.011	0.004	2.62**
CLO	0.238	0.318	0.75
EW_SPD	-0.111	0.020	-5.63***
TEMP	0.235	0.281	9.00***
SOLAR	0.001	0.000	2.87**
R_HUMID	-0.003	0.010	-0.31
Summary Statistics	N = 701 Log likelihood = -978.382 Likelihood ratio Chi^2 = 336.15 $p < 0.001$ McFadden's pseudo R^2 = 0.147		

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The following is a summary of each significant variable's net effect on thermal sensation, when the other variables in the model are held constant.

- Being female would result in a 0.494 unit decrease in the ordered log-odds of being a higher thermal sensation category.
- Visiting the place four or more times per week would result in a 0.434 unit increase in the ordered log-odds of being a higher thermal sensation category.
- Being in Van Ness would result in a 0.611 unit increase in the ordered log-odds of being a higher thermal sensation.
- Being in Civic Center would result in a 0.666 unit increase in the ordered log-odds of being a higher thermal sensation category.
- A one *met* increase in metabolic rate would result in a 0.360 unit increase in the ordered log-odds of being in a higher thermal sensation category.
- A one minute increase in time spent outside in the last 60 minutes would result in a 0.011 unit increase in the ordered log-odds of being in a higher thermal sensation category.

- A one mph increase in equivalent wind speed would result in a 0.111 unit decrease in the ordered log-odds of being in a higher thermal sensation category.
- A one degree increase in temperature would result in a 0.235 unit increase in the ordered log-odds of being in a higher thermal sensation category.
- A one W/m^2 increase in solar radiation would result in a 0.001 unit increase in the ordered log-odds of being in a higher thermal sensation category.

In other words,

- Women are likely to feel cooler than men.
- People who frequently visit (4 or more times per week) a place feel warmer, suggesting that they get used to the place's coolness.
- In the Van Ness study area, people feel warmer. It may be interpreted that they already expect the place to be cool.
- In the Civic Center study area, people feel warmer. It may be interpreted that they already expect the place to be cool.
- Physical activity (high metabolic rate) makes people feel warmer.
- Having spent more time outside makes people feel warmer. They get used to the coolness of the outside.
- Increase in wind speed makes people feel cooler.
- Increase in temperature makes people feel warmer.
- Increase in the warmth of sunshine makes people feel warmer.

Since this model is based on the proportional odds ratios, they can be obtained by exponentiating the ordinal logistic coefficients. With regard to wind, for a one mph increase in equivalent wind speed, the odds of the combined higher categories of thermal sensation is 0.895 ($= e^{-0.1114111}$) times lower than the combined lower categories. For example, the odds of the combined slightly warm, warm, and hot are 0.895 times lower than the combined cold, cool, slightly cool, and neutral.

Table 18. Estimation of wind sensation using ordinal logistic regression.

Variable	W_FEEL		
	Coefficient	Standard Error	Z
SEXID	0.238	0.155	1.53
OFTEN1	0.176	0.214	0.82
OFTEN2	0.017	0.245	0.07
OFTEN3	-0.167	0.234	-0.72
PURPS1	-0.216	0.388	-0.56
PURPS2	0.192	0.523	1.37
PURPS3	0.426	0.262	1.62
PURPS4	0.119	0.190	0.63
LOCYB	-0.186	0.250	-0.74
LOCVN	0.007	0.286	0.02
LOCCC	-0.823	0.263	-3.13^{**}
MET	-0.083	0.169	-0.49
OUT_MIN	-0.001	0.004	-0.20
CLO	-0.354	0.339	-1.05
EW_SPD	0.237	0.023	10.47^{***}
TEMP	-0.094	0.029	-3.27^{**}
SOLAR	0.001	0.000	1.52
R_HUMID	-0.005	0.011	-0.45
Summary Statistics	N = 701 Log likelihood = -699.970 Likelihood ratio Chi^2 = 261.32 $p < 0.001$ McFadden's pseudo R^2 = 0.157		

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 18 presents that LOCCC, EW_SPD, and TEMP are the variables that are significant at 0.05, 0.01, or 0.001 level when estimating wind sensation (W_FEEL) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

The following is a summary of each significant variable's net effect on wind sensation, when the other variables in the model are held constant.

- Being in Civic Center would result in a 0.823 unit decrease in the ordered log-odds of being a higher wind sensation category.
- A one mph increase in equivalent wind speed would result in a 0.237 unit decrease in the ordered log-odds of being in a higher wind sensation category.
- A one degree increase in temperature would result in a 0.094 unit decrease in the ordered log-odds of being in a higher wind sensation category.

In other words,

- In the Civic Center study area, people feel less windy. It may be interpreted that they already expect the place to be windy.
- Increase in wind speed makes people feel stronger wind.

- Increase in temperature makes people feel less windy.

With regard to wind, for a one mph increase in equivalent wind speed, the odds of the combined higher categories of wind sensation is 1.267 (= $e^{0.2365854}$) times higher than the combined lower categories. For example, the odds of the combined strong wind and very strong wind are 1.267 times higher than the combined no wind, slight wind, and moderate wind.

Table 19 presents that SEXID, PURPS2, LOCVN, LOCCC, MET, EW_SPD, and TEMP are variables that are significant at 0.05, 0.01, or 0.001 level when estimating wind preference (W_PREF) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

Table 19. Estimation of wind preference using ordinal logistic regression.

Variable	**W_PREF**		
	Coefficient	Standard Error	Z
SEXID	0.501	0.167	3.00**
OFTEN1	0.057	0.232	0.24
OFTEN2	0.032	0.266	0.12
OFTEN3	0.116	0.256	0.45
PURPS1	0.254	0.429	0.59
PURPS2	-1.099	0.536	-2.05*
PURPS3	0.289	0.285	1.02
PURPS4	-0.162	0.200	-0.81
LOCYB	0.160	0.274	0.58
LOCVN	-0.695	0.318	-2.19*
LOCCC	-1.009	0.284	-3.56***
MET	-0.449	0.183	-2.45*
OUT_MIN	-0.005	0.005	-1.05
CLO	0.131	0.363	0.36
EW_SPD	0.122	0.024	5.17***
TEMP	-0.091	0.030	-2.98**
SOLAR	0.001	0.000	1.91
R_HUMID	0.013	0.012	1.09
Summary Statistics	N = 701 Log likelihood = -512.661 Likelihood ratio Chi^2 = 130.94 p < 0.001 McFadden's pseudo R^2 = 0.113		

* p < 0.05, ** p < 0.01, *** p < 0.001

The following is a summary of each significant variable's net effect on wind preference, when the other variables in the model are held constant.

- Being female would result in a 0.501 unit increase in the ordered log-odds of being a higher wind preference category.
- Visiting the place to rest or linger would result in a 1.099 unit decrease in the ordered log-odds of being a higher wind preference category.

- Being in Van Ness would result in a 0.695 unit decrease in the ordered log-odds of being a higher wind preference category.
- Being in Civic Center would result in a 1.009 unit decrease in the ordered log-odds of being a higher wind preference category.
- A one *met* increase in metabolic rate would result in a 0.449 unit increase in the ordered log-odds of being in a higher wind preference category.
- A one mph increase in equivalent wind speed would result in a 0.122 unit increase in the ordered log-odds of being in a higher wind preference category.
- A one degree increase in temperature would result in a 0.091 unit decrease in the ordered log-odds of being in a higher wind preference category.

In other words,

- Women are likely to want less wind than men (because they are more sensitive to wind).
- People whose purpose is taking rest of lingering are likely to feel windier (because they want less wind to take rest or linger).
- In the Van Ness study area, people want more wind, meaning that they feel less windy. It may be interpreted that they already expect the place to be windy.
- In the Civic Center study area, people want more wind, meaning that they feel less windy. It may be interpreted that they already expect the place to be windy.
- Physical activity (high metabolic rate) makes people feel warmer, so that they want more wind.
- Increase in wind speed makes people want less wind.
- Increase in temperature makes people want more wind.

With regard to wind, for a one mph increase in equivalent wind speed, the odds of the combined higher categories of wind preference is 1.130 ($= e^{0.1222656}$) times higher than the combined lower categories. For example, the odds of wanting less wind is 1.130 times higher than the combined waning more wind and being neutral.

Table 20. Estimation of overall comfort using simple logistic regression.

Variable	COMFD		
	Coefficient	Standard Error	Z
SEXID	-0.784	0.218	-3.59***
OFTEN1	0.310	0.291	1.07
OFTEN2	0.249	0.330	0.75
OFTEN3	0.063	0.318	0.20
PURPS1	-0.273	0.494	-0.55
PURPS2	1.120	0.862	1.30
PURPS3	-0.261	0.347	-0.75
PURPS4	0.181	0.272	0.66
LOCYB	-0.498	0.375	-1.33
LOCVN	0.142	0.403	0.35
LOCCC	0.212	0.402	0.53
MET	0.649	0.269	2.41*
OUT_MIN	0.002	0.006	0.27
CLO	0.567	0.485	1.17
EW_SPD	-0.145	0.030	-4.85***
TEMP	0.176	0.045	3.89***
SOLAR	0.001	0.001	1.83
R_HUMID	0.006	0.016	0.37
constant	-9.883	3.910	-2.53*
Summary Statistics	N = 701 Log likelihood = -291.815 Likelihood ratio Chi^2 = 136.38 p < 0.001 McFadden's pseudo R^2 = 0.189		

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 20 presents that SEXID, MET, EW_SPD, and TEMP are variables that are significant at 0.05, 0.01, or 0.001 level when estimating overall comfort (COMFD) using a simple logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

The following is a summary of each significant variable's net effect on overall comfort, when the other variables in the model are held constant.

- Being female would result in a 0.783 decrease in the log-odds of being comfortable.
- A one *met* increase in metabolic rate would result in a 0.649 increase in the log-odds of being comfortable.
- A one mph increase in equivalent wind speed would result in a 0.145 decrease in the log-odds of being comfortable.
- A one degree increase in temperature would result in a 0.175 increase in the log-odds of being comfortable.

In other words,

- Women are likely to feel less comfortable than men.
- Physical activity (high metabolic rate) makes people feel more comfortable.

- Increase in wind speed makes people feel less comfortable.
- Increase in temperature makes people feel more comfortable.

With regard to wind, for a one mph increase in equivalent wind speed, the odds of being comfortable is 0.864 (= $e^{-0.1450976}$) times lower being uncomfortable.

In sum, a series of logistic regression models suggest that equivalent wind speed is a highly significant variable that determines people's thermal sensation, wind sensation, wind preference, and overall comfort, and that increase in wind speed adversely affects people's outdoor comfort. In addition, it was found that there exists a gender difference that women are more likely to feel cold, windy, and uncomfortable and want less wind than men as wind speed increases. Also, people seem to have a low thermal expectation on Van Ness and Civic Center by taking it for granted that the two areas are cold and windy. Lastly, considering the cool climate condition of San Francisco, more physical activity, less wind, and higher temperature are usually accepted as the factors that promote outdoor comfort.

6.2 Effectiveness of Wind Speed Criteria

This section explorers the effectiveness of San Francisco's wind speed criteria for comfort. Among the three criteria specified in the city's planning code, 7, 11, and 26 mph, only the effectiveness of only 11 mph, a comfort criterion of place for walking, was examined in this study. The effectiveness of 7 mph, a comfort criterion of places for seating, was not studied because the field study was carried out in a manner that the participants were standing up. That of 26 mph, a safety criterion, was also not studied for its very low probability of occurrence and for safety reasons.

In the following part of this section, two ways in examining effectiveness are adopted. The key for this examination is to verify whether there exist any differences between a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher. First, the frequency distribution of people's response to the four comfort measures and test their differences is compared. Second, the differences in the net effect of wind on comfort by using piece-wise regression models are analyzed.

Difference in Comfort Response

The main purpose of this part is to find out whether there exists any difference in people's responses to comfort between a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher. More specifically, the frequency distribution of people's responses to thermal sensation, wind sensation, wind preference, and overall comfort under the two conditions and test their significance of differences was compared using statistical models. Among the many statistical techniques have been suggested to measure the association of datasets, Kruskal-Wallis one-way ANOVA, suitable for use with ordinal variables, was used.

Figure 97 shows the frequency distributions of thermal sensation by each category under two different wind conditions. The share of people feeling cold or cool increases and that of those feeling warm or hot decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value generated by Kruskal-Wallis one-way ANOVA is 53.786 at a probability level of < 0.001, indicating that there exists a significant difference between the two frequency distributions. It also means that that people's response to thermal sensation, when the equivalent wind speed is higher than 11 mph, significantly differs from that when the speed is lower than 11 mph. In addition, it is interesting to note that the share of those who chose cold, cool, warm, and hot, which are regarded as "dissatisfied" in the PMV/PPD method, is 20.0 percent (67 / 334) when the equivalent wind speed is less than 11 mph. The reverse share (80%) happens to be exactly same as the acceptability limit for typical applications of comfort modeling by the ANSI/ASHRAE Standard 55-2010.

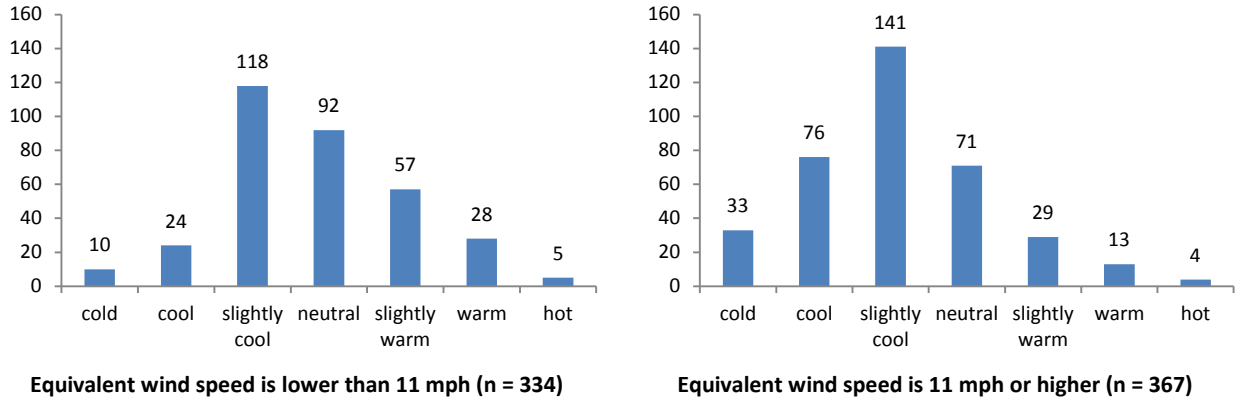


Figure 97. Frequency distributions of thermal sensation responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

Figure 98 presents the frequency distributions of wind sensation. The share of people feeling stronger winds increases and that of those feeling slighter wind decreases, when the equivalent wind speed is 11 mph or higher. The Chi^2 with ties value is 108.232 at a probability level of < 0.001, indicating that there exists a significant difference between the two frequency distributions. It also means that people's response to wind sensation, when equivalent wind speed is 11 mph or higher, significantly differs from that when the speed is lower than 11 mph.

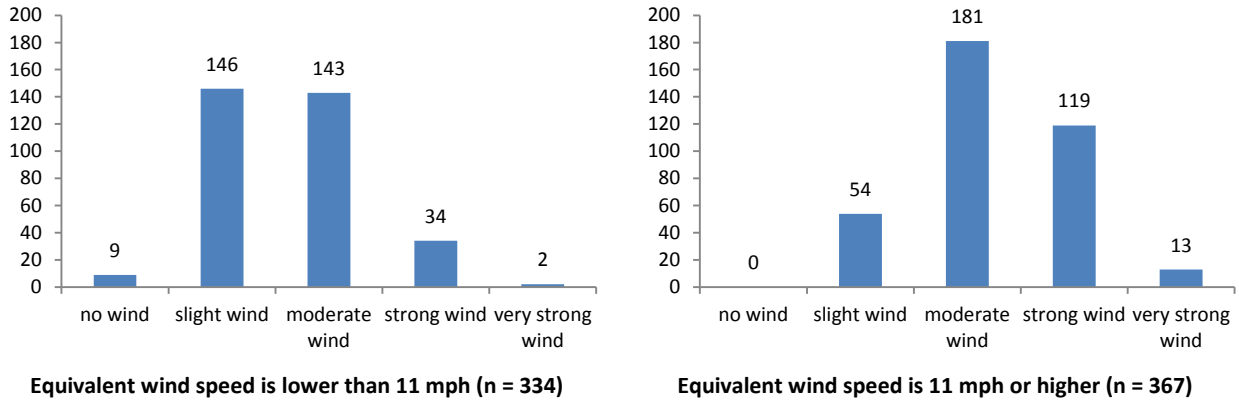


Figure 98. Frequency distributions of wind sensation responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

Figure 99 shows the frequency distributions of wind preference. The share of people who want less wind increases and that of those who want more wind decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value is 25.954 at a probability level of < 0.001, indicating that there exists a significant difference between the two frequency distributions. It also means that people's response to wind preference, when equivalent wind speed is 11 mph or higher, significantly differs from that when the speed is less than 11 mph.

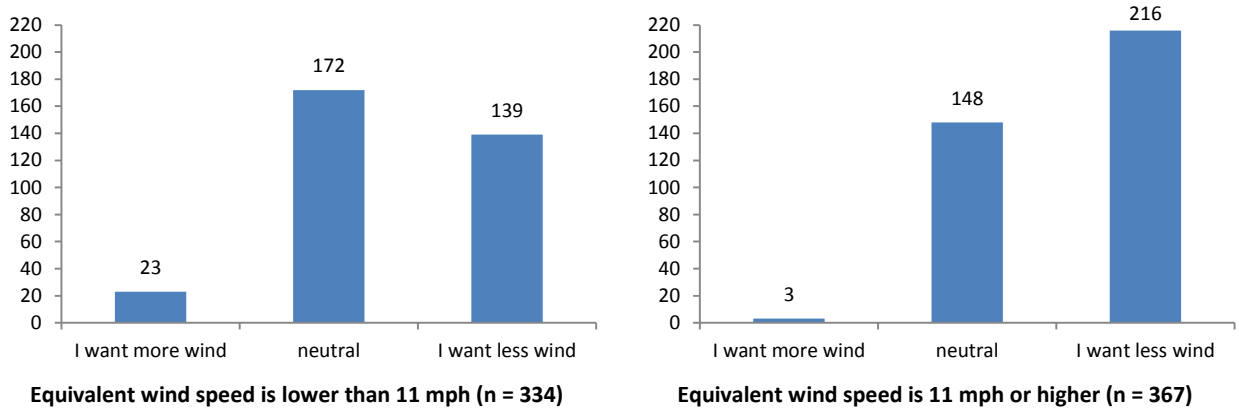


Figure 99. Frequency distributions of wind preference responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

Figure 100 presents the frequency distributions of overall comfort. The share of people who feel uncomfortable increases and that of those who feel comfortable decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value is 29.060 at a probability level of < 0.001, indicating that there exists a significant difference between the two frequency distributions. It also means that people's response to overall comfort, when equivalent wind speed is 11 mph or higher, significantly differs from that when the speed is less than 11 mph.

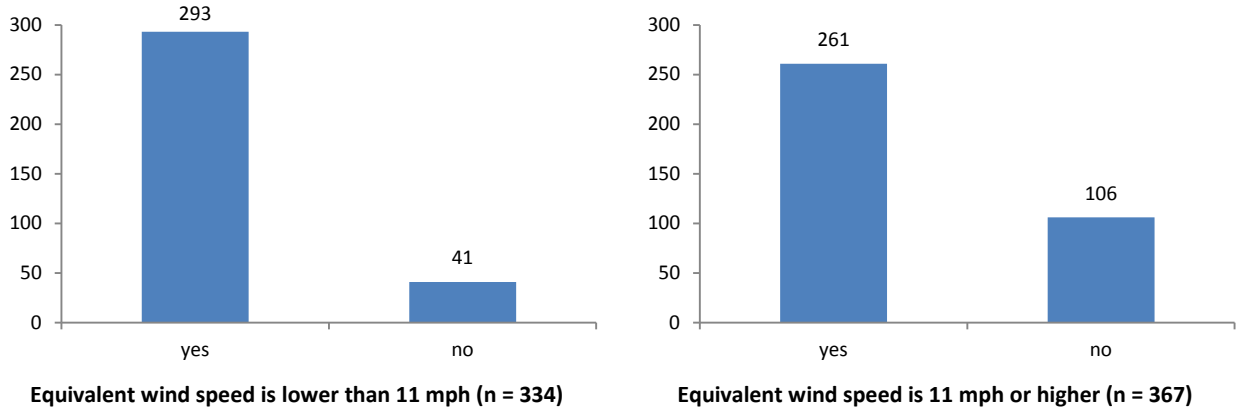


Figure 100. Frequency distributions of overall comfort responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

To sum up, a clear difference in the frequency distributions of people's response to the four comfort measures – thermal sensation, wind sensation, wind preference, and overall comfort – exists between under a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher.

Difference in the Net Effect of Wind on Comfort

In this section, the differences in the net effect of wind on comfort between when the equivalent wind speed is less than 11 mph and when the speed is 11 mph or higher are analyzed by using piece-wise regression models and comparing logistic regression coefficients in each range. Piece-wise regression is a statistical modeling method in which the independent variable is partitioned into two or more intervals, and a separate line segment is to fit each interval. In other words, the method is almost identical to carrying out two or more regressions, each having a separate range within in independent variable.

The same regression models are used that estimated thermal sensation (FEEL), wind sensation (W_FEEL), wind preference (W_PREF), and overall comfort (COMFD) in Section 6.1. The same independent variables are used in this part, which include SEXID, OFTEN1, OFTEN2, OFTEN3, PURPS1, PURPS2, PURPS3, PURPS4, LOCYB, LOCVN, LOCCC, MET, OUT_MIN, CLO, EW_SPD, TEMP, SOLAR, and R_HUMID.

Table 21 presents estimation results of the piece-wise regression coefficients of equivalent wind speed (EW_SPD) for the four comfort measures in comparison with their full regression models from Section 6.1. It shows that the absolute values of the coefficients in all four cases have become smaller – meaning that the net effect of equivalent wind speed is reduced – when the equivalent wind speed is 11 mph or higher than when the speed is less than 11 mph. For example, when the equivalent wind speed is less than 11 mph, for a one mph increase in the equivalent

wind speed the odds of the combined higher categories of wind sensation is 1.543 (= $e^{0.4334941}$) times higher than the combined lower categories. On the other hand, when the equivalent wind speed is 11 mph or higher, for a one mph increase in the equivalent wind speed, the odds of the combined higher categories of wind sensation is only 1.182 (= $e^{0.1668444}$) times higher than the combined lower categories.

Table 21. Comparison of coefficients of equivalent wind speed in piece-wise and full regression models.

Comfort	**EW_SPD < 11** (n = 334)			**EW_SPD ≥ 11** (n = 367)			**Full Model** (n = 701)		
Measure	Coef.	Z	Model Sig.	Coef.	Z	Model Sig.	Coef.	Z	Model Sig.
FEEL	-0.099	-1.88	***	-0.092	-2.65**	***	-0.111	-5.63***	***
W_FEEL	0.433	6.81***	***	0.167	4.36***	***	0.237	10.47***	***
W_PREF	0.201	3.34***	***	0.133	2.98**	***	0.122	5.17***	***
COMFD	-0.254	-2.25*	***	-0.166	-3.50***	***	-0.145	-4.85***	***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

In other words, people are more sensitive to increases in wind speed when it is below 11 mph because it has a greater impact their perception of comfort and changes their comfort level. However, when the wind speed exceeds the comfort criteria, they are less aware of the changes in wind speed because they already feel uncomfortable and they remain uncomfortable as the wind speed increases.

6.3 Open-Ended Questions

Two open-ended questions in the survey were designed to incorporate a qualitative approach to understanding how people perceive wind in relation to comfort. The first question asked where within San Francisco people have experienced wind-discomfort, and the second asked how the wind impacted their comfort level and outdoor activities.

"Wind-Uncomfortable" Places in San Francisco

Among the 701 participants of the field survey, 531 answered the first question while 170 wrote down "no," "none," or "nowhere," or did not reply. Places mentioned by the 531 people include various neighborhoods, streets, street intersections, open spaces, and specific locations. Many participants wrote down two or more places. The following part shows places that were mentioned at least five times.

- Neighborhoods: Downtown, Civic Center, Noe Valley, Richmond District, Sunset District, South of Market, Pacific Heights, the whole city
- Streets: Market Street, Van Ness Avenue, Montgomery Street, Yerba Buena Lane, the Embarcadero, Pine Street, Polk Street

- Street Intersections: Van Ness & Market, Van Ness & California, Van Ness & Polk, Market & 9th, Market & 10th, King & 4th, Berry & 4th, Howard & 9th
- Open Spaces: Crissy Fields, UN Plaza, Ocean Beach, Alamo Square
- Specific Locations: P. B. Federal Building, Fisherman's Wharf, Twin Peaks, Golden Gate Bridge, Fox Plaza, BART Stations

However, among all places mentioned, 37 percent were the exact location, street, or neighborhood where the field studies took place. Many of them even said "here." Although these places are indeed some of the windiest parts of San Francisco, it was concluded that the four places were over-represented in people's responses.

Wind Experience

On the other hand, the second question received a wide range of answers from 504 participants that are divided into six categories: complain, avoid, adapt, surrender, positive, and no effect. Each response is not necessarily classified into one category since quite a few of them are associated with two or more categories. In the following part, several representative responses in each category are introduced.

The vast majority of the responses were associated with complaint about wind. 270 people answered that wind makes them uncomfortable, dissatisfied, and annoying during their outdoor activities.

"I hate the wind. [I feel] very cold, very uncomfortable, [and] disorienting."

"I can tolerate snow, freezing weather, rain and humidity but cannot stand wind. My hair sticks to my lips. It blows my skirt up all the time so I can hardly wear dresses. It is cold [and] messes up my hair. I hate it and realized I'm probably in the wrong city."

"Since it's near a bank I am afraid the wind blowing money away. Lost papers held in hand."

"If I am trying to read a newspaper and the wind makes it difficult to turn the pages. The wind wants to blow away some loose papers that I am working with."

"It's difficult and uncomfortable to bike into the wind, especially when biking up hills. Can't see. Gotta put jacket on. Have to work harder."

"The Federal Building causes high winds in this area which make traveling here uncomfortable."

Another group of people reported that they try to avoid the wind. 162 responded that they stay outside shorter, stay inside more, and do less outdoor activities.

"If it's too windy, I don't do too many activities outdoors."

“Strong winds aren't fun but I do go outdoors all the same. I wouldn't stay in one place though if it were very windy.”

“Makes walking to and from home rather uncomfortable, especially at night. [Wind] makes me walk faster. Sometimes I get something blown into my eye or [that] makes it dry. Wind can be fun and dramatic but not very enjoyable to spend a long time in. I'd rather be inside.”

“It just makes it colder, not super inconvenient. When it’s windy and foggy, I usually stay inside.”

A fair number of people adjust to the wind in San Francisco by adapting themselves to the circumstances. 64 replied that they carry extra clothing or walk faster to adapt to the adverse wind conditions.

“I always have to have a jacket. If I forget my jacket, I will probably cut short what I am doing.”

“I walked faster and more carefully, then took a warm sweater and dried off.”

“I always dress with the wind in mind. Layers. [I] always have a scarf and usually a hat!”

Some showed the sign of surrender to the wind. 26 responded that they do not take any action against the adverse wind situations and live with them.

“It comes with living in SF. You get used to it.”

“It is usually windy. If I want any sun or exercise, I put up with it.”

A group of people expressed their positive attitude towards wind in San Francisco. 22 answered how much they like the wind and how they enjoy it.

“I like wind.”

“I love wind. It is refreshing. It feels good on my face. It blows my hair. It makes me laugh.”

A fairly large number of people said that they are not affected by the wind. 56 responded that they do not see any effect or seemed to be indifferent about wind.

“Not much.”

“No impact. There's no sure thing as bad weather, only bad emotion.”

“No. Wind in SF seems pretty moderate.”

6.4 Discussion of Findings

Section 6.1 examined the relationship between wind and comfort by analyzing whether there are relationships between the equivalent wind speed and comfort measures. By comparing the distribution of equivalent wind speeds by each category of the four comfort measures and using ANOVA to verify the differences between each category, a significant relationship between wind and comfort was found. By using ordinal logistic and simple logistic regression models, it was also found that equivalent wind speed is a highly significant variable that effectively estimates people's thermal sensation, wind sensation, wind preference, and overall comfort, and that increase in wind speed adversely affects people's outdoor comfort.

Section 6.2 studied the effectiveness of wind speed criterion, 11 mph, a comfort criterion of place for walking. By comparing the frequency distributions of people's responses to comfort and adopting Kruskal-Wallis one-way ANOVA, a clear difference in people's perceived comfort was found between under a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher. Also, by using piece-wise regression models and comparing the coefficients of equivalent wind speed, it was found that people are more sensitive to wind speed increase when the speed is below 11 mph and that they are less aware of the changes in wind speed when it is 11 mph or higher.

Section 6.3 incorporated additional information about wind and comfort using a qualitative approach, and found that there are a wide range of reactions to wind which can be categorized into complain, avoid, adapt, surrender, positive, and no effect.

Based on the findings in this chapter, it could be concluded that wind affects comfort and that 11 mph is an effective criterion that determines outdoor comfort in San Francisco for people that are walking. There are significant differences with regard to people's perceived comfort and the net effect of wind speed on comfort between under a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher. At the same time, there exist many dimensions on how people perceive wind and comfort, which makes it difficult to judge the effectiveness easily.

CHAPTER 7. WIND, COMFORT, AND WILLINGNESS TO USE SUSTAINABLE TRANSPORTATION MODES[41]

This chapter provides the rest of the results from the field study, method used to study the relationship between wind, comfort, and willingness to use sustainable transportation modes. More specifically, it tries to present an answer to the third research sub-question of this research: *does the plan achieve a wind comfort level that would increase people's willingness to use sustainable transportation modes?* Section 7.1 provides a literature review on the relationship between weather conditions and travel behavior. Section 7.2 examines the relationship between wind speed and willingness to use sustainable transportation modes, and Section 7.3 investigates the effectiveness of 11 mph, a comfort criterion for places of walking, as well as the four comfort measures studied Chapter 6, in estimating willingness to use sustainable transportation modes. Details of the field study procedure were presented in Section 4.4.

Sustainable transportation modes are defined as those that "produce fewer pollutants, use less infrastructure, and take up less public space per traveler than private automobiles" (Schneider, 2011, p. 7). Typically, this includes taking public transit, bicycling, walking, and any other modes that would curb the use of private automobiles. Here, using sustainable transportation modes is defined as riding public transit, bicycling, and walking. With respect to riding public transit, the proxy of waiting at a transit stop with no shelter is used, since the possibility of waiting for a bus or streetcar in a comfortable place may support the use of a transportation mode. With regard to walking, sitting outside is included as another dimension of outdoor pedestrian activity besides walking. Moreover, willingness to use sustainable transportation modes is examined in the opposite way. Instead of directly asking the participant's willingness, they were asked the degree of discouragement for waiting at transit stop with no shelter, discouragement for bicycling, discouragement for walking, and discouragement for sitting outside in three-point scale. This was done to make correlating the responses with the increase in wind speed more convenient, because it was hypothesized that an increase in wind speed would increase the level of discouragement.

7.1 Literature on the Relationship between Weather Conditions and Travel Behavior

Only a small body of literature exists that examines the relationship between weather conditions and travel behavior. Among them, most studies derive from datasets collected by electronic devices and management systems. Guo, Wilson, and Rahbee (2007), using the Chicago Transit Authority (CTA) in Illinois as a case study, found that mild weather tends to increase transit ridership, and that temperature, rain, snow, and wind all affect transit ridership in the expected direction. Sabir, van Ommeren, Koetse, and Rietveld (2010), based on Dutch travelers' data for 10 years and locally measured meteorological data, identified the strong effects of weather on transportation mode choice. They found that precipitation increases the modal shift from bicycle to public transit and private automobile, and that commuting and business trips are least influenced by weather, whereas recreational trips are more sensitive. Stover and McCormack

[41] See Appendix H for all outputs of statistical modeling in this chapter.

(2012), using the bus ridership data in Pierce County, Washington, found that high winds negatively affected ridership in winter, spring, and fall; cold temperatures led to decreases in ridership; rain negatively affected ridership in all four seasons; and snow was associated with lower ridership in fall and winter. Arana, Cabezudo, and Peñalba (2014) analyzed bus ridership data that are generated from using smartcards in Gipuzkoa, Spain, and found that wind and rain could result in a decrease in the number of bus trips, whereas a temperature rise caused an increase in the number of trips.

While the aforementioned studies used aggregate data at the city or regional level, a study by Cools, Moons, Creemers, and Wets (2010) is one of the very few that examined the relationship at the individual user level. They carried out a survey, completed by 586 respondents, and found that people's travel behavior is significantly dependent upon cold and warm temperatures, snow, rain, fog, and storm. However, they simply measure whether the weather conditions make any difference to mode choice based on each participant's memory, while any finding or consideration of how much change they make is not found.

In short, while the literature is growing, there is no study that examines the direct effect of various weather conditions, including wind, at the individual level. In this sense, this study seeks to fill this research gap by providing findings on the immediate relationship between wind and willingness to use sustainable transportation modes.

7.2 Wind and Willingness to Use Sustainable Transportation Modes

This section explores the relationship between wind and willingness to use sustainable transportation modes, which include discouragement for waiting at transit stop with no shelter, biking, walking outside, and sitting outside. After summarizing the descriptive statistics of the variables, analysis was carried out in two ways. First, the simple relationship between wind and the willingness was examined. Second, a more complex relationship between the two that generates the net effect of wind was studied by taking into consideration additional variables that influence willingness to use sustainable transportation modes.

Descriptive Statistics

Table 22 summarizes the descriptive statistics of the variables collected from the field survey and used in this analysis. While many of them are already used in Chapter 6, variables on the usual use of sustainable transportation modes, such as frequency of transit use and frequency of bicycling, are included as additional independent variables in this part. Those on the willingness to use sustainable transportation modes, including discouragement for waiting at transit stop with no shelter, discouragement for bicycling, discouragement for walking, and discouragement for sitting outside, are incorporated as the dependent variables of this analysis. The majority of participants answered that they frequently use public transit (58%) but rarely bike (63%). With respect to willingness to use sustainable transportation modes in relation to increase in wind speed, most people reported that thy are not affected to wait at transit stop with no shelter (51%),

to bike (45%), and to walk outside (59%). However, they answered that wind would strongly discourage them from sitting outside (40%).

Table 22. Descriptive statistics and frequencies of variables.

Variable			**Unit**	**Descriptive Statistics or Frequency**	**Variable Name**
Independent Variable	Individual	Gender	-	Female: 295 (42%) Male: 406 (58%)	SEXID (Female=1)[a]
	Location	Location	-	Yerba Buena: 239 (34%) Van Ness: 161 (23%) Civic Center: 183 (26%) Mission Bay North: 118 (17%)	LOCYB (Yerba Buena=1)[a] LOCVN (Van Ness=1)[a] LOCCC (Civic Center=1)[a]
	Thermal history and status	Metabolic rate	met	Min: 0.6; Max 4.5; Mean: 1.7; Std Dev: 0.5	MET
		Time spent outside in the last 1 hour	minute	Min: 0; Max: 60; Mean: 26; Std Dev: 20	OUT_MIN
		Clothing insulation	clo	Min: 0.30; Max: 1.64; Mean: 0.86; Std Dev: 0.24	CLO
	Microclimatic Condition	Equivalent wind speed	mph	Min: 1.9; Max: 29.2; Mean: 11.7; Std Dev: 4.4	EW_SPD
		Temperature	°F	Min: 54.2; Max: 75.8; Mean: 63.3; Std Dev: 4.3	TEMP
		Solar radiation	W/m^2	Min: 6; Max: 949; Mean: 238; Std Dev: 249	SOLAR
		Humidity	%	Min: 46.2; Max: 94.4; Mean: 69.8; Std Dev: 11.1	R_HUMID
	Use of Sustainable Transportation Modes	Frequency of transit use	-	Rarely: 117 (17%) Sometimes: 117 (17%) Frequently: 407 (58%)	TRNST_SO (sometimes=1)[a] TRNST_FR (frequently=1)[a]
		Frequency of bicycling	-	Rarely: 442 (63%) Sometimes: 136 (19%) Frequently: 123 (18%)	BIKG_SO (sometimes=1)[a] BIKG_FR (frequently=1)[a]
Dependent Variable	Willingness to use sustainable transportation modes	Discouragement for waiting at transit stop with no shelter	-	No effect: 357 (51%) Slightly: 221 (32%) Strongly: 123 (18%)	WAIT_TR (no effect=1, slightly=2, strongly=3)
		Discouragement for bicycling	-	No effect: 318 (45%) Slightly: 222 (32%) Strongly: 161 (23%)	BIKE (no effect=1, slightly=2, strongly=3)
		Discouragement for walking	-	No effect: 417 (59%) Slightly: 223 (32%) Strongly: 61 (9%)	WALK_O (no effect=1, slightly=2, strongly=3)
		Discouragement for sitting outside	-	No effect: 158 (23%) Slightly: 260 (37%) Strongly: 283 (40%)	SIT_O (no effect=1, slightly=2, strongly=3)

Notes: a. Dummy variables were used for categorical variables.

Simple Relationship between Wind and Willingness to Use Sustainable Transpiration Modes

This part examines whether there exist relationships between the equivalent wind speed and willingness to use sustainable transportation modes, which is measured in the form of discouragement for waiting at transit stop with no shelter, discouragement for biking, discouragement for walking outside, and discouragement for sitting outside. To see whether a relationship exists, the distribution of equivalent wind speeds was compared by the three common categories of the four dependent variables which are "no effect," "slightly," and "strongly." In each process, ANOVA analysis was carried out to verify whether the relationship is significant, which is, in other words, whether there exist differences between each category's mean equivalent wind speed. In this part, it is assumed that equivalent wind speed is the dependent variable for convenience.

Figure 101 shows the relationship between the three categories of discouragement for waiting at transit stop with no shelter and equivalent wind speed. It presents an overall trend that faster winds make people more discouraged to wait at transit stop with no shelter. The F value generated by ANOVA is 12.58 and the significance level is 0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

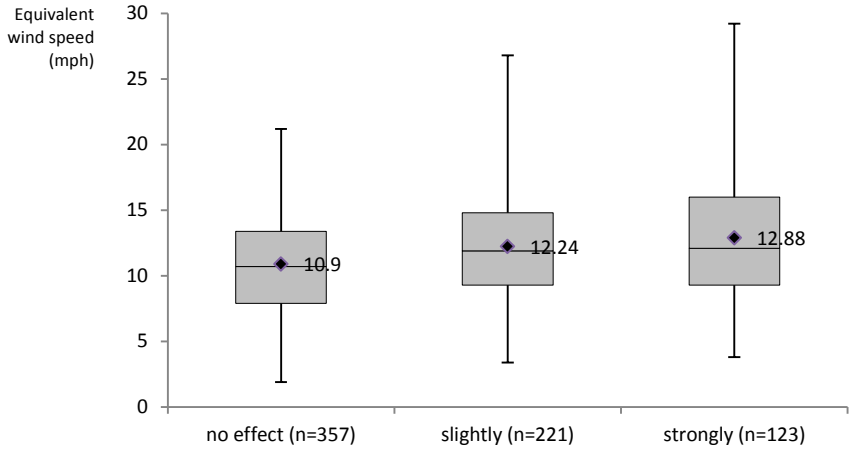


Figure 101. Distribution of equivalent wind speed (mph) by discouragement for waiting at transit stop with no shelter (N=701).

Figure 102 shows the relationship between the three categories of discouragement for biking and equivalent wind speed. It presents an overall trend that faster winds make people more discouraged to bike. The F value generated by ANOVA is 12.43 and the significance level is 0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

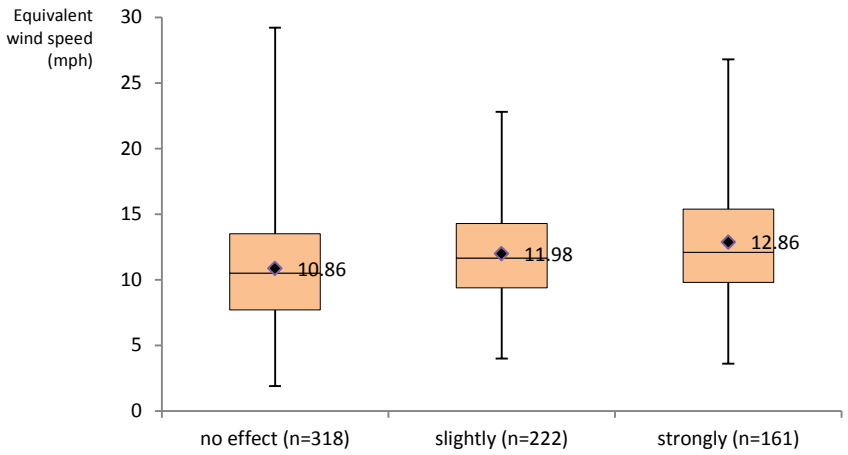


Figure 102. Distribution of equivalent wind speed (mph) by discouragement for biking (N=701).

Figure 103 shows the relationship between the three categories of discouragement for walking outside and equivalent wind speed. It presents an overall trend that faster winds make people more discouraged to walk outside. The F value generated by ANOVA is 12.60 and the significance level is 0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

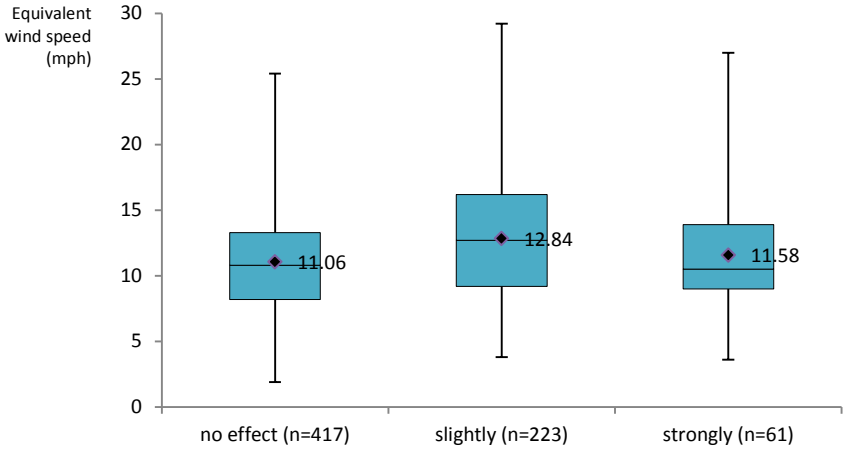


Figure 103. Distribution of equivalent wind speed (mph) by discouragement for walking outside (N=701).

Figure 104 shows the relationship between the three categories of discouragement for sitting outside and equivalent wind speed. It presents an overall trend that faster winds make people more discouraged to sit outside. The F value generated by ANOVA is 20.52 and the significance

level is 0.000, indicating that the differences in the mean equivalent wind speeds are statistically significant.

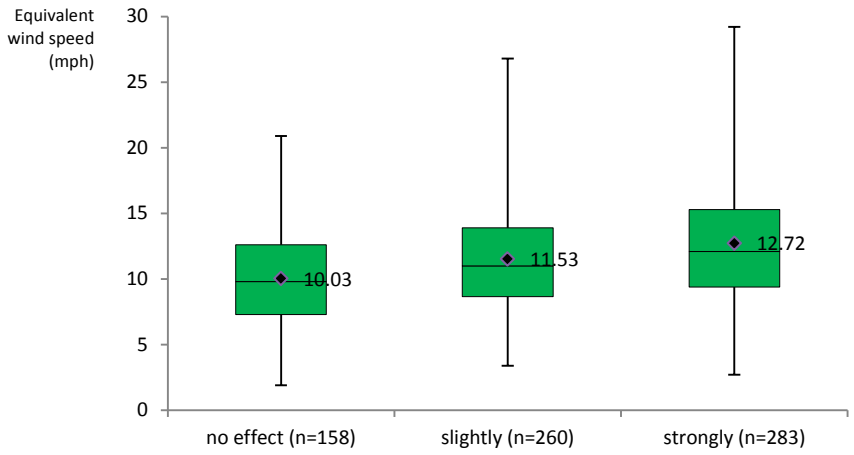


Figure 104. Distribution of equivalent wind speed (mph) by discouragement for sitting outside (N=701).

In sum, significant differences exist between the mean equivalent wind speed of the categories within all willingness measures, implying that there are significant relationships between wind and willingness to use sustainable transportation modes.

The Net Effect of Wind on Willingness to Use Sustainable Transportation Modes

This part examines the relationship between wind and willingness to use sustainable transportation modes by taking into consideration additional variables as summarized in Table 22. This process also makes it possible to identify the net effect of wind – more specifically, the equivalent wind speed – on the willingness measures. Ordinal logistic regression models are used for estimating the relationship between the variables and discouragement for waiting at transit stop with no shelter, discouragement for biking, discouragement for walking outside, and discouragement for sitting outside.

Table 23 presents that LOCVN, EW_SPD, and TEMP are the variables that are significant at 0.05 or 0.001 level when estimating discouragement for waiting at transit stop with no shelter (WAIT_TR) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

Table 23. Estimation of discouragement for waiting at a transit stop with no shelter using ordinal logistic regression.

Variable	WAIT_TR		
	Coefficient	Standard Error	Z
SEXID	0.284	0.153	1.86
LOCYB	-0.054	0.243	-0.22
LOCVN	-0.568	0.284	-2.00*
LOCCC	-0.278	0.260	-1.07
MET	0.193	0.168	1.15
OUT_MIN	-0.005	0.004	-1.13
CLO	-0.155	0.334	-0.46
EW_SPD	0.079	0.020	3.87***
TEMP	-0.060	0.028	-2.13*
SOLAR	0.000	0.000	0.54
R_HUMID	0.002	0.011	0.16
TRNST_SO	-0.419	0.235	-1.78
TRNST_FR	-0.262	0.208	-1.26
BIKG_SO	0.115	0.188	0.61
BIKG_FR	-0.413	0.212	-1.95
Summary Statistics	N = 701 Log likelihood = -684.745 Likelihood ratio Chi^2 = 50.64 p < 0.001 McFadden's pseudo R^2 = 0.036		

* p < 0.05, ** p < 0.01, *** p < 0.001

The following is a summary of each significant variable's net effect, when the other variables in the model are held constant.

- Being in Van Ness would result in a 0.568 unit decrease in the ordered log-odds of being a stronger discouragement category.
- A one mph increase in equivalent wind speed would result in a 0.079 unit increase in the ordered log-odds of being a stronger discouragement category.
- A one degree increase in temperature would result in a 0.060 unit decrease in the ordered log-odds of being a stronger discouragement category.

In other words,

- In the Van Ness study area, people are less discouraged to wait at transit stop with no shelter as the wind speed increases. It may be interpreted that they already expect the place to be windy.
- Increase in wind speed makes people more discouraged to wait at transit stop with no shelter.
- Increase in temperature makes people less discouraged to wait at transit stop with no shelter.

With regard to wind, for a one mph increase in equivalent wind speed, the odds of the combined higher categories of discouragement category is 1.082 (= $e^{0.0787067}$) times higher than the

combined lower categories. For example, the odds of being strongly discouraged is 1.082 times higher than the combined no effect and slightly discouraged.

Table 24 shows that EW_SPD is the only variable that is significant at 0.001 level when estimating discouragement for biking (BIKE) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

Table 24. Estimation of discouragement for biking using ordinal logistic regression.

Variable	**BIKE**		
	Coefficient	Standard Error	Z
SEXID	0.188	0.151	1.25
LOCYB	0.089	0.237	0.38
LOCVN	-0.349	0.276	-1.26
LOCCC	-0.158	0.251	-0.63
MET	0.026	0.167	0.16
OUT_MIN	-0.002	0.004	-0.43
CLO	0.077	0.326	0.24
EW_SPD	0.080	0.021	3.91^{***}
TEMP	-0.034	0.027	-1.26
SOLAR	0.000	0.000	0.56
R_HUMID	0.005	0.011	0.51
TRNST_SO	-0.012	0.228	-0.05
TRNST_FR	0.078	0.202	0.39
BIKG_SO	0.087	0.182	0.48
BIKG_FR	-0.276	0.200	-1.38
Summary Statistics	N = 701 Log likelihood = -724.078 Likelihood ratio Chi^2 = 38.79 $p < 0.001$ McFadden's pseudo R^2 = 0.026		

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The following is a summary of the significant variable's net effect, when the other variables in the model are held constant.

- A one mph increase in equivalent wind speed would result in a 0.080 unit increase in the ordered log-odds of being a stronger discouragement category.

In other words,

- Increase in wind speed makes people more discouraged to bike.

This means that for a one mph increase in equivalent wind speed, the odds of the combined higher categories of discouragement category is 1.084 (= $e^{0.0803364}$) times higher than the combined lower categories. For example, the odds of being strongly discouraged is 1.084 times higher than the combined no effect and slightly discouraged.

Table 25 shows that EW_SPDis the only variable that is significant at 0.05 level when estimating discouragement for walking outside (WALK_O) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

Table 25. Estimation of discouragement for walking outside using ordinal logistic regression.

Variable	**WALK_O**		
	Coefficient	Standard Error	Z
SEXID	0.270	0.161	1.67
LOCYB	-0.060	0.253	-0.24
LOCVN	-0.293	0.288	-1.02
LOCCC	-0.368	0.271	-1.36
MET	0.036	0.176	0.20
OUT_MIN	0.000	0.005	0.10
CLO	0.652	0.347	1.88
EW_SPD	0.054	0.021	2.58*
TEMP	-0.048	0.030	-1.59
SOLAR	-0.000	0.000	-0.44
R_HUMID	0.007	0.012	0.63
TRNST_SO	-0.126	0.252	-0.50
TRNST_FR	0.188	0.221	0.85
BIKG_SO	-0.160	0.206	-0.78
BIKG_FR	-0.064	0.216	-0.30
Summary Statistics	N = 701 Log likelihood = -598.966 Likelihood ratio Chi^2 = 43.96 p < 0.001 McFadden's pseudo R^2 = 0.035		

* p < 0.05, ** p < 0.01, *** p < 0.001

The following is a summary of the significant variable's net effect, when the other variables in the model are held constant.

- A one mph increase in equivalent wind speed would result in a 0.054 unit increase in the ordered log-odds of being a stronger discouragement category.

In other words,

- Increase in wind speed makes people more discouraged to walk outside.

This means that for a one mph increase in equivalent wind speed, the odds of the combined higher categories of discouragement category is 1.056 (= $e^{0.0540196}$) times higher than the combined lower categories. For example, the odds of being strongly discouraged is 1.056 times higher than the combined no effect and slightly discouraged.

Table 26 presents that SEXID, LOCCC, OUT_MIN, EW_SPD, and TEMP are the variables that are significant at 0.05, 0.01, or 0.001 level when estimating discouragement for sitting outside

(SIT_O) using an ordinal logistic regression model. The summary statistics results indicate that the overall model is statistically significant.

Table 26. Estimation of discouragement for sitting outside using ordinal logistic regression.

Variable	**SIT_O**		
	Coefficient	Standard Error	Z
SEXID	0.524	0.155	3.39***
LOCYB	-0.267	0.244	-1.09
LOCVN	-0.473	0.289	-1.64
LOCCC	-0.830	0.260	-3.19**
MET	-0.217	0.172	-1.26
OUT_MIN	-0.011	0.004	-2.41*
CLO	-0.329	0.329	-1.00
EW_SPD	0.072	0.021	3.40***
TEMP	-0.118	0.028	-4.22***
SOLAR	-0.000	0.000	-0.55
R_HUMID	0.008	0.011	0.76
TRNST_SO	-0.300	0.234	-1.28
TRNST_FR	-0.217	0.207	-1.05
BIKG_SO	-0.238	0.191	-1.24
BIKG_FR	-0.095	0.205	-0.46
Summary Statistics	N = 701 Log likelihood = -689.365 Likelihood ratio Chi^2 = 121.23 p < 0.001 McFadden's pseudo R^2 = 0.081		

* p < 0.05, ** p < 0.01, *** p < 0.001

The following is a summary of each significant variable's net effect, when the other variables in the model are held constant.

- Being female would result in a 0.524 unit increase in the ordered log-odds of being a stronger discouragement category.
- Being in Civic Center would result in a 0.830 unit decrease in the ordered log-odds of being a stronger discouragement category.
- A one minute increase in time spent outside in the last 1 hour would result in a 0.011 unit decrease in the ordered log-odds of being a stronger discouragement category.
- A one mph increase in equivalent wind speed would result in a 0.072 unit increase in the ordered log-odds of being a stronger discouragement category.
- A one degree increase in equivalent wind speed would result in a 0.118 unit decrease in the ordered log-odds of being a stronger discouragement category.

In other words,

- Women are likely to be more discouraged to sit outside than men.

- In the Civic Center study area, people are less discouraged to sit outside as the wind speed increases. It may be interpreted that they already expect the place to be windy.
- Increase in time spent outside in the last hour makes people less discouraged to sit outside (because they have got used to the outside thermal condition).
- Increase in wind speed makes people more discouraged to sit outside.
- Increase in temperature makes people less discouraged to sit outside.

With regard to wind, for a one mph increase in equivalent wind speed, the odds of the combined higher categories of discouragement category is 1.074 (= $e^{0.0716654}$) times higher than the combined lower categories. For example, the odds of being strongly discouraged is 1.074 times higher than the combined no effect and slightly discouraged.

In sum, a series of logistic regression models suggest that equivalent wind speed is a highly significant variable when estimating people's willingness to use sustainable transportation modes, and that increase in wind speed discourages them to wait at transit stop with no shelter, to bike, to walk outside, and to sit outside. Especially in the case of sitting outside, women are likely to be more discouraged. Also, people seem to have a low thermal expectation in Civic Center by taking it for granted that the place is windy. People also are likely to sit outside if they have spent longer amount of time already. Lastly, considering the cool climate condition of San Francisco, higher temperature encourages people to sit outside.

7.3 Comfort and Willingness to Use Sustainable Transportation Modes

In this section, the relationship between comfort and willingness to use sustainable transportation modes is explored by using three methods. First, the frequency distribution of people's response to the four willingness measures and test their differences between under a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher is compared. Second, the differences in the net effect of wind on willingness to use sustainable transportation mode between the two wind conditions are analyzed by using piece-wise regression models. Third, as an alternative to 11 mph, a comfort criterion, the four comfort measures – thermal sensation, wind sensation, wind preference, and overall comfort – used in Chapter 6 are applied in estimating willingness to use sustainable transportation modes and verify whether they are significantly associated.

Difference in Comfort Response

The main purpose of this part is to find out whether there exists any difference in people's responses to willingness to use sustainable transportation modes between when the equivalent wind speed is less than 11 mph and when the speed is 11 mph or higher. More specifically, the frequency distribution of people's responses to the four discouragements under the two conditions is compared and the significance of differences is tested using Kruskal-Wallis one-way ANOVA.

Figure 105 shows the frequency distributions of discouragement for waiting at transit stop with no shelter. The share of people feeling slightly or strongly discouraged increases and that of people who are not discouraged decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value generated by Kruskal-Wallis one-way ANOVA is 7.692 at a probability level of < 0.01, meaning that there exists a significant difference between the two distributions and that people's response to discouragement for waiting at a transit stop with no shelter, when equivalent wind speed is more than 11 mph, significantly differs from that when the speed is less than 11 mph.

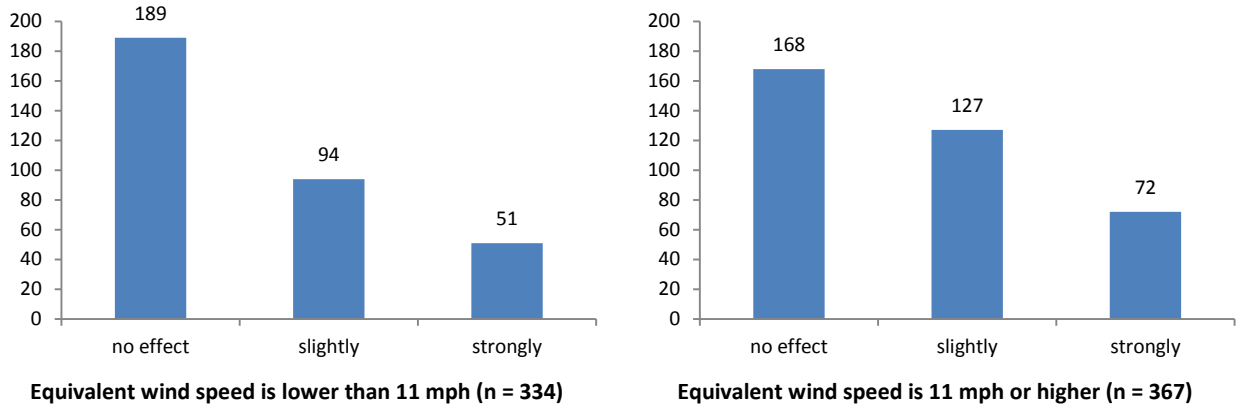


Figure 105. Frequency distributions of discouragement for waiting at transit stop with no shelter responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

Figure 105 presents the frequency distributions of discouragement for biking. The share of people feeling slightly or strongly discouraged increases and that of people who are not discouraged decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value is 10.254 at a probability level of < 0.01. It means that there exists a significant difference between the two distributions and that people's response to discouragement for biking, when equivalent wind speed is more than 11 mph, significantly differs from that when the speed is less than 11 mph.

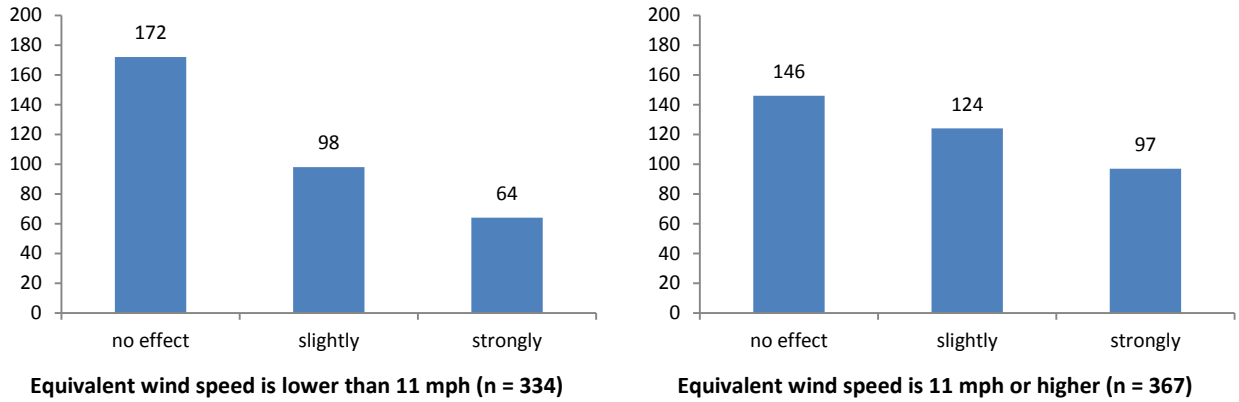


Figure 106. Frequency distributions of discouragement for biking responses when EW_SPD < or ≥ 11.

Figure 107 presents the frequency distributions of discouragement for walking outside. The share of people feeling slightly discouraged increases and that of people who are not discouraged and strongly discouraged decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value is 4.574 at a probability level of < 0.05. It means that there exists a significant difference between the two distributions and that people's response to discouragement for walking outside, when equivalent wind speed is more than 11 mph, significantly differs from that when the speed is less than 11 mph.

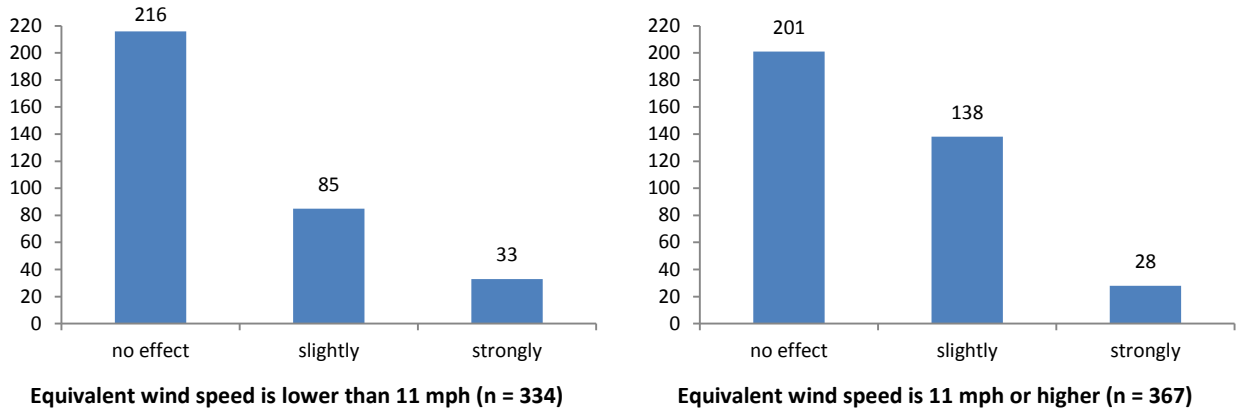


Figure 107. Frequency distributions of discouragement for walking outside responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

Figure 108 shows the frequency distributions of discouragement for sitting outside. The share of people feeling strongly discouraged increases and that of those with no effect decreases, when the equivalent wind speed is 11 mph or more. The Chi^2 with ties value is 16.838 at a probability level of < 0.001. It means that there exists a significant difference between the two distributions

and that people's response to discouragement for sitting outside, when equivalent wind speed is more than 11 mph, significantly differs from that when the speed is less than 11 mph.

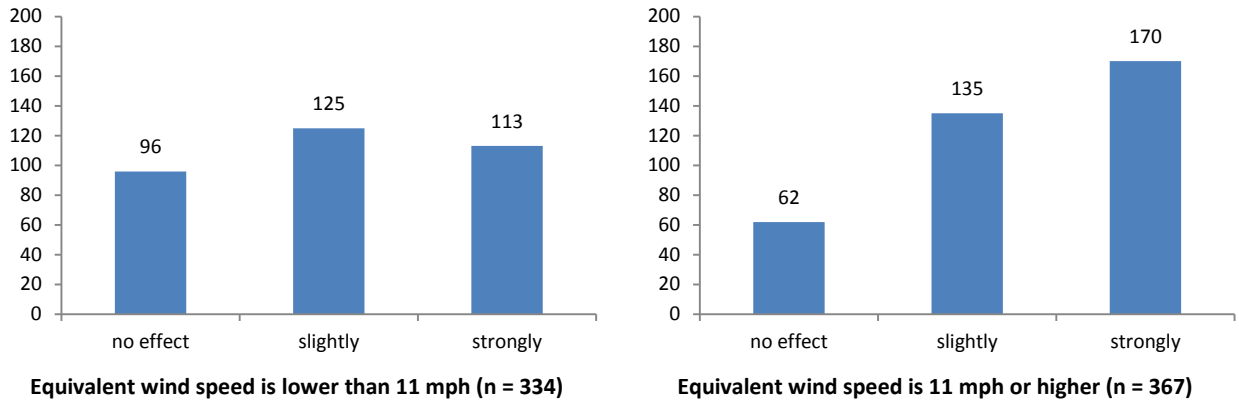


Figure 108. Frequency distributions of discouragement for sitting outside responses when equivalent wind speed is lower than 11 mph and 11 mph or higher.

In addition, considering that San Francisco's comfort criterion for places of seating is 7 mph, another comparison based on 7 mph was carried out. As shown in Figure 109, the share of people feeling strongly discouraged increases and that of people who are not discouraged decreases, when the equivalent wind speed is 7 mph or more. The Chi^2 with ties value is 9.164 at a probability level of < 0.01. It means that there exists a significant difference between the two distributions and that people's response to discouragement for sitting outside, when equivalent wind speed is more than 7 mph, significantly differs from that when the speed is less than 7 mph.

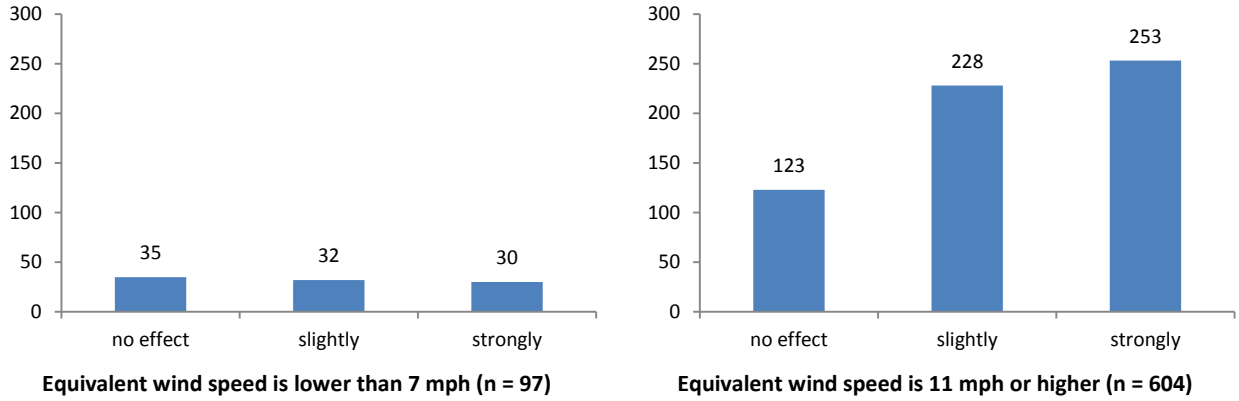


Figure 109. Frequency distributions of discouragement for sitting outside responses when equivalent wind speed is lower than 7 mph and 7 mph or higher.

To sum up, a clear difference in the frequency distributions of people's response to the four discouragement measures exists between when the equivalent wind speed is less than 11 mph and when the speed is 11 mph or higher, and same holds true for 7 mph in the case of sitting outside.

Difference in the Net Effect of Wind on Willingness to Use Sustainable Transportation Modes

This section presents an analysis of the differences in the net effect of wind on willingness to use sustainable transportation modes between when the equivalent wind speed is less than 11 mph and when the speed is 11 mph or higher by using piece-wise regression models and comparing logistic regression coefficients in each range. 7 mph was also incorporated in examining discouragement for sitting outside since it is San Francisco's criterion of places for sitting.

The same ordinal logistic regression models that estimated discouragement for waiting at transit stop with no shelter (WAIT_TR), discouragement for biking (BIKE), discouragement for walking outside (WALK_O), and discouragement for sitting outside (SIT_O) in Section 7.2 was used in this part. The same independent variables are used, which include SEXID, LOCYB, LOCVN, LOCCC, MET, OUT_MIN, CLO, EW_SPD, TEMP, SOLAR, R_HUMID, TRNST_SO, TRNST_FR, BIKG_SO, and BIKG_FR.

Table 27 presents the piece-wise regression coefficients of equivalent wind speed (EW_SPD) for WAIT_TR, BIKE, WALK_O, and SIT_O in comparison with their full regression models from Section 7.2. While a similar model applied in studying the net effects of wind on comfort in Section 6.2 generated significant results, the piece-wise regression models in this section do not provide any. The coefficients or the models for each willingness measure are not always significant at 0.05 level at the same time, indicating that there are not any significant differences in the changes in the net effect of equivalent wind speed ratio. In addition, it is also unclear whether 11 mph, as well as 7 mph for sitting outside, is an effective determinant of willingness to use sustainable transportation modes.

Table 27. Comparison of coefficients of equivalent wind speed in piece-wise and full regression models.

Willingness to Use Sustainable Transportation Modes	**EW_SPD < 11** (n = 334) Coef.	Z	Model Sig.	**EW_SPD ≥ 11** (n = 367) Coef.	Z	Model Sig.	**Full Model** (n = 701) Coef.	Z	Model Sig.
WAIT_TR	0.075	1.27	*	0.101	2.91**	**	0.079	3.87***	***
BIKE	0.181	3.06**	**	0.071	1.99**		0.080	3.91***	***
WALK_O	0.014	0.24		0.093	2.55*	***	0.054	2.58*	***
SIT_O	0.086	1.55	***	0.072	1.88	***	0.072	3.40***	***
	EW_SPD < 7 (n = 97)			**EW_SPD ≥ 7** (n = 604)					
SIT_O	-0.103	-0.48	***	0.071	2.73**	***	0.072	3.40***	***

* p < 0.05, ** p < 0.01, *** p < 0.001

Effectiveness of Comfort Measures in Estimating Willingness to Use Sustainable Transportation Modes

As an alternative, the four comfort measures were applied, which include thermal sensation, wind sensation, wind preference, and overall comfort, in estimating willingness to use sustainable transportation modes. In this process, the Goodman and Kruskal's gamma (γ), a test widely used in measuring the strength and direction of two ordinal variables, was adoped.

Table 28 shows that among the four comfort measures, thermal sensation (FEEL) is the only one that is significantly, negatively associated with all of WAIT_TR, BIKE, WALK_O, and SIT_O, while the other measures are associated with two or three. However, the relationship between FEEL and the four willingness measures are "weak" except for the one with BIKE which is regarded as "no relationship."[42] The relationships between wind sensation (W_FEEL) and WAIT_TR, BIKE, and SIT_O are significant but weak. Those between wind preference (W_PREF) and WAIT_TR and SIT_O, and that between overall comfort (COMFD) and BIKE are strong. In the end, it is unclear whether any of the four comfort measures are effective in estimating all of the four measures of willingness to use sustainable transportation modes.

Table 28. Goodman and Kruskal's gamma (γ) values of comparing comfort measures and willingness to use sustainable transportation modes.

	Comfort Measure			
	FEEL	W_FEEL	W_PREF	COMFD
WAIT_TR	-0.2608*	0.3440*	0.5171*	-0.6141
BIKE	-0.1756*	0.3106*	0.2997	-0.4226
WALK_O	-0.2917*	0.3515	0.5619	-0.6375*
SIT_O	-0.4245*	0.4239*	0.6552*	-0.7391*

* $p < 0.05$

7.4 Discussion of Findings

The literature review discussed in Section 7.1 revealed that to date no studies have examined the direct relationship between various weather conditions, including wind, and willingness to use sustainable transportation modes at the individual level.

Section 7.2 explored the relationship between wind and willingness to use sustainable transportation modes. By comparing the distribution of equivalent wind speeds by the three common categories ("no effect," "slightly," and "strongly") of the four dependent variables, significant differences were found between the mean equivalent wind speeds of the categories within each willingness to use sustainable transportation modes. The net effect of wind speed on willingness to use sustainable transportation modes was also analyzed by using ordinal logistic

[42] In principle, the following rule of thumb is accepted when determining the strength of relationship between two variables: $0 \leq \gamma < 0.25$ no relationship; $0.25 \leq \gamma < 0.50$ weak relationship; $0.50 \leq \gamma < 0.75$ moderate relationship; and $0.75 \leq \gamma < 1$ "strong relationship.

regression models and found that wind speed is a highly significant variable, and that increase in wind speed discourages them to wait at transit stop with no shelter, to bike, to walk outside, and to sit outside.

Section 7.3 analyzed the effect of comfort on willingness to use sustainable transportation modes. The first comfort criterion tested was 11 mph, a comfort standard for places of walking. By comparing the frequency distributions of people's response to the four willingness measures, a clear difference was found between a condition in which the equivalent wind speed is less than 11 mph and another in which the speed is 11 mph or higher, and the same for 7 mph in the case of sitting outside. The differences in the net effect of wind on willingness to use sustainable transportation modes were studied under the two wind conditions using piece-wise regression models and comparing the logistic regression coefficients in each range. It was found that the coefficients or the models are not always significant at 0.05 level, indicating that their differences are not also significant. Alternatively, the association of the four comfort measures with the four willingness measures was tested, but was suggested that there was no comfort measure that had at least moderate association with all willingness measures.

Equivalent wind speed is a highly significant variable in estimating people's willingness to use sustainable transportation modes, and increase in wind speed discourages them from waiting at transit stops with no shelter, bicycling, walking outside, and sitting outside. Also, there exist significant differences between all willingness measures to use sustainable transportation modes between when the equivalent wind speed is less than 11 mph and when the speed is 11 mph or higher, as well as 7 mph for the case of sitting outside. However, it is difficult to say that the plan achieves a wind comfort level that increases people's willingness to use sustainable transportation modes because net effects in both wind conditions are not significant. In addition, the four comfort measures do not provide at least moderate associations with all of the measures of willingness to use sustainable transportation modes.

CHAPTER 8. CONCLUSION

In 1985, spurred by the residents' strong interest in the quality of the built environment and in securing comfort in public open spaces, San Francisco became the first city in North America to adopt a downtown plan, supplemented by a planning code, on ground-level wind currents to mitigate the effects of adverse wind. Since then, the plan has mandated that new developments in the downtown and four additional areas in the Rincon Hill, South of Market, Van Ness, and South Beach neighborhoods, all associated with high density or development potential and substantial outdoor activities, be designed or adopt wind-baffling measures so as to not cause ground-level wind current in excess of 7 mph in places for seating and 11 mph in those for walking for no more than ten percent of the time year round, between 7 am and 6 pm, to minimize potential discomfort generated by excessive ground-level wind currents; and 26 mph for no more than one hour per year to secure pedestrian safety.

The previous chapters of this dissertation have investigated whether San Francisco's plan on ground-level wind currents made the city's public open spaces more comfortable and what its impact is on use of sustainable transportation modes. More specifically, Chapter 2 provided a review of vernacular urban form and literature on wind and the city. Chapter 3 introduced the contexts of San Francisco and the details of its wind planning. Chapter 4 presented methodology. Chapter 5 through Chapter 7 explored the three research sub-questions, which are:

- Has the plan changed San Francisco's urban form so as to provide a more wind-comfortable environment?
- Are the wind speed criteria stipulated in the plan effective determinants of outdoor comfort in San Francisco?
- Does the plan achieve a wind comfort level that would increase the residents' willingness to use sustainable transportation modes?

In this concluding chapter, the findings from the Chapters 5, 6, and 7 are briefly summarized. This chapter also provides policy suggestions, and discusses the limitations and contributions of this dissertation research.

8.1 Summary of Findings

First, San Francisco's wind planning, first implemented in 1985, has changed the city's urban form so as to provide a more wind comfortable environment. Through a series of simulations using the boundary layer wind tunnel and comparing the wind speed ratios at 318 locations in the selected sites of Yerba Buena, Van Ness, Civic Center, and Mission Bay North in the 1985 and 2013 urban form conditions, it was discovered that the overall mean wind speed ratio dropped by 22 percent from 0.279 in 1985 to 0.218 in 2013. It means that the urban forms of the four sites have been changed so that the expected actual ground-level wind speeds have decreased by the same rate. However, there still exist a number of excessively windy places in San Francisco that are associated with specific urban form conditions, including direct exposure of street orientation

to the prevailing (west) wind, high-rise building façades that directly meet the ground, and continuous street walls.

Second, through on-site surveys and microclimate measurements, it was discovered that wind speed significantly affects people's perceived outdoor comfort and that 11 mph is an effective criterion that determines outdoor comfort in San Francisco. Significant differences are found in the frequency distributions of people's responses to all of the four comfort measures, which are thermal sensation, wind sensation, wind preference, and overall comfort. Also, the net effects of equivalent wind speed on the comfort measures are strong when the speed is less than 11 mph but become weaker when the speed is 11 mph or higher, meaning that there exists a difference in how much wind determines comfort between the two wind conditions. However, a wide range of dimensions on how people perceive wind and comfort exists, including adaptation, surrender, and avoid, which makes it difficult to judge the effectiveness easily.

Third, the research findings suggest that San Francisco's wind planning does not achieve a wind comfort level that would increase people's willingness to use sustainable transportation modes. It was found that higher wind levels discourage people to wait at transit stop with no shelter, to bike, to walk outside, or to sit outside. Also, significant differences with regard to people's willingness to use sustainable transportation modes exist between when the equivalent wind speed is less than 11 mph and when it is 11 mph or higher. However, the net effects of equivalent wind speed in both wind conditions were not statistically significant, indicating that the criterion does not successfully determine whether people are comfortable enough to be willing to use sustainable transportation modes. Although the criterion was not originally developed to consider the use of sustainable transportation modes, it can be suggested that the criterion can be revised.

8.2 Policy Suggestions

Four policy suggestions result from the research. First, the wind planning of San Francisco should be revised so as to more reflect the unique conditions of the city's climate, topography, and perceived outdoor comfort by engaging residents' participation to listen to their diverse perspectives on wind. Although the current wind planning has contributed to making the city more wind-comfortable, whether the comfort criteria, which include wind speed levels and time constraints suggested by studies carried out in other parts of the world, well-responds to the environmental conditions of San Francisco is at question. Additionally, its uniform application throughout the designated areas of the city may not be able to address the diversity in the residents' attitudes and perspectives on wind.

Second, the wind planning of San Francisco should be revised in a way that it incorporates more tangible guidelines and principles for urban designers and architects, perhaps in the form of Form-Based Codes. The current measures stipulated in the Downtown Area Plan and Planning Code wholly rely on the three wind speed criteria and time constraints. However, as found in this study, the windiest places in San Francisco are typically associated with specific urban form conditions, which are direct exposure of street orientation to the prevailing (west) wind, high-rise building façades that directly meet the ground, and continuous street wall. In this sense, San

Francisco's wind planning should be revised in a way that directly addresses the physical forms of blocks, streets, open spaces, and buildings; so that it can be more conveniently applied in the design practice.

Third, planners and policy makers must look beyond the current spatial scope of San Francisco's wind planning, meaning that the plan should be adopted in additional parts of the city. Although there are several spontaneous efforts to create wind-comfortable environments, as exemplified in the case of Treasure Island Redevelopment Plan, it is difficult to expect that such action would happen in other parts of the city. Also, as found in this research, substantial parts of Van Ness and Civic Center neighborhoods, where only a limited number of parcels are under the implementation of the wind planning, still remain excessively windy but are without any plans or possibility to mitigate the adverse effects of wind. The list of such windy places and their wind environment conditions should be identified by collaboration between planners and urban climatologists. The places should be "fixed" by incorporating appropriate measures. Otherwise, places like Yerba Buena Lane in the Financial District, Pine Street in Van Ness, and Fulton Street in Civic Center will keep upsetting their users.

Fourth, planners and policy makers also need to consider studying wind planning cases in other contexts. For example, wind planning in Wellington, New Zealand, which also has been implemented since 1985, has made the city more wind-comfortable and safer (Donn, 2011). The city has not only provided a pragmatic guide on building form examples that should be avoided or promoted to urban designers and architects (Wellington City Council, 2000), but also constructed 90 micro wind shelters for pedestrians in major downtown locations. It also affected many building designs of the city to make a more wind-comfortable urban environment, and gained supported by the local community and architects who had a clear understanding that "badly designed buildings can make the wind significantly worse" (Donn, 2011, p. 13). The Wellington case will provide valuable lessons and implications which San Francisco can learn from.

8.3 Limitations and Contributions of Research

There are several limitations of this research. First, when comparing the wind speed ratios of the four selects sites in 1985 and 2013 in the wind tunnel study, wind speed was used instead of calculating equivalent wind speed. This was inevitable since the original anemometer, which collects both wind speed and standard deviation, installed in the tunnel was not available, and a different anemometer, which does not perform well in collecting standard deviation, had to be used. However, the wind speed data measured by the alternative anemometer is highly reliable. Also, since the main purpose was focused on comparing the wind environment in 1985 and 2013 such shortcoming do not generate any critical problems.

Second, fewer field studies were carried out than originally anticipated, thus fewer survey samples were collected in the late fall and winter than in summer and early fall because of the frequent wet days during the later periods. Although the variables in the existing dataset show normal distributions and cover a very wide range of values that represent diverse weather

conditions, it would have been better if more samples could have been collected in the final months, so that every month of the six month period was evenly represented.

Third, measuring the impact of wind on public transit use was based primarily on user reports rather than measures of user behavior such as number of transit passengers per hour on windy days versus quiet days. In this sense, a future study can incorporate actual transit data, such as number of riders on various transit lines or stops, under various weather conditions and cross-check with user-based data to generate more robust findings on the relationship between wind and the use of sustainable transportation modes.

Lastly, many of the variables collected in the survey were ordinal scale form. A variety of statistical modeling methods that are suitable for this type of variable have been developed and are widely used. However, it would have been better if the variables were interval scale or close to being interval scale so that other statistical methods, which are more convenient to apply and interpret, could be incorporated when analyzing the data collected from the field study.

The research makes several significant contributions. First, it evaluates an urban policy that has been in effect for almost 30 years and benchmarked by a number of North American cities. The findings of this research provides important feedback to the City of San Francisco and other cities that have implemented planning codes on wind and may encourage refinement of the codes and decisions to apply them to additional parts of the city.

Second, this research seeks to reinforce the interdisciplinary bridging between city planning and urban climatology fields. It combines qualitative planning approaches with quantitative scientific methods in solving urban problems and issues. Importantly, it expands urban design knowledge about how built form impacts ground-level wind and hence outdoor thermal comfort.

8.4 Concluding Remarks

How can wind impacts on pedestrian comfort be regulated? We might not have the best answer yet, but San Francisco's wind planning experience since 1985 clearly shows that it has been a meaningful effort. It also calls for a more climate-based approach in planning and design research and practice in other parts of the country and the world to create a more comfortable, livable, sustainable, and vibrant urban environment.

A wide range of solutions must be studies for cities in varied climate regions. Cities and regions should not only study and develop their own climate-based ways to make a more climate-responsive city but also vigorously evaluate their effectiveness. They should also share their experience with others who have similar goals. Higher education in urban design, planning, architecture, and landscape architecture should expand their curriculum on climate-based design approaches. Collaboration and cooperation between urban design, urban climatology, and many other relevant fields of expertise is crucial, not to mention the participation of the public.

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APPENDICES

Appendix A. Annual and Monthly Average Wind Speeds of Major U.S. Cities[a]

Rank	City	Ave	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Boston, MA	12.3	13.7	13.6	13.6	13.0	12.0	11.2	11.0	10.8	11.2	11.8	12.5	13.3
2	Oklahoma City, OK	12.2	12.5	13.1	14.3	14.2	12.5	11.8	10.8	10.4	10.8	11.8	12.3	12.3
3	Wichita, KS	12.2	11.9	12.3	13.8	14.0	12.3	12.2	11.2	11.1	11.6	11.8	12.1	11.7
4	Milwaukee, WI	11.5	12.6	12.2	12.7	12.8	11.5	10.4	9.7	9.5	10.4	11.4	12.4	12.2
5	Dallas-Fort Worth, TX	10.7	11.0	11.7	12.6	12.4	11.1	10.7	9.7	8.9	9.3	9.7	10.7	10.8
6	Kansas City, MO	10.6	11.1	11.1	12.3	12.3	10.4	9.9	9.2	8.8	9.5	10.5	11.2	10.9
7	Minneapolis-St. Paul, MN	10.5	10.5	10.4	11.3	12.2	11.1	10.4	9.4	9.2	10.0	10.6	11.0	10.4
8	Cleveland, OH	10.5	12.2	11.8	12.0	11.5	10.0	9.2	8.6	8.2	8.9	9.9	11.7	12.0
9	Chicago, IL	10.3	11.6	11.3	11.8	11.9	10.5	9.3	8.4	8.2	8.9	10.0	11.1	11.0
10	Tulsa, OK	10.2	10.3	10.7	11.9	11.9	10.6	9.9	9.3	8.8	9.1	9.6	10.3	10.1
11	Detroit, MI	10.2	11.8	11.3	11.4	11.3	10.0	9.1	8.5	8.1	8.4	9.7	11.0	11.3
12	St. Louis, MO	9.6	10.6	10.8	11.6	11.3	9.4	8.8	8.0	7.6	8.2	8.9	10.2	10.3
13	Indianapolis, IN	9.6	10.9	10.8	11.6	11.2	9.6	8.5	7.5	7.2	7.9	8.9	10.5	10.5
14	Philadelphia, PA	9.5	10.3	10.9	11.3	10.8	9.5	8.8	8.2	8.0	8.3	8.8	9.6	10.0
15	Washington, D.C.	9.4	10.0	10.3	10.9	10.5	9.3	8.9	8.3	8.1	8.3	8.7	9.4	9.6
16	Miami, FL	9.2	9.5	10.0	10.4	10.5	9.5	8.3	7.9	7.9	8.2	9.2	9.7	9.1
17	Las Vegas, NV	9.1	7.3	8.4	10.0	11.0	10.8	10.7	9.9	9.5	8.9	8.1	7.7	7.3
18	New York, NY	9.1	10.4	10.6	10.8	10.1	8.7	8.0	7.5	7.3	7.9	8.6	9.6	9.9
19	Atlanta, GA	9.1	10.4	10.6	10.9	10.1	8.7	8.1	7.7	7.3	8.1	8.5	9.1	9.8
20	Omaha, NE	9.1	9.9	9.2	10.5	10.2	8.9	8.3	7.5	7.6	8.6	9.0	9.7	9.8
21	San Antonio, TX	9.1	8.8	9.3	10.1	10.1	9.8	9.7	9.1	8.4	8.3	8.3	8.6	8.4
22	Pittsburgh, PA	9.0	10.4	10.3	10.5	10.2	8.7	8.0	7.3	6.8	7.3	8.3	9.5	10.1
23	Albuquerque, NM	8.9	8.0	8.8	9.9	10.7	10.5	9.8	8.9	8.1	8.4	8.2	7.9	7.6
24	El Paso, TX	8.8	8.3	9.1	10.9	11.0	10.3	9.3	8.3	7.7	7.6	7.5	8.0	7.9
25	Memphis, TN	8.8	10.0	10.1	10.7	10.2	8.8	7.9	7.5	6.9	7.5	7.7	9.0	9.6
26	Seattle, WA	8.8	9.5	9.3	9.4	9.3	8.9	8.6	8.1	7.8	8.0	8.3	9.0	9.6
27	San Francisco, CA	8.7	6.7	7.5	8.5	9.5	10.4	10.9	11.2	10.5	9.1	7.6	6.3	6.5
28	Baltimore, MD	8.7	9.2	9.7	10.6	10.1	8.7	8.2	7.5	7.4	7.6	7.9	8.6	8.8
29	Denver, CO	8.7	8.7	8.7	9.6	10.0	9.3	8.8	8.3	8.1	8.0	7.8	8.3	8.4
30	Austin, TX	8.5	8.8	9.1	9.9	9.7	9.2	8.6	8.0	7.5	7.3	7.5	8.2	8.4
31	Tucson, AZ	8.3	7.9	8.1	8.6	8.9	8.8	8.7	8.4	7.9	8.3	8.2	8.1	7.8
32	Columbus, OH	8.3	9.8	9.6	10.1	9.6	8.1	7.2	6.5	6.2	6.4	7.4	9.1	9.4
33	Louisville, KY	8.3	9.5	9.5	10.1	9.7	8.0	7.4	6.8	6.4	6.8	7.2	8.9	9.1
34	Tampa, FL	8.3	8.6	9.1	9.4	9.2	8.6	7.9	7.1	6.9	7.6	8.3	8.2	8.3
35	New Orleans, LA	8.2	9.3	9.8	9.9	9.4	8.1	6.8	6.1	5.9	7.3	7.6	8.7	9.0
36	Nashville, TN	8.0	9.1	9.3	9.9	9.2	7.6	7.0	6.5	6.2	6.5	6.8	8.4	8.9
37	Portland, OR	7.9	9.9	9.2	8.3	7.4	7.1	7.2	7.6	7.1	6.5	6.5	8.5	9.6
38	Jacksonville, FL	7.8	8.1	8.7	9.1	8.5	7.9	7.7	7.0	6.7	7.5	7.7	7.6	7.6
39	Sacramento, CA	7.8	6.9	7.3	8.3	8.6	9.0	9.6	8.9	8.4	7.4	6.4	5.9	6.4
40	Houston, TX	7.6	8.1	8.5	9.0	9.0	8.1	7.3	6.6	6.1	6.5	6.9	7.6	7.7
41	Charlotte, NC	7.4	7.8	8.2	8.8	8.6	7.5	6.9	6.6	6.4	6.6	6.7	6.9	7.3
42	San Diego, CA	7.0	6.0	6.6	7.5	7.8	7.9	7.8	7.5	7.4	7.1	6.5	5.9	5.6
43	San Jose, CA	6.9	5.4	6.6	7.0	8.0	8.2	8.4	7.7	7.4	6.5	5.8	5.3	6.0
44	Phoenix, AZ	6.2	5.3	5.8	6.6	6.9	7.0	6.7	7.1	6.6	6.3	5.8	5.3	5.1
45	Long Beach, CA	6.2	5.2	5.8	6.5	7.2	7.0	6.9	6.8	6.6	6.2	5.6	5.1	5.0
46	Los Angeles, CA	5.1	5.5	5.8	5.9	5.7	5.5	4.8	4.4	4.3	4.5	4.6	5.2	5.2

Notes: a. Cities with population over 300,000.

Source: National Climatic Data Center (http://www.ncdc.noaa.gov/)

Appendix B. San Francisco Planning Code on Ground-Level Wind Currents

SEC. 148. REDUCTION OF GROUND-LEVEL WIND CURRENTS IN C-3 DISTRICTS.

(a) **Requirement and Exception.** In C-3 Districts, buildings and additions to existing buildings shall be shaped, or other wind-baffling measures shall be adopted, so that the developments will not cause ground-level wind currents to exceed, more than 10 percent of the time year round, between 7:00 a.m. and 6:00 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of substantial pedestrian use and seven m.p.h. equivalent wind speed in public seating areas.

When preexisting ambient wind speeds exceed the comfort level, or when a proposed building or addition may cause ambient wind speeds to exceed the comfort level, the building shall be designed to reduce the ambient wind speeds to meet the requirements. An exception may be granted, in accordance with the provisions of Section 309, allowing the building or addition to add to the amount of time that the comfort level is exceeded by the least practical amount if (1) it can be shown that a building or addition cannot be shaped and other wind-baffling measures cannot be adopted to meet the foregoing requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question, and (2) it is concluded that, because of the limited amount by which the comfort level is exceeded, the limited location in which the comfort level is exceeded, or the limited time during which the comfort level is exceeded, the addition is insubstantial.

No exception shall be granted and no building or addition shall be permitted that causes equivalent wind speeds to reach or exceed the hazard level of 26 miles per hour for a single hour of the year.

(b) **Definition.** The term "equivalent wind speed" shall mean an hourly mean wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

(c) **Guidelines.** Procedures and Methodologies for implementing this section shall be specified by the Office of Environmental Review of the Department of City Planning.

SEC. 243. VAN NESS SPECIAL USE DISTRICT.

(c) **Controls.** All provisions of the City Planning Code applicable to an RC-4 District shall apply except as otherwise provided in this Section.

(10) **Reduction of Ground Level Wind Currents.**

(A) New buildings and additions to existing buildings shall be shaped, or other wind baffling measures shall be adopted, so that the development will not cause year-round ground level wind currents to exceed, more than 10 percent of the time, between 7:00 a.m. and 6:00 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of pedestrian use and seven m.p.h. equivalent wind speed in public seating areas. When pre-existing ambient wind speeds exceed the comfort levels specified above, the building shall be designed to reduce the ambient wind speeds in efforts to meet the goals of this requirement.

(B) An exception to this requirement may be permitted but only if and to the extent that the project sponsor demonstrates that the building or addition cannot be shaped or wind baffling measures cannot be adopted without unduly restricting the development potential of the building site in question.

(i) The exception may permit the building or addition to increase the time that the comfort level is exceeded, but only to the extent necessary to avoid undue restriction of the development potential of the site.

(ii) Notwithstanding the above, no exception shall be allowed and no building or addition shall be permitted that causes equivalent wind speeds to reach or exceed the hazard level of 26 m.p.h. for a single hour of the year.

For the purposes of this Section, the term "equivalent wind speed" shall mean an hourly wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

SEC. 249.1. FOLSOM AND MAIN RESIDENTIAL/COMMERCIAL SPECIAL USE DISTRICT..

(b) **Controls.** The following zoning controls are applicable in the Residential/Commercial Special Use District.

(1) **Reduction of Ground-Level Wind Currents.**

(A) **Requirement.** New buildings and additions to existing buildings shall be shaped, or other wind-baffling measures shall be adopted, so that the developments will not cause ground-level wind currents to exceed, more than 10 percent of the time year-round, between 7:00 a.m. and 6:00 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of substantial pedestrian use and seven m.p.h. equivalent wind speed in public seating areas. The term "equivalent wind speed" shall mean an hourly mean wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

When preexisting ambient wind speeds exceed the comfort level, or when a proposed building or addition may cause ambient wind speeds to exceed the comfort level, the building shall be designed to reduce the ambient wind speeds to meet the requirements. The provisions of this Section 249.1(b)(3) shall not apply to any buildings or additions to existing buildings for which a draft EIR has been published prior to January 1, 1985.

(B) **Exception.** The Zoning Administrator may allow the building or addition to add to the amount of time the comfort level is exceeded by the least practical amount if (1) it can be shown that a building or addition cannot be shaped and other wind-baffling measures cannot be adopted to meet the foregoing requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question, and (2) it is concluded that, because of the limited amount by which the comfort level is exceeded, the limited location in which the comfort level is exceeded, or the limited time during which the comfort level is exceeded, the addition is insubstantial.

The Zoning Administrator shall not grant an exception and no building or addition shall be permitted that causes equivalent wind speeds to reach or exceed the hazard level of 26 miles per hour for a single hour of the year.

(C) **Procedures.** Procedures and methodologies for implementing this Section shall be specified by the Office of Environmental Review of the Planning Department.

SEC. 263.11. SPECIAL HEIGHT EXCEPTIONS: SOUTH OF MARKET RSD 40-X/85-B HEIGHT DISTRICT.

(c) **Reduction of Ground Level Wind Currents.** New buildings or additions subject to this Section shall be shaped, or other wind baffling measures shall be adopted, so that the development will not cause ground level wind currents to exceed, more than 10 percent of the time year-round, between 7:00 a.m. and 6:00 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of substantial pedestrian use and seven m.p.h. equivalent wind speed in public seating areas. When pre-existing ambient wind speeds exceed the comfort level, the building or addition shall be designed to reduce the ambient wind speeds to meet the requirements.

If it is shown that a building or addition cannot be shaped or wind baffling measures cannot be adopted to meet the foregoing requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question, and/or it is concluded that, because of the limited amount by which the comfort level is exceeded, the limited location in which the comfort level is exceeded, the limited time during which the comfort level is exceeded, or the addition is insubstantial, an exception may be granted as part of the conditional use process, allowing the building or addition to add to the amount of time that the comfort level is exceeded by the least practical amount.

No exception shall be allowed and no building or addition shall be permitted that causes equivalent wind speeds to reach or exceed the hazard level of 26 miles per hour for a single hour of the year.

For the purposes of this Section, the term "equivalent wind speed" shall mean an hourly mean wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

SEC. 825. DTR – DOWNTOWN RESIDENTIAL DISTRICTS.

(d) **Reduction of Ground Level Wind Currents.**

(1) **Requirement.** New buildings and additions to existing buildings shall be shaped, or other wind-baffling measures shall be adopted, so that the developments will not cause ground-level wind currents to exceed, more than 10 percent of the time year-round, between 7:00 a.m. and 6:00 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of substantial pedestrian use and seven m.p.h. equivalent wind speed in public seating areas. The term "equivalent wind speed" shall mean an hourly mean wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

(2) When preexisting ambient wind speeds exceed the comfort level, or when a proposed building or addition may cause ambient wind speeds to exceed the comfort level, the building shall be designed to reduce the ambient wind speeds to meet the requirements.

(3) **Exception.** The Zoning Administrator may allow the building or addition to add to the amount of time the comfort level is exceeded by the least practical amount if (i) it can be shown that a building or addition cannot be shaped and other wind-baffling measures cannot be adopted to meet the foregoing requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question, and (ii) the Zoning Administrator concludes that, because of the limited amount by which the comfort level is exceeded, the addition is insubstantial. The Zoning Administrator shall not grant an exception, and, no building or addition shall be permitted that causes equivalent winds speeds to reach or exceed the hazard level of 26 miles per hour for a single hour of the year.

(4) **Procedures.** Procedures and methods for implementing this Section shall be specified by the Environmental Review Officer of the Planning Department.

Appendix C. Wind Speed Criteria from Studies Used in San Francisco's Criteria

1. Davenport (1972)

Activity	Areas Applicable	Relative Comfort*							
		Perceptible		Tolerable		Unpleasant		Dangerous	
		m/s	mph	m/s	mph	m/s	mph	m/s	mph
Walking fast	Sidewalks	9.3	20.8	12.0	26.8	17.0	38.0	18.9	42.3
Strolling, skating	Parks, entrances, skating rinks	6.7	15.0	9.3	20.8	12.0	26.8	18.9	42.3
Standing, siting – short exposure	Parks, plazas	4.4	9.8	6.7	15.0	9.3	20.8	18.9	42.3
Standing, sitting – long exposure	Outdoor restaurants, bandshell theaters	2.5	5.6	4.4	9.8	6.7	15.0	18.9	42.3
Acceptability Criteria				Less than once/week		Less than once/week		Less than once/week	

* Beaufort scale was originally used but has been converted to mean values.

2. Penwarden (1973, p. 266)

Perception	Mean Wind Speed*	
	m/s	mph
Onset of discomfort, when hair and clothes flap and dust and loose paper begin to be blown around	5	11
Definitely unpleasant, with the wind exerting a considerable force on the body	10	22
Dangerous, with the probability of people being blown over, particularly if they are old or infirm	20	45

* Beaufort scale was originally used but has been converted.

3. Penwarden and Wise (1975)

Reaction	Mean Wind Speed*		Probability
	m/s	mph	
Condition acceptable or no remedial action required	5	11	20% or less the time
Sufficiently uncomfortable to prompt remedial reaction	20	45	20% or more the time

* Beaufort scale was originally used but has been converted.

4. Hunt et al. (1976, p. 25)

Wind Type	Activity	Should be Less than	
		m/s	mph
Steady uniform wind	For comfort and little effect on performance	6	13
	For east of walking	13 – 15	29 - 34
	For safety of walking	20 – 30	45 - 67
Non-uniform winds (wind speed varies by 70% over a distance less than 2m)	To avoid momentary loss of balance and to be able to walk straight	9	20
	For safety (for elderly people this criterion may be too high)	13 – 20	29 - 45
Gusty winds (in terms of equivalent wind speed, $U_{eqv} = \bar{U}(1 + 3I)$)	For comfort and little effect on performance	6	13
	Most performance unaffected	9	20
	Control of walking	15	34
	Safety of walking	20	45

5. Melbourne (1978, p. 245)

Activity	Maximum Wind Speed		Maximum Gust Wind Speed*		Probability
	m/s	mph	m/s	mph	
Stationary, long exposure	5	11	10.0	22	once/year
Stationary, short exposure	6.5	15	13.0	29	once/year
Walking	8	18	16.0	36	once/year
Unacceptable for any activity	11.5	26	23.0	51	once/year

* Gust wind speed was taken as $U_{eqv} = \bar{U}(1 + 3.5I)$.

Appendix D. Metabolic Rates for Typical Tasks

Activity	Metabolic Rate		
	Met Units	W/m^2	$Btu/h \cdot ft^2$
Resting			
Sleeping	0.7	40	13
Reclining	0.8	45	15
Seated, quiet	1.0	60	18
Standing, relaxed	1.2	70	22
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	37
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	48
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	70
Office Activities			
Reading, seated	1.0	55	18
Writing	1.0	60	18
Typing	1.1	65	20
Filing, seated	1.2	70	22
Filing, standing	1.4	80	26
Walking about	1.7	100	31
Lifting/packaging	2.1	120	39
Driving/Flying			
Automobile	1.0 – 2.0	60 – 115	18 – 37
Aircraft, routine	1.2	70	22
Aircraft, instrument landing	1.8	105	33
Aircraft, combat	2.4	140	44
Heavy vehicle	3.2	185	59
Miscellaneous Occupational Activities			
Cooking	1.6 – 2.0	95 – 115	29 – 37
House cleaning	2.0 – 3.4	115 – 120	37 – 63
Seated, heavy limb movement	2.2	130	41
Machine work			
Sawing (table saw)	1.8	105	33
Light (electrical industry)	2.0 – 2.4	115 – 140	37 – 44
Heavy	4.0	235	74
Handling 50 kg (100 lb) bags	4.0	235	74
Pick and shovel work	4.0 – 4.8	235 – 280	74 – 88
Miscellaneous Leisure Activities			
Dancing, social	2.4 – 4.4	140 – 255	44 – 81
Calisthenics/exercise	3.0 – 4.0	175 – 235	55 – 74
Tennis, single	3.6 – 4.0	210 – 270	66 – 74
Basketball	5.0 – 7.6	290 – 440	90 – 140
Wrestling, competitive	7.0 – 8.7	410 – 505	130 – 160

Source: American Society of Heating, Refrigerating, and Air-Conditioning Engineers (2010, p. 15)

Appendix E. Clothing Insulation Values for Various Garments and Typical Ensembles

Various Garments

Garment Description	I_{cl} (clo)	Garment Description	I_{cl} (clo)
Underwear		**Dress and Skirts**	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick)	0.27
Half-slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20	**Sweaters**	
Footwear		Sleeveless vest (thin)	0.13
Ankle-length athletic socks	0.02	Sleeveless vest (thick)	0.22
Pantyhose/stockings	0.02	Long-sleeve (thin)	0.25
Sandals/thongs	0.02	Long-sleeve (thick)	0.36
Shoes	0.02	**Suit Jackets and Vests**	
Slippers (quilted, pile lined)	0.03	Sleeveless vest (thin)	0.10
Calf-length socks	0.03	Sleeveless vest (thick)	0.17
Knee socks (thick)	0.06	Single-breasted (thin)	0.36
Boots	0.10	Single-breasted (thick)	0.44
Shirts and Blouses		Double-breasted (thin)	0.42
Sleeveless/scoop-neck blouse	0.12	Double-breasted (thick)	0.48
Short-sleeve knit sport shirt	0.17	**Sleepwear and Robes**	
Short-sleeve dress shirt	0.19	Sleeveless short gown (thin)	0.18
Long-sleeve dress shirt	0.25	Sleeveless long gown (thin)	0.20
Long-sleeve flannel shirt	0.34	Short-sleeve hospital gown	0.31
Long-sleeve sweatshirt	0.34	Short-sleeve short robe (thin)	0.34
Trousers and Coveralls		Short-sleeve pajamas (thin)	0.42
Short shorts	0.06	Long-sleeve long gown (thick)	0.46
Walking shorts	0.08	Long-sleeve short wrap robe (thick)	0.48
Straight trousers (thin)	0.15	Long-sleeve pajamas (thick)	0.57
Straight trousers (thick)	0.24	Long-sleeve long wrap robe (thick)	0.69
Sweatpants	0.28		
Overalls	0.30		
Coveralls	0.49		

Source: American Society of Heating, Refrigerating, and Air-Conditioning Engineers (2010, p. 19)

Typical Ensembles

Clothing Description	Garments Included[a]	I_{cl} (clo)
Trousers	1. Trousers, short-sleeve shirt	0.57
	2. Trousers, long-sleeve shirt	0.61
	3. #2 plus suit jacket	0.96
	4. #2 plus suit jacket, vest, T-shirt	1.14
	5. #2 plus long-sleeve sweater, T-shirt	1.01
	6. #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7. Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8. Knee-length skirt, long-sleeve shirt, full slip	0.67
	9. Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10. Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11. Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12. Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13. Long-sleeve coveralls, T-shirt	0.72
	14. Overalls, long-sleeve shirt, T-shirt	0.89
	15. Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16. Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17. Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

Notes: a. All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and briefs or panties. All skirt/dress clothing ensembles include pantyhose and no additional socks.

Source: American Society of Heating, Refrigerating, and Air-Conditioning Engineers (2010, p. 18)

Appendix F. Wind Speed Data by Location and Maps

1. Yerba Buena

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
1	Street corner	1.30	0.461	0.29	0.103	-78
2	Street corner	0.28	0.099	0.68	0.241	+143
3	Street corner	0.24	0.085	0.23	0.082	-4
4	Street corner	0.77	0.273	0.86	0.305	+12
5	Street corner	0.25	0.089	0.46	0.163	+84
6	Street corner	0.98	0.347	0.41	0.145	-58
7	Street corner	1.66	0.588	1.10	0.390	-34
8	Street corner	1.23	0.436	1.01	0.358	-18
9	Street corner	1.11	0.393	0.90	0.319	-19
10	Street corner	1.17	0.415	0.90	0.319	-23
11	Street corner	1.14	0.404	0.30	0.106	-74
12	Street corner	0.30	0.106	0.21	0.075	-30
13	Street corner	0.34	0.120	0.68	0.241	+100
14	Street corner	0.45	0.159	0.40	0.142	-11
15	Street corner	0.25	0.089	0.36	0.128	+44
16	Street corner	1.03	0.365	0.19	0.067	-82
17	Street corner	0.46	0.163	0.66	0.234	+44
18	Transit stop	0.84	0.298	0.28	0.099	-67
19	Mid-block	0.36	0.128	0.22	0.078	-39
20	Mid-block	0.44	0.156	0.25	0.089	-43
21	Transit stop	1.28	0.454	0.77	0.273	-40
22	Mid-block	0.72	0.255	0.63	0.224	-12
23	Mid-block	0.41	0.145	0.40	0.142	-2
24	Mid-block	0.39	0.138	0.57	0.202	+46
25	Mid-block	0.85	0.301	0.39	0.138	-54
26	Mid-block	1.17	0.415	0.58	0.206	-50
27	Mid-block	0.23	0.082	0.46	0.163	+100
28	Mid-block	1.17	0.415	0.20	0.071	-83
29	Mid-block	0.48	0.170	0.31	0.110	-35
30	Mid-block	1.19	0.422	0.27	0.096	-77
31	Mid-block	1.47	0.521	1.09	0.387	-26
32	Mid-block	0.29	0.103	0.92	0.326	+218
33	Mid-block	0.72	0.255	0.38	0.135	-47
34	Transit stop	0.76	0.269	0.68	0.241	-10
35	Mid-block	1.55	0.549	1.67	0.593	+8
36	Mid-block	0.93	0.330	0.83	0.295	-11
37	Mid-block	0.68	0.241	0.38	0.135	-44
38	Mid-block	1.28	0.454	0.22	0.078	-83
39	Mid-block	1.00	0.354	0.47	0.167	-53
40	Mid-block	1.10	0.390	0.19	0.067	-83
41	Mid-block	1.22	0.432	0.28	0.099	-77
42	Mid-block	1.20	0.425	0.26	0.092	-78
43	Street corner	0.18	0.064	0.31	0.110	+72
44	Transit stop	0.87	0.308	0.60	0.213	-31
45	Bicycle lane	0.33	0.117	0.42	0.149	+27
46	Bicycle lane	0.57	0.202	0.48	0.170	-16
47	Bicycle lane	0.40	0.142	0.31	0.110	-22

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
48	Bicycle lane	0.37	0.131	0.24	0.085	-35
49	Bicycle lane	0.32	0.113	0.64	0.227	+100
50	Bicycle lane	0.66	0.234	0.98	0.348	+49
51	Bicycle lane	0.33	0.117	1.07	0.380	+225
52	Bicycle lane	0.30	0.106	0.34	0.121	+13
53	Open space	1.50	0.532	1.34	0.476	-11
54	Open space	1.18	0.418	1.55	0.550	+32
55	Open space	0.53	0.188	1.56	0.554	+195
56	Open space	1.10	0.390	0.75	0.266	-32
57	Open space	0.91	0.322	1.05	0.373	+16
58	Open space	0.91	0.322	0.37	0.131	-59
59	Open space	1.06	0.376	0.35	0.124	-67
60	Open space	0.45	0.159	0.36	0.128	-20
61	Open space	0.57	0.202	0.25	0.089	-56
62	Open space	0.60	0.213	0.41	0.145	-32
63	Open space	0.19	0.067	0.29	0.103	+53
64	Open space	0.82	0.291	0.24	0.085	-71
65	Open space	1.56	0.553	0.29	0.103	-81
66	Open space	1.44	0.510	0.25	0.089	-83
67	Open space	1.52	0.539	1.03	0.366	-32
68	Open space	1.47	0.521	0.35	0.124	-76
69	Open space	1.67	0.592	1.13	0.401	-32
70	Open space	1.61	0.571	0.31	0.110	-81
71	Open space	1.67	0.592	0.92	0.326	-45
72	Open space	1.69	0.599	1.04	0.369	-38

Notes: a. Reference wind speed: 2.82 m/s; b. Reference wind speed: 2.83 m/s

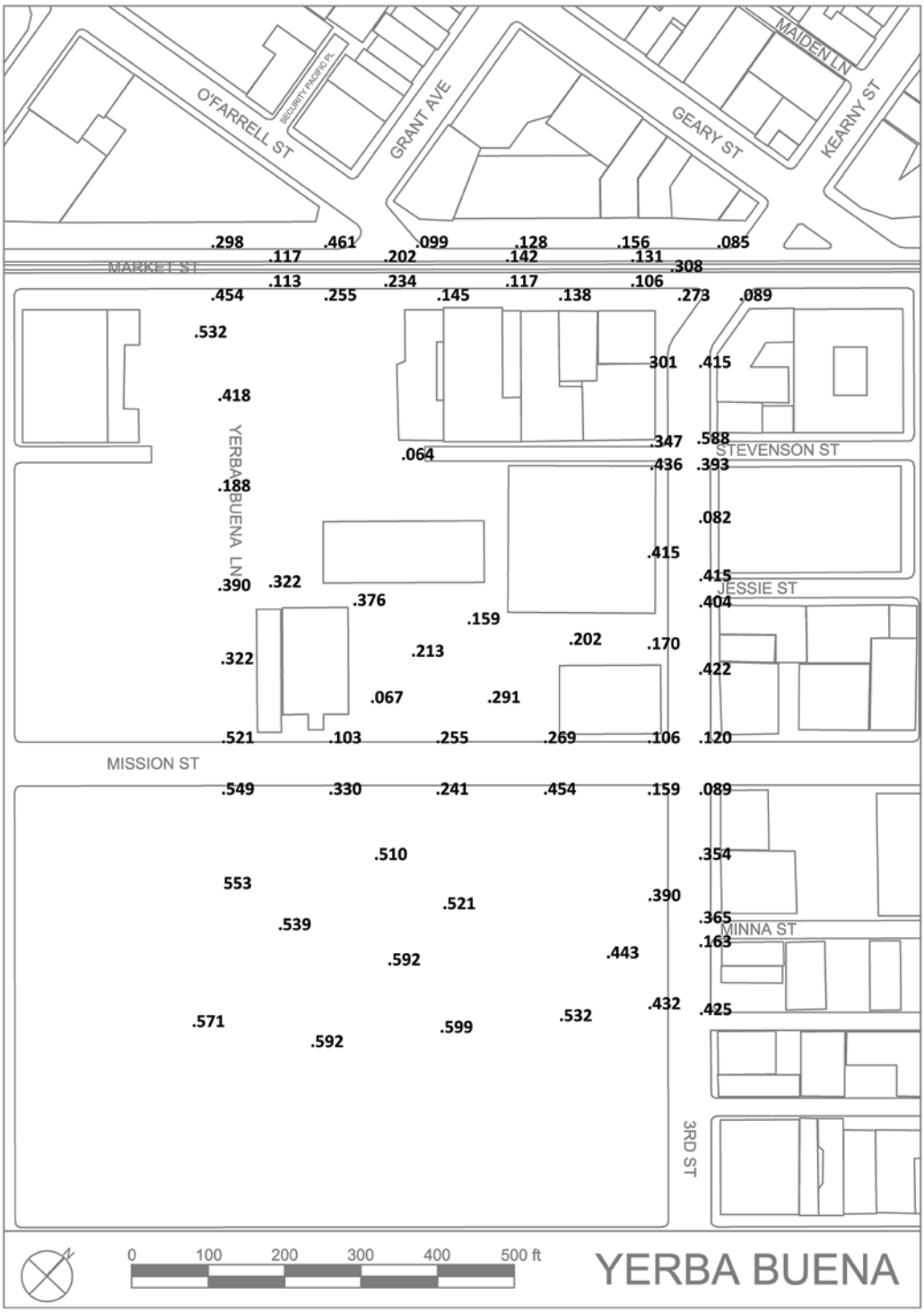

Figure 110. Wind speed ratios in Yerba Buena in 1985.

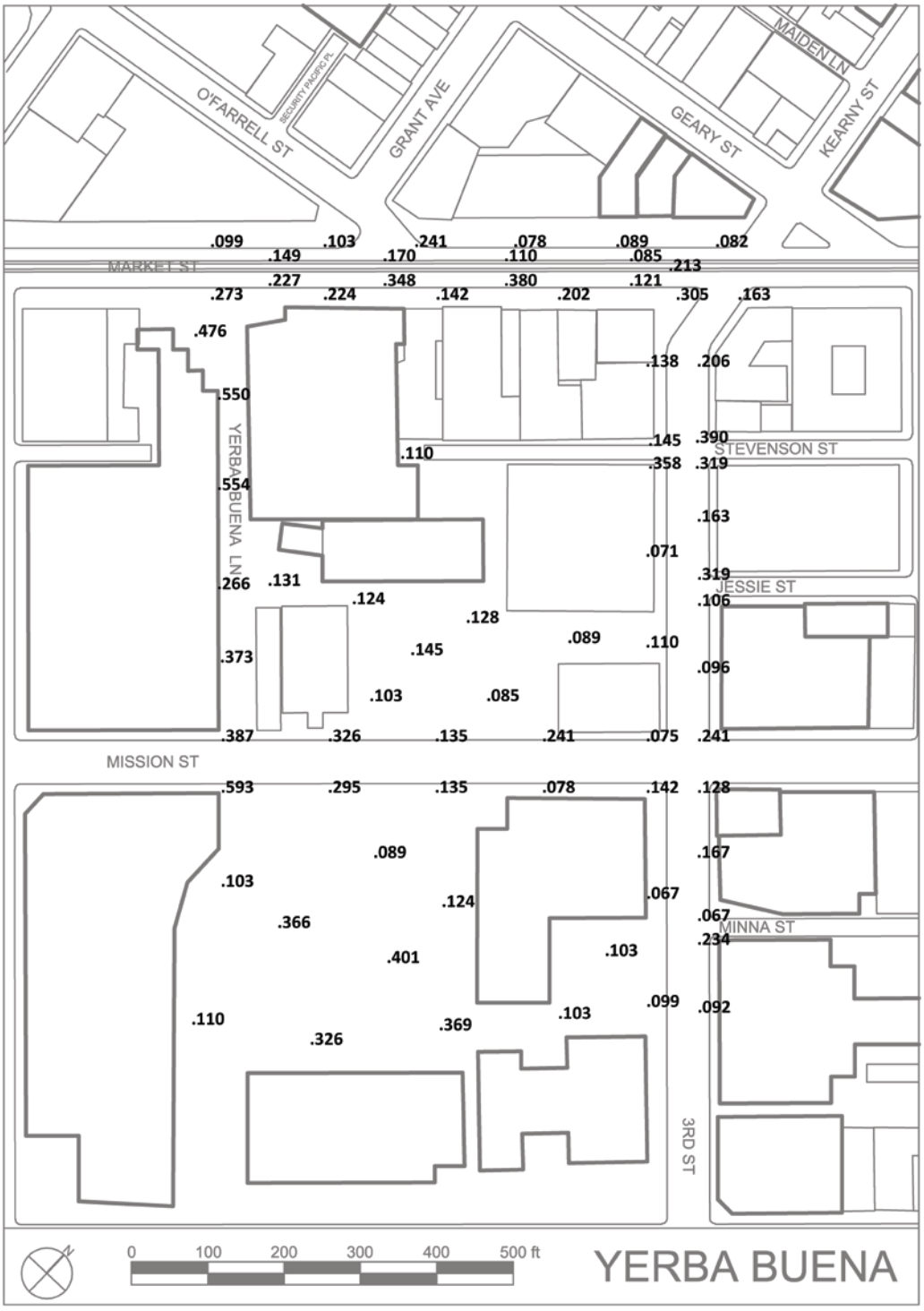

Figure 111. Wind speed ratios in Yerba Buena in 2013.

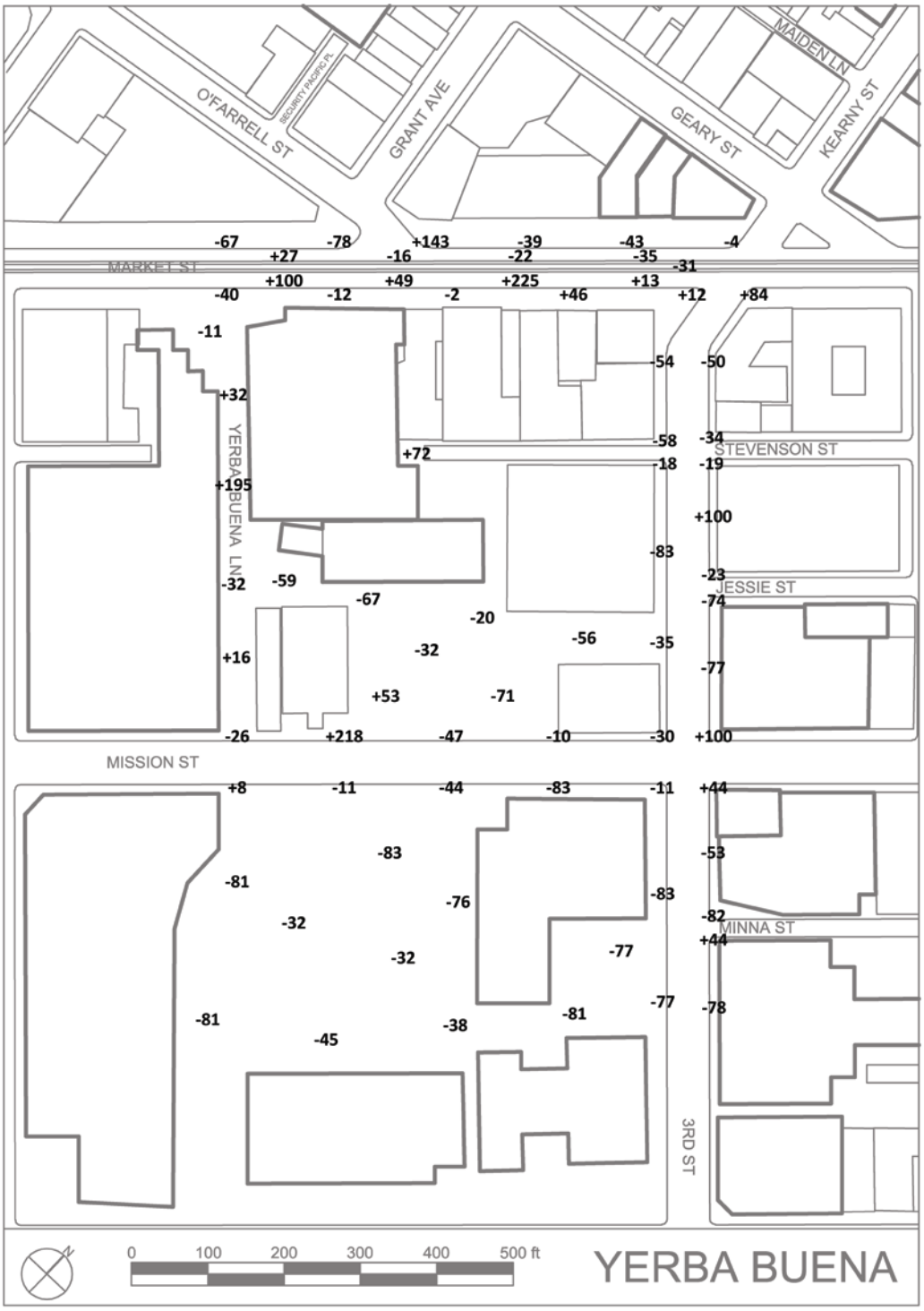

Figure 112. Changes (%) in wind speed ratios in Yerba Buena between 1985 and 2013.

2. Van Ness

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
1	Street corner	0.26	0.092	0.96	0.335	+266
2	Street corner	0.19	0.067	0.22	0.077	+15
3	Street corner	0.78	0.275	0.96	0.335	+22
4	Street corner	1.30	0.458	0.84	0.293	-36
5	Street corner	0.52	0.183	1.03	0.359	+96
6	Street corner	0.40	0.141	0.33	0.115	-18
7	Street corner	1.00	0.352	1.06	0.370	+5
8	Street corner	0.49	0.173	0.91	0.318	+84
9	Street corner	1.10	0.388	0.73	0.255	-34
10	Street corner	0.54	0.190	0.64	0.223	+17
11	Street corner	0.70	0.247	0.41	0.143	-42
12	Street corner	0.66	0.233	0.19	0.066	-71
13	Street corner	0.23	0.081	0.27	0.094	+16
14	Street corner	0.22	0.078	0.22	0.077	-1
15	Street corner	0.88	0.310	0.98	0.342	+10
16	Street corner	0.72	0.254	0.80	0.279	+10
17	Street corner	0.61	0.215	0.47	0.164	-24
18	Street corner	0.45	0.159	0.80	0.279	+76
19	Street corner	0.76	0.268	1.03	0.359	+34
20	Street corner	0.47	0.166	0.75	0.262	+58
21	Street corner	0.27	0.095	0.73	0.255	+168
22	Street corner	0.73	0.257	0.52	0.181	-29
23	Street corner	0.25	0.088	0.25	0.087	-1
24	Street corner	0.18	0.063	0.30	0.105	+65
25	Mid-block	0.94	0.331	0.92	0.321	-3
26	Mid-block	0.64	0.226	0.52	0.181	-20
27	Mid-block	0.78	0.275	0.56	0.195	-29
28	Mid-block	1.22	0.430	0.64	0.223	-48
29	Mid-block	1.27	0.447	1.09	0.380	-15
30	Mid-block	1.11	0.391	0.51	0.178	-55
31	Mid-block	1.58	0.557	1.00	0.349	-37
32	Mid-block	1.09	0.384	0.87	0.304	-21
33	Mid-block	0.17	0.060	0.16	0.056	-7
34	Mid-block	0.24	0.085	0.40	0.140	+65
35	Mid-block	0.47	0.166	0.21	0.073	-56
36	Mid-block	0.49	0.173	0.23	0.080	-54
37	Mid-block	0.87	0.307	0.72	0.251	-18
38	Mid-block	1.39	0.490	0.74	0.258	-47
39	Mid-block	1.37	0.483	1.41	0.492	+2
40	Mid-block	0.51	0.180	0.20	0.070	-61
41	Mid-block	0.95	0.335	1.34	0.468	+40
42	Mid-block	1.48	0.521	1.34	0.468	-10
43	Mid-block	1.49	0.525	1.39	0.485	-8
44	Mid-block	0.70	0.247	0.45	0.157	-36
45	Mid-block	0.17	0.060	0.22	0.077	+28
46	Mid-block	0.22	0.078	0.20	0.070	-10
47	Mid-block	0.22	0.078	0.30	0.105	+35
48	Mid-block	0.14	0.049	0.22	0.077	+56
49	Mid-block	0.93	0.328	0.83	0.290	-12
50	Mid-block	1.88	0.662	1.86	0.649	-2

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
51	Mid-block	1.61	0.567	1.72	0.600	+6
52	Mid-block	0.92	0.324	0.89	0.311	-4
53	Mid-block	0.60	0.211	0.49	0.171	-19
54	Mid-block	1.60	0.564	1.80	0.628	+11
55	Mid-block	1.23	0.433	1.39	0.485	+12
56	Mid-block	0.44	0.155	0.63	0.220	+42
57	Transit stop	0.21	0.074	0.29	0.101	+37
58	Transit stop	0.78	0.275	0.29	0.101	-63
59	Transit stop	0.26	0.092	0.19	0.066	-28
60	Transit stop	0.23	0.081	0.16	0.056	-31
61	Transit stop	1.27	0.447	1.20	0.419	-6
62	Transit stop	0.48	0.169	0.43	0.150	-11
63	Transit stop	1.29	0.455	0.82	0.286	-37
64	Transit stop	0.48	0.169	0.18	0.063	-63
65	Bicycle lane	0.57	0.201	0.55	0.192	-4
66	Bicycle lane	0.53	0.187	0.42	0.147	-22
67	Bicycle lane	0.24	0.085	0.18	0.063	-26
68	Bicycle lane	0.23	0.081	0.25	0.087	+8
69	Bicycle lane	0.21	0.074	0.20	0.070	-6
70	Bicycle lane	0.18	0.063	0.19	0.066	+5
71	Bicycle lane	0.22	0.078	0.31	0.108	+40
72	Bicycle lane	0.20	0.070	0.20	0.070	-1

Notes: a. Reference wind speed: 2.85 m/s; b. Reference wind speed: 2.88 m/s

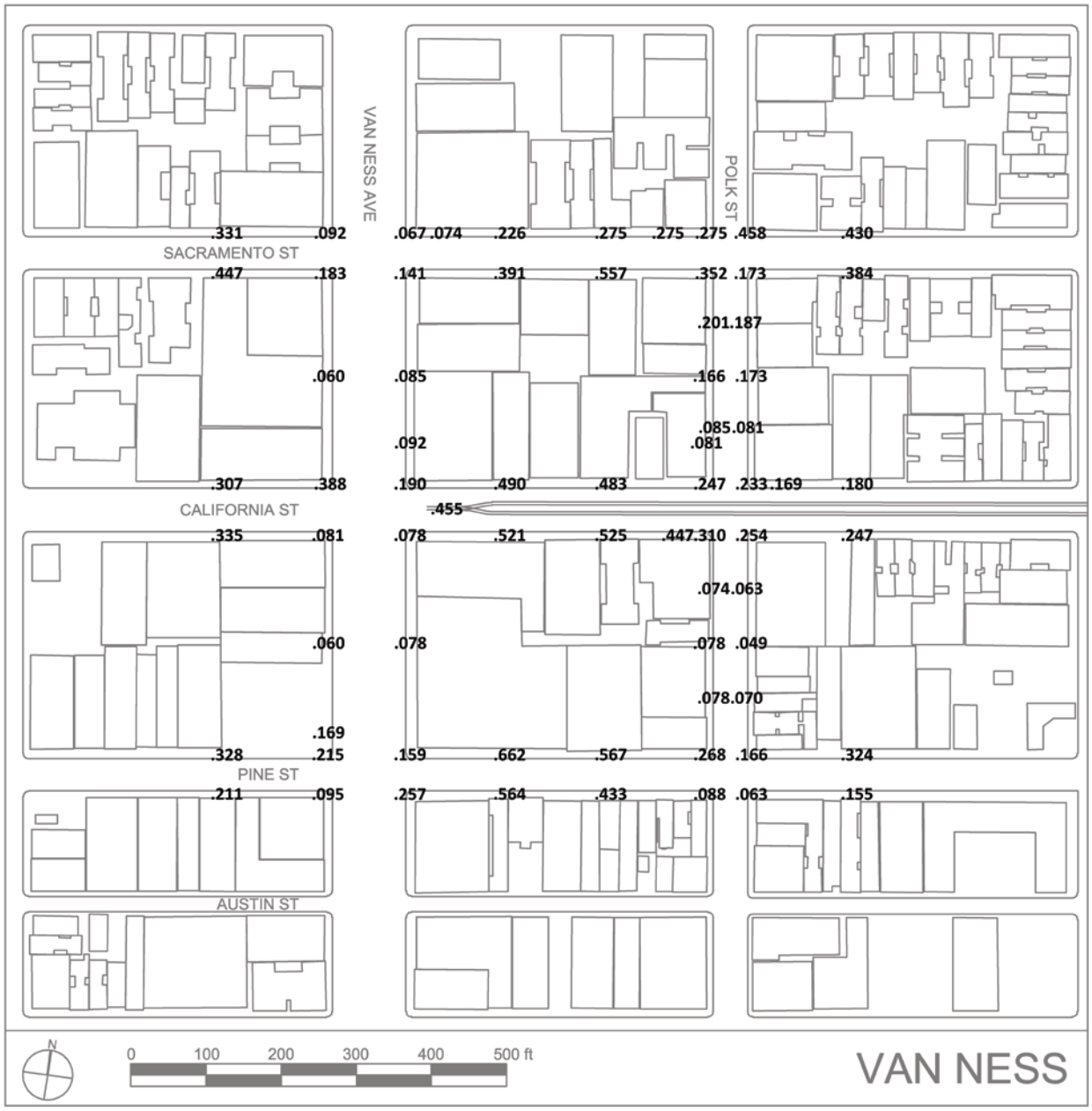

Figure 113. Wind speed ratios in Van Ness in 1985.

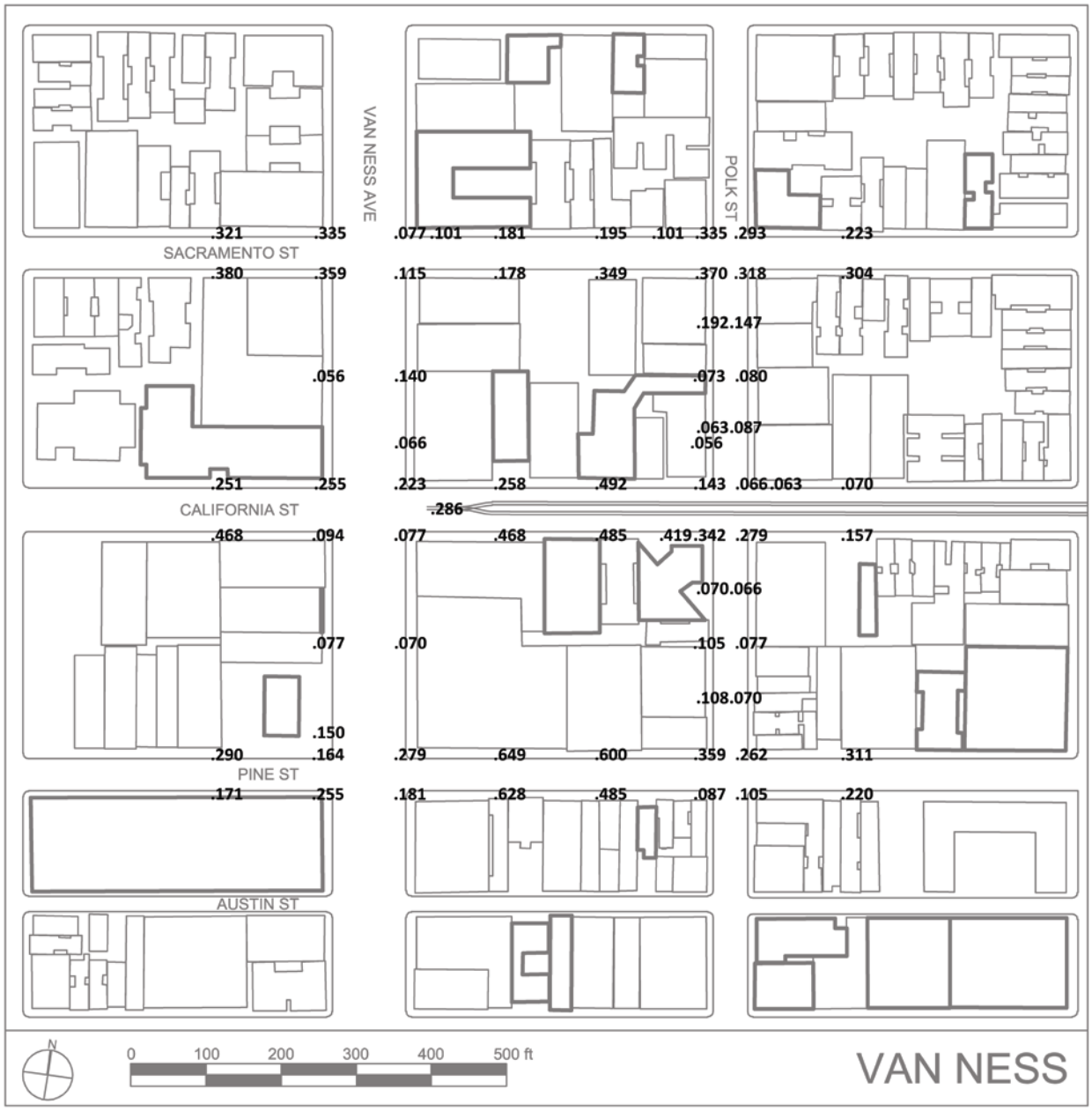

Figure 114. Wind speed ratios in Van Ness in 2013.

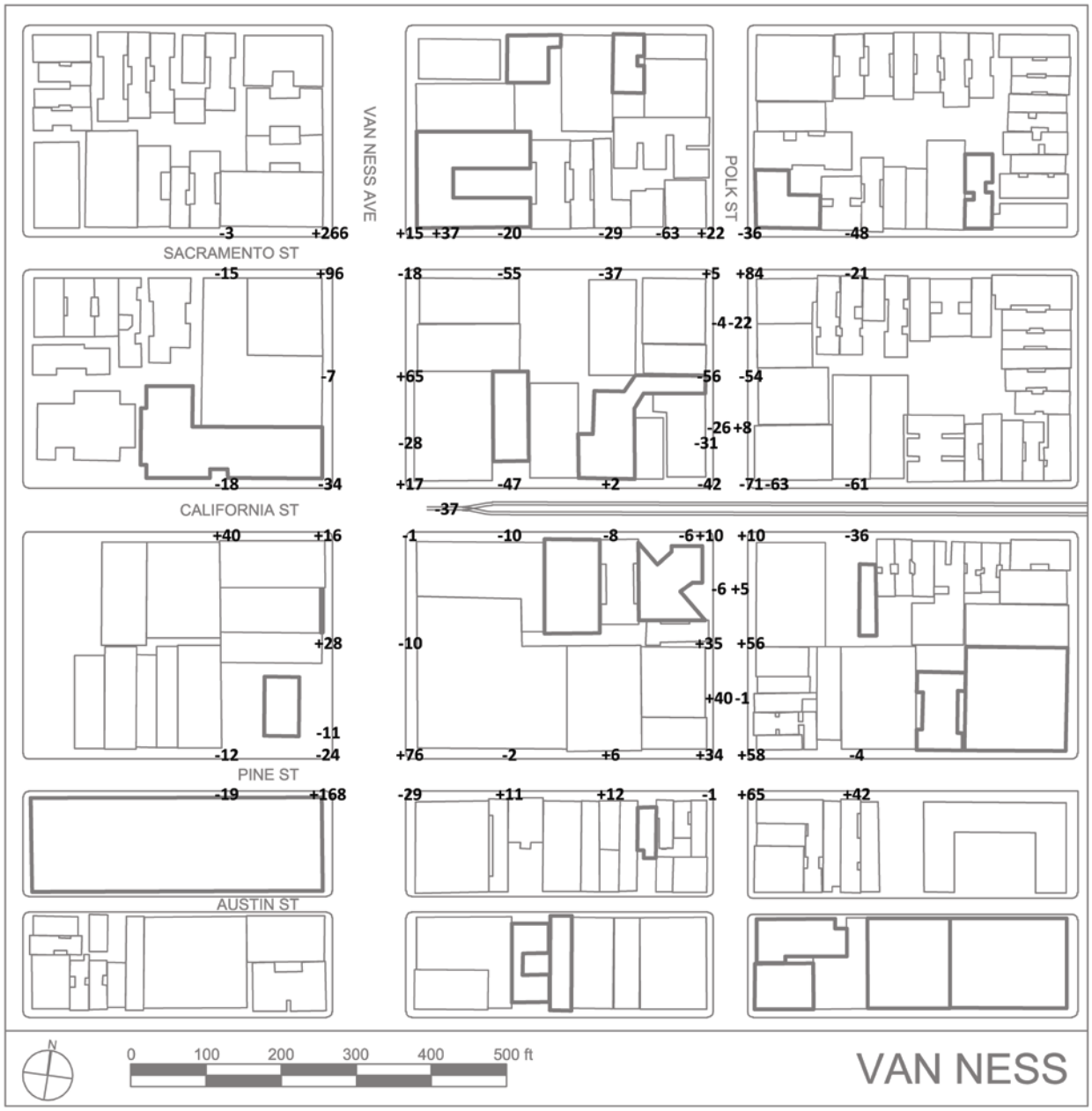

Figure 115. Changes (%) in wind speed ratios in Van Ness between 1985 and 2013.

3. Civic Center

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
1	Street corner	0.78	0.271	0.56	0.196	-28
2	Street corner	0.37	0.129	0.24	0.084	-35
3	Street corner	0.64	0.223	0.33	0.116	-48
4	Street corner	0.31	0.108	0.19	0.067	-38
5	Street corner	0.37	0.129	0.29	0.102	-21
6	Street corner	0.50	0.174	0.20	0.070	-60
7	Street corner	1.39	0.483	0.77	0.270	-44
8	Street corner	0.88	0.306	0.31	0.109	-65
9	Street corner	1.07	0.372	0.94	0.329	-12
10	Street corner	0.68	0.237	0.88	0.308	+30
11	Street corner	0.52	0.181	0.37	0.130	-28
12	Street corner	0.84	0.292	0.42	0.147	-50
13	Street corner	0.23	0.080	0.52	0.182	+128
14	Street corner	0.41	0.143	0.42	0.147	+3
15	Street corner	0.76	0.264	1.14	0.399	+51
16	Street corner	0.89	0.310	0.98	0.343	+11
17	Street corner	0.68	0.237	1.39	0.487	+106
18	Street corner	0.77	0.268	0.95	0.333	+24
19	Street corner	0.97	0.337	1.15	0.403	+19
20	Street corner	0.90	0.313	0.67	0.235	-25
21	Street corner	0.41	0.143	0.69	0.242	+69
22	Street corner	0.42	0.146	0.49	0.172	+17
23	Street corner	0.76	0.264	0.46	0.161	-39
24	Street corner	0.76	0.264	0.57	0.200	-24
25	Street corner	1.15	0.400	0.98	0.343	-14
26	Street corner	0.74	0.257	0.36	0.126	-51
27	Street corner	1.12	0.390	1.28	0.448	+15
28	Street corner	0.91	0.317	1.00	0.350	+11
29	Street corner	0.86	0.299	0.94	0.329	+10
30	Street corner	0.23	0.080	0.42	0.147	+84
31	Street corner	0.75	0.261	1.21	0.424	+62
32	Street corner	1.06	0.369	0.86	0.301	-18
33	Mid-block	1.06	0.369	0.87	0.305	-17
34	Mid-block	0.90	0.313	0.34	0.119	-62
35	Mid-block	0.85	0.296	0.49	0.172	-42
36	Mid-block	0.22	0.077	0.21	0.074	-4
37	Mid-block	1.02	0.355	0.93	0.326	-8
38	Mid-block	1.00	0.348	0.58	0.203	-42
39	Mid-block	1.05	0.365	0.63	0.221	-40
40	Mid-block	1.03	0.358	0.47	0.165	-54
41	Mid-block	0.83	0.289	0.25	0.088	-70
42	Mid-block	0.71	0.247	0.44	0.154	-38
43	Mid-block	0.24	0.083	0.25	0.088	+5
44	Mid-block	0.35	0.122	0.29	0.102	-17
45	Mid-block	0.24	0.083	0.19	0.067	-20
46	Mid-block	0.54	0.188	0.56	0.196	+4
47	Mid-block	2.30	0.800	1.45	0.508	-37
48	Mid-block	1.57	0.546	1.36	0.476	-13
49	Mid-block	0.40	0.139	0.76	0.266	+91
50	Mid-block	1.32	0.459	0.57	0.200	-57

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
51	Mid-block	1.38	0.480	1.38	0.483	+1
52	Mid-block	1.28	0.445	0.98	0.343	-23
53	Mid-block	0.67	0.233	1.07	0.375	+61
54	Mid-block	1.07	0.372	0.71	0.249	-33
55	Mid-block	0.38	0.132	0.83	0.291	+120
56	Mid-block	0.24	0.083	0.41	0.144	+72
57	Mid-block	0.31	0.108	0.24	0.084	-22
58	Mid-block	0.19	0.066	0.21	0.074	+11
59	Mid-block	1.42	0.494	1.16	0.406	-18
60	Mid-block	0.97	0.337	0.66	0.231	-31
61	Mid-block	1.10	0.383	0.62	0.217	-43
62	Mid-block	1.13	0.393	1.16	0.406	+3
63	Mid-block	0.92	0.320	0.91	0.319	-0
64	Mid-block	1.07	0.372	1.14	0.399	+7
65	Mid-block	1.06	0.369	1.12	0.392	+6
66	Mid-block	0.30	0.104	0.28	0.098	-6
67	Mid-block	0.25	0.087	0.20	0.070	-19
68	Mid-block	0.33	0.115	0.27	0.095	-18
69	Mid-block	0.69	0.240	0.79	0.277	+15
70	Mid-block	0.22	0.077	0.42	0.147	+92
71	Mid-block	0.31	0.108	0.26	0.091	-16
72	Mid-block	0.25	0.087	0.29	0.102	+17
73	Mid-block	1.05	0.365	1.06	0.371	+2
74	Mid-block	1.16	0.403	1.34	0.469	+16
75	Mid-block	1.38	0.480	1.37	0.480	-0
76	Street corner	0.23	0.080	0.19	0.067	-17
77	Transit stop	0.36	0.125	0.24	0.084	-33
78	Transit stop	0.23	0.080	0.29	0.102	+27
79	Transit stop	1.42	0.494	1.11	0.389	-21
80	Transit stop	1.06	0.369	0.66	0.231	-37
81	Transit stop	1.12	0.390	1.04	0.364	-6
82	Bicycle lane	0.66	0.230	1.04	0.364	+59
83	Bicycle lane	0.27	0.094	0.27	0.095	+1
84	Bicycle lane	0.59	0.205	0.30	0.105	-49
85	Bicycle lane	0.31	0.108	0.50	0.175	+62
86	Bicycle lane	1.18	0.410	0.71	0.249	-39
87	Bicycle lane	0.32	0.111	0.19	0.067	-40
88	Open space	1.58	0.550	1.52	0.532	-3
89	Open space	0.95	0.330	1.62	0.567	+72
90	Open space	0.83	0.289	1.51	0.529	+83
91	Open space	0.60	0.209	1.26	0.441	+111
92	Open space	0.40	0.139	1.01	0.354	+154
93	Open space	0.52	0.181	0.58	0.203	+12
94	Open space	0.24	0.083	0.20	0.070	-16
95	Open space	0.80	0.278	0.64	0.224	-19
96	Open space	0.69	0.240	0.95	0.333	+39
97	Open space	1.05	0.365	0.57	0.200	-45
98	Open space	0.19	0.066	0.21	0.074	+11
99	Open space	0.73	0.254	0.49	0.172	-32
100	Open space	0.62	0.216	0.83	0.291	+35
101	Open space	0.97	0.337	1.10	0.385	+14
102	Open space	0.97	0.337	1.37	0.480	+42

Notes: a. Reference wind speed: 2.88 m/s; b. Reference wind speed: 2.86 m/s

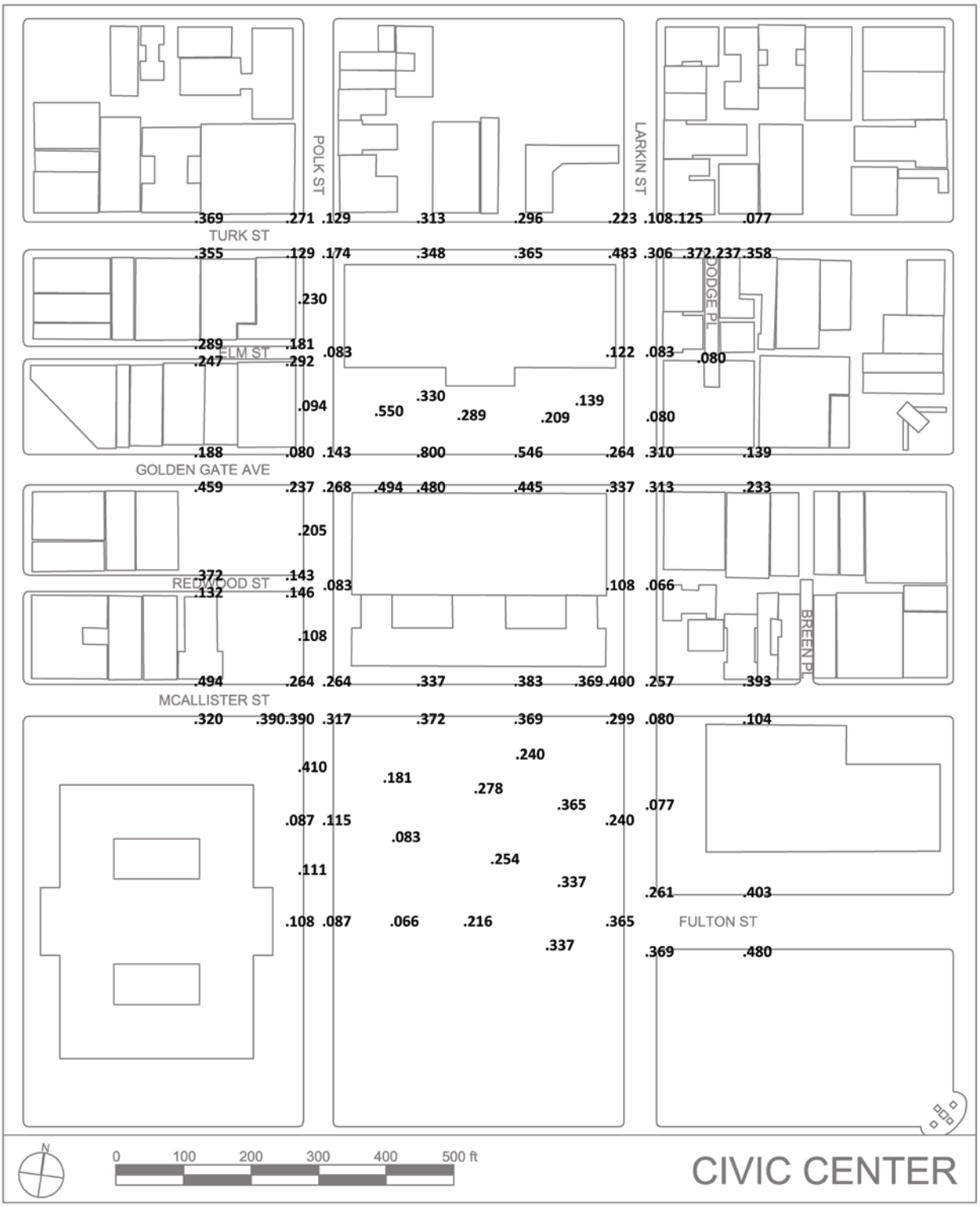

Figure 116. Wind speed ratios in Civic Center in 1985.

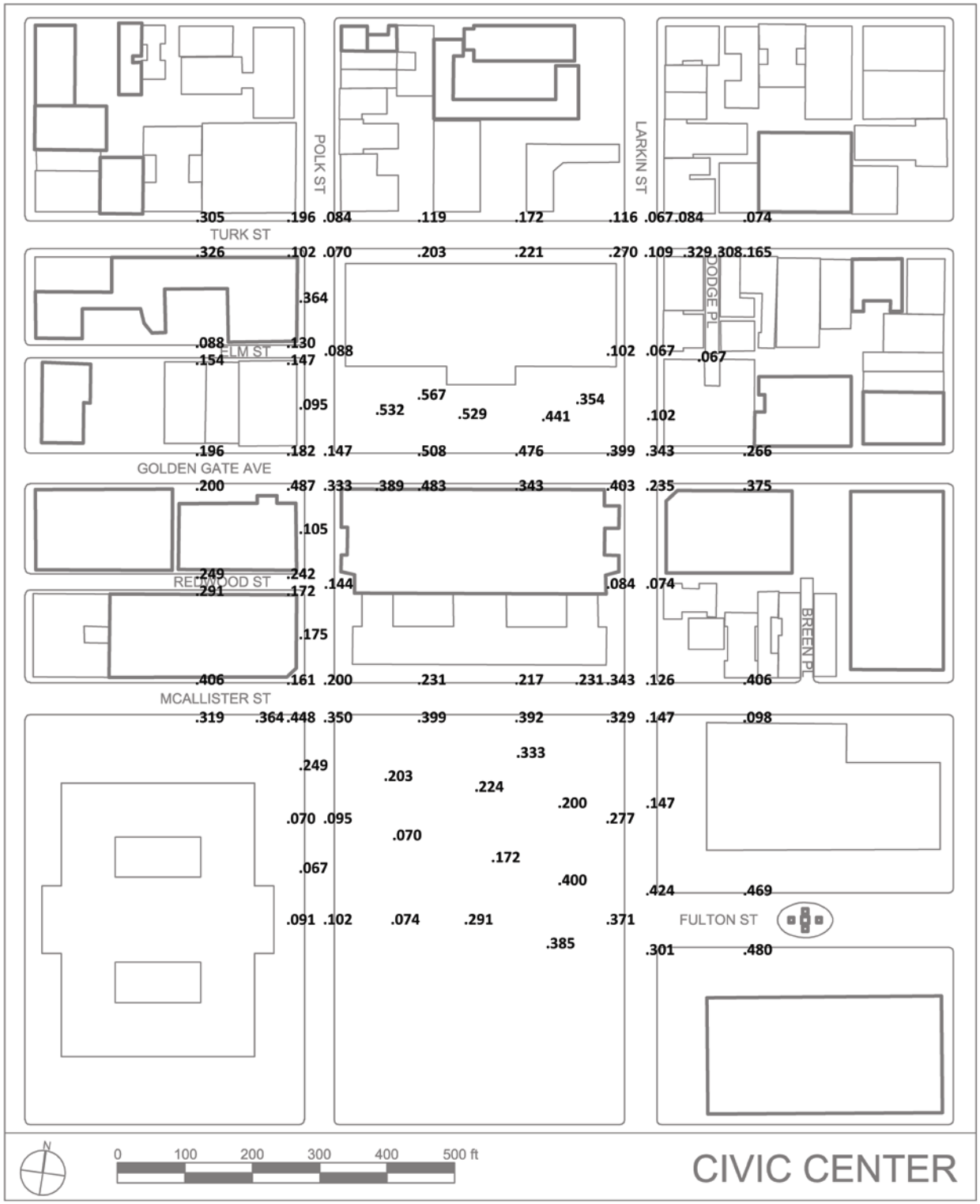

Figure 117. Wind speed ratios in Civic Center in 2013.

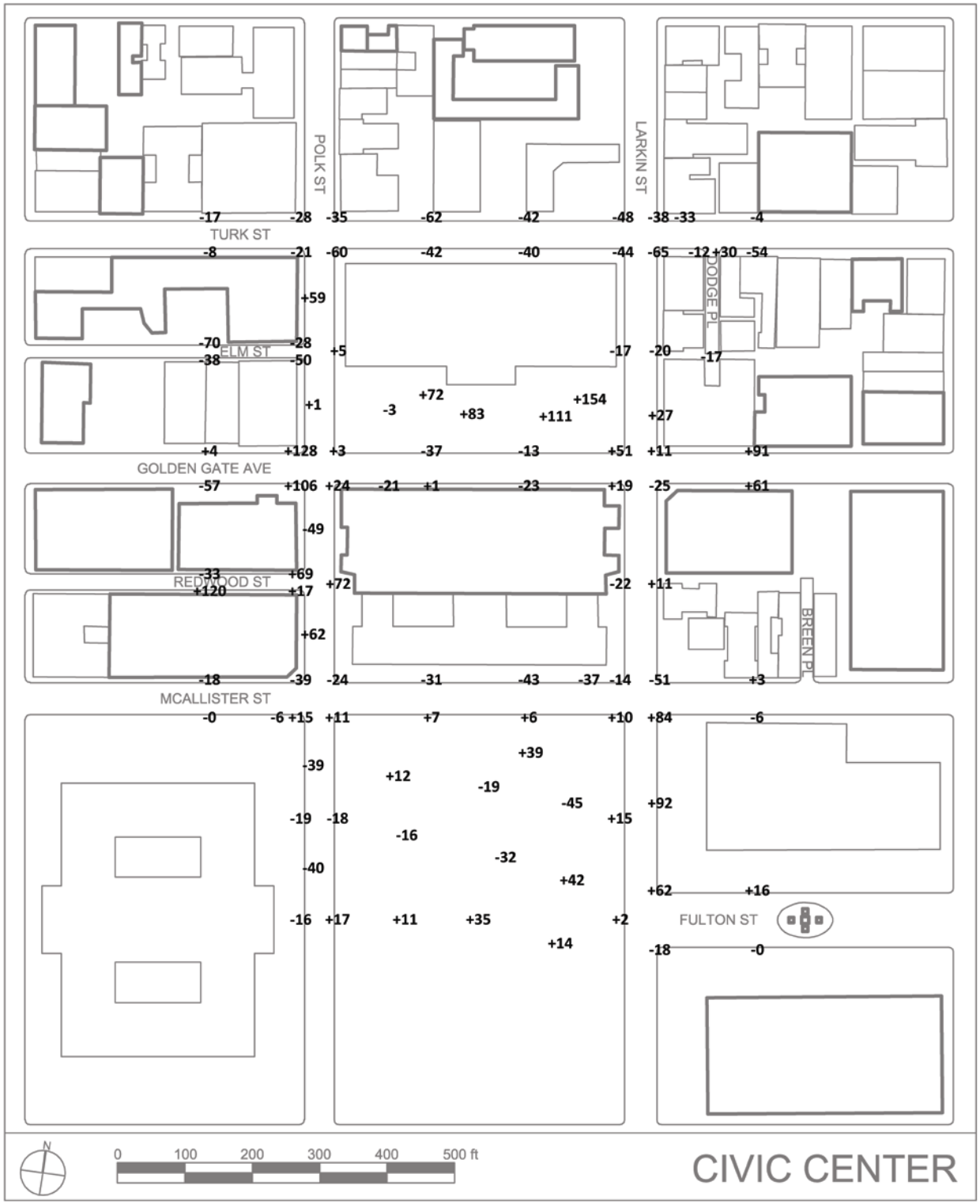

Figure 118. Changes (%) in wind speed ratios in Civic Center between 1985 and 2013.

4. Mission Bay North

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
1	Street corner	0.36	0.124	0.18	0.063	-49
2	Street corner	0.90	0.311	0.21	0.074	-76
3	Street corner	0.23	0.080	0.24	0.084	+6
4	Street corner	0.29	0.100	0.28	0.098	-2
5	Street corner	0.27	0.093	0.21	0.074	-21
6	Street corner	0.30	0.104	0.32	0.112	+8
7	Street corner	1.17	0.405	0.56	0.197	-51
8	Street corner	1.38	0.477	0.25	0.088	-82
9	Street corner	0.66	0.228	0.53	0.186	-18
10	Street corner	1.02	0.353	1.04	0.365	+4
11	Street corner	1.63	0.564	1.54	0.541	-4
12	Street corner	1.41	0.488	0.93	0.327	-33
13	Street corner	1.46	0.505	0.27	0.095	-81
14	Street corner	0.83	0.287	1.19	0.418	+46
15	Street corner	1.13	0.391	0.52	0.183	-53
16	Street corner	1.43	0.494	0.42	0.147	-70
17	Mid-block	0.80	0.277	0.24	0.084	-70
18	Mid-block	0.20	0.069	0.29	0.102	+47
19	Mid-block	0.91	0.315	0.29	0.102	-68
20	Mid-block	1.00	0.346	0.82	0.288	-17
21	Mid-block	0.50	0.173	0.43	0.151	-13
22	Mid-block	0.61	0.211	0.26	0.091	-57
23	Mid-block	0.25	0.086	1.10	0.386	+347
24	Mid-block	0.55	0.190	0.28	0.098	-48
25	Mid-block	0.72	0.249	0.28	0.098	-61
26	Mid-block	0.70	0.242	0.46	0.162	-33
27	Mid-block	1.60	0.553	1.13	0.397	-28
28	Mid-block	0.87	0.301	0.23	0.081	-73
29	Mid-block	1.00	0.346	0.58	0.204	-41
30	Mid-block	1.19	0.411	0.53	0.186	-55
31	Mid-block	1.28	0.443	0.24	0.084	-81
32	Mid-block	1.37	0.474	0.90	0.316	-33
33	Mid-block	1.00	0.346	1.24	0.435	+26
34	Mid-block	1.02	0.353	1.33	0.467	+32
35	Mid-block	1.13	0.391	1.35	0.474	+21
36	Mid-block	1.18	0.408	1.23	0.432	+6
37	Mid-block	1.24	0.429	0.43	0.151	-65
38	Mid-block	1.02	0.353	0.86	0.302	-14
39	Mid-block	1.03	0.356	0.25	0.088	-75
40	Mid-block	1.10	0.380	0.50	0.176	-54
41	Mid-block	1.16	0.401	0.51	0.179	-55
42	Mid-block	1.07	0.370	0.40	0.140	-62
43	Mid-block	1.18	0.408	0.91	0.320	-22
44	Mid-block	0.94	0.325	0.51	0.179	-45
45	Mid-block	0.97	0.335	0.80	0.281	-16
46	Mid-block	1.07	0.370	0.76	0.267	-28
47	Mid-block	1.11	0.384	0.73	0.256	-33
48	Mid-block	1.24	0.429	0.92	0.323	-25
49	Transit stop	0.56	0.194	0.24	0.084	-56
50	Transit stop	0.72	0.249	0.41	0.144	-42

Location Number	Location Type	1985		2013		Wind Speed Ratio Change (%)
		Wind Speed (m/s)	Wind Speed Ratio[a]	Wind Speed (m/s)	Wind Speed Ratio[b]	
51	Transit stop	0.63	0.218	0.27	0.095	-56
52	Transit stop	1.47	0.508	0.94	0.330	-35
53	Transit stop	1.31	0.453	0.40	0.140	-69
54	Bicycle lane	1.08	0.373	0.23	0.081	-78
55	Bicycle lane	0.82	0.284	0.32	0.112	-60
56	Bicycle lane	0.25	0.086	0.27	0.095	+10
57	Bicycle lane	0.34	0.118	0.20	0.070	-40
58	Bicycle lane	0.34	0.118	0.34	0.119	+2
59	Bicycle lane	1.30	0.450	0.64	0.225	-50
60	Bicycle lane	0.80	0.277	0.37	0.130	-53
61	Bicycle lane	0.45	0.156	0.39	0.137	-12
62	Bicycle lane	0.35	0.121	0.23	0.081	-33
63	Bicycle lane	0.52	0.180	0.34	0.119	-34
64	Open space	0.59	0.204	0.40	0.140	-31
65	Open space	0.40	0.138	0.28	0.098	-29
66	Open space	1.04	0.360	0.19	0.067	-81
67	Open space	1.11	0.384	0.17	0.060	-84
68	Open space	1.10	0.380	0.20	0.070	-82
69	Open space	1.08	0.373	0.18	0.063	-83
70	Open space	0.98	0.339	0.26	0.091	-73

Notes: a. Reference wind speed: 2.89 m/s; b. Reference wind speed: 2.85 m/s

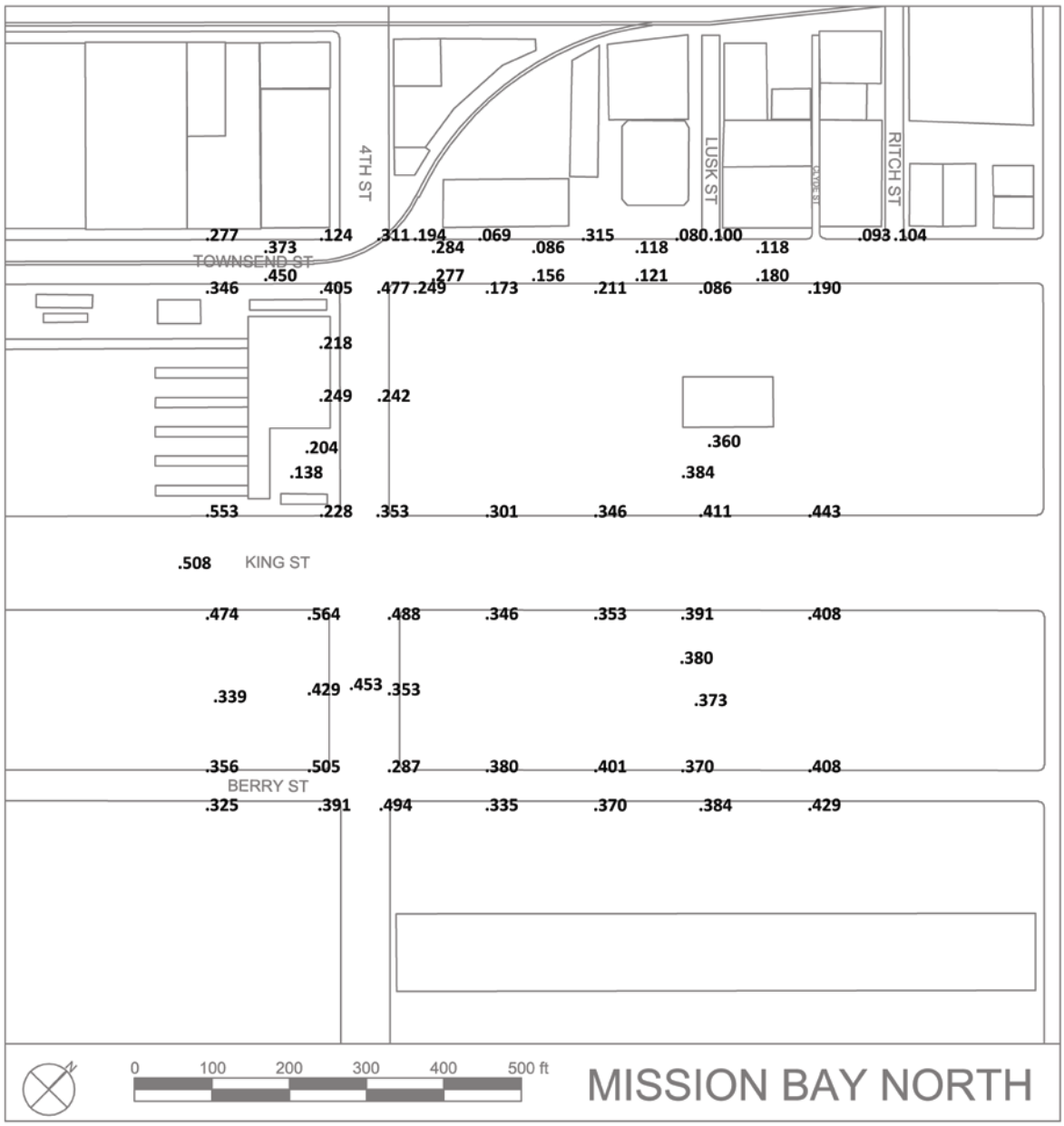

Figure 119. Wind speed ratios in Mission Bay North in 1985.

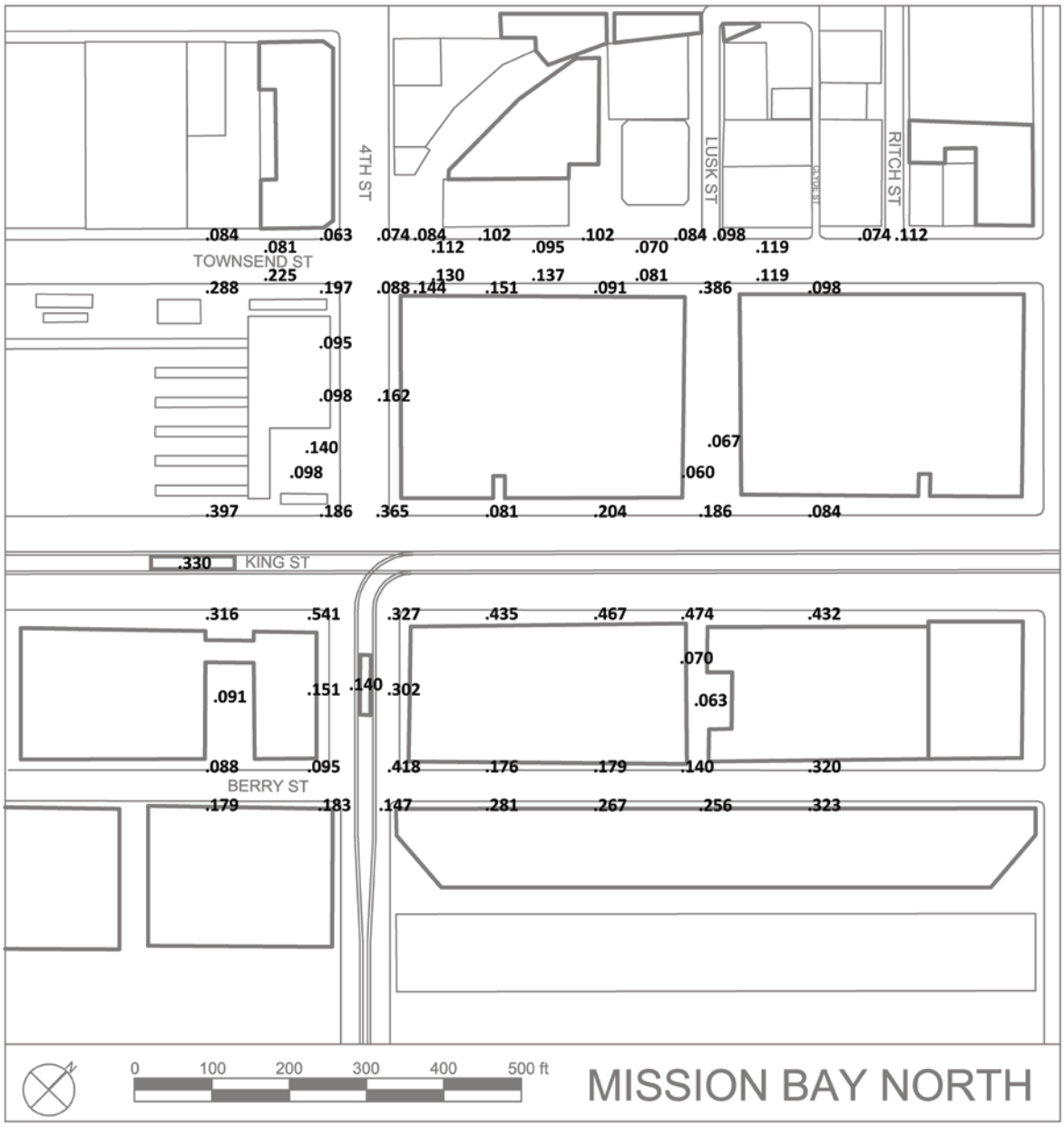

Figure 120. Wind speed ratios in Mission Bay North in 2013.

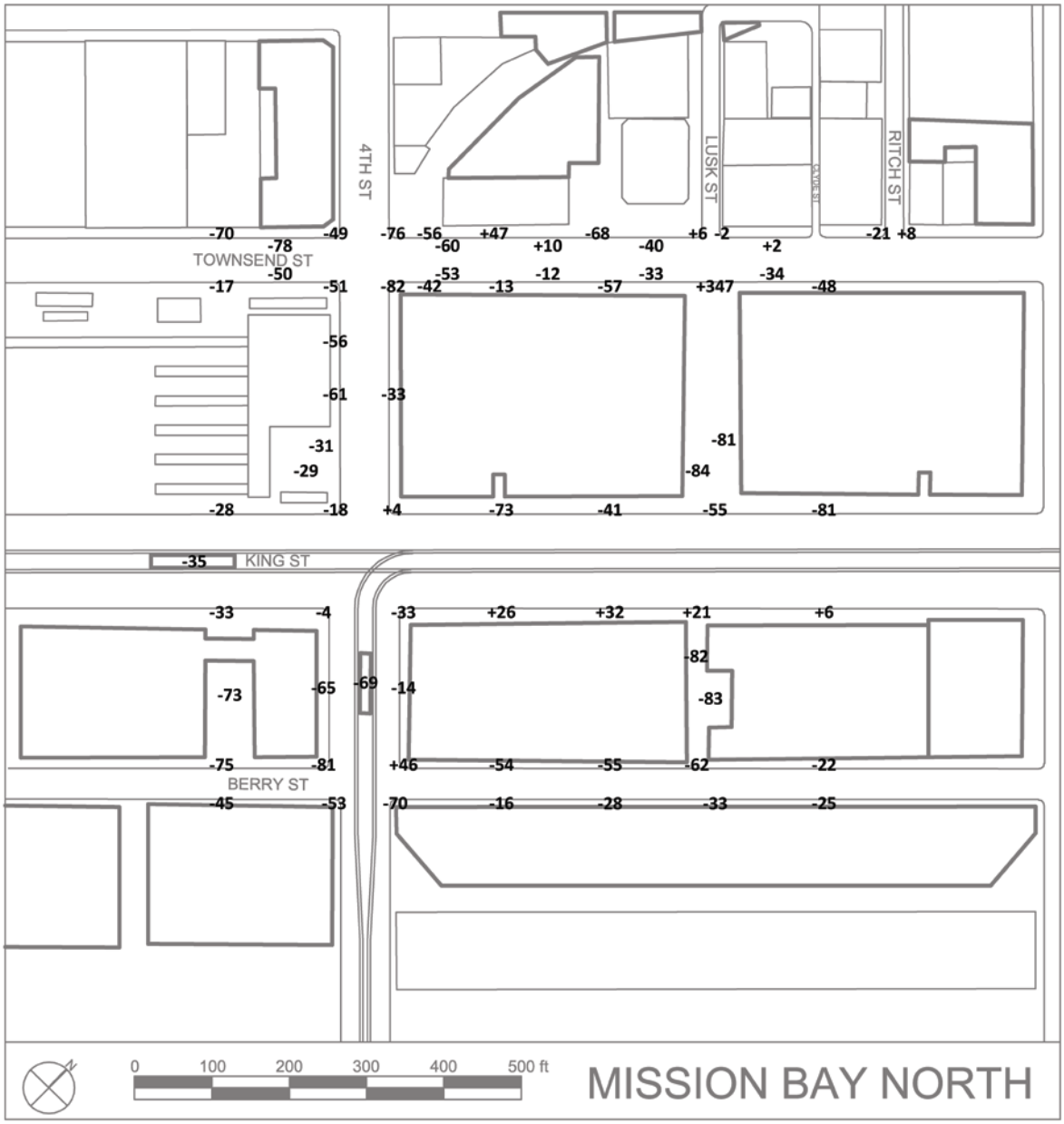

Figure 121. Changes (%) in wind speed ratios in Mission Bay North between 1985 and 2013.

Appendix G. Stata Outputs

ANOVA Comparison of EW_SPD and FEEL (Section 6.1)

```
                Number of obs =     701     R-squared     =  0.1258
                Root MSE      = 4.10308     Adj R-squared =  0.1183

    Source |  Partial SS    df       MS           F     Prob > F
-----------+----------------------------------------------------
     Model |  1681.90052     6  280.316753      16.65     0.0000
           |
     feel2 |  1681.90052     6  280.316753      16.65     0.0000
           |
  Residual |  11683.6981   694  16.8352999
-----------+----------------------------------------------------
     Total |  13365.5987   700  19.0937124
```

ANOVA Comparison of EW_SPD and W_FEEL (Section 6.1)

```
                Number of obs =     701     R-squared     =  0.2771
                Root MSE      = 3.72587     Adj R-squared =  0.2729

    Source |  Partial SS    df       MS           F     Prob > F
-----------+----------------------------------------------------
     Model |  3703.64252     4   925.91063      66.70     0.0000
           |
    w_feel |  3703.64252     4   925.91063      66.70     0.0000
           |
  Residual |  9661.95613   696  13.8821209
-----------+----------------------------------------------------
     Total |  13365.5987   700  19.0937124
```

ANOVA Comparison of EW_SPD and W_PREF (Section 6.1)

```
                Number of obs =     701     R-squared     =  0.0807
                Root MSE      = 4.19555     Adj R-squared =  0.0781

    Source |  Partial SS    df       MS           F     Prob > F
-----------+----------------------------------------------------
     Model |  1078.94816     2  539.474081      30.65     0.0000
           |
    w_pref |  1078.94816     2  539.474081      30.65     0.0000
           |
  Residual |  12286.6505   698  17.6026511
-----------+----------------------------------------------------
     Total |  13365.5987   700  19.0937124
```

ANOVA Comparison of EW_SPD and COMFD (Section 6.1)

```
                Number of obs =     701     R-squared     =  0.0907
                Root MSE      = 4.16967     Adj R-squared =  0.0894

    Source |  Partial SS    df       MS           F     Prob > F
```

```
-----------+------------------------------------------------------
     Model |  1212.66951     1  1212.66951      69.75     0.0000
           |
     comfd |  1212.66951     1  1212.66951      69.75     0.0000
           |
  Residual |  12152.9291   699  17.3861647
-----------+------------------------------------------------------
     Total |  13365.5987   700  19.0937124
```

Ordinal Logistic Regression Estimation of FEEL (Section 6.1)

```
Iteration 0:   log likelihood = -1146.4543
Iteration 1:   log likelihood =  -988.0259
Iteration 2:   log likelihood = -978.48778
Iteration 3:   log likelihood = -978.38167
Iteration 4:   log likelihood = -978.38164

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(18)     =     336.15
                                                Prob > chi2     =     0.0000
Log likelihood = -978.38164                     Pseudo R2       =     0.1466

------------------------------------------------------------------------------
       feel2 |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -.4938428   .1463848    -3.37   0.001    -.7807517   -.2069339
      often1 |   .4335346   .2036058     2.13   0.033     .0344745    .8325946
      often2 |    .313734   .2333906     1.34   0.179    -.1437032    .7711712
      often3 |   .4276022   .2244108     1.91   0.057    -.0122349    .8674394
      purps1 |   .4843399   .3634453     1.33   0.183    -.2279998     1.19668
      purps2 |  -.0966478   .4913954    -0.20   0.844    -1.059765    .8664694
      purps3 |   .0311712   .2457584     0.13   0.899    -.4505064    .5128489
      purps4 |   .1642893   .1771242     0.93   0.354    -.1828677    .5114464
      locdyb |  -.3846978   .2344156    -1.64   0.101    -.8441441    .0747484
      locdvn |    .610584   .2658097     2.30   0.022     .0896066    1.131561
      locdcc |   .6657075   .2453119     2.71   0.007     .1849051     1.14651
         met |   .3596899   .1624505     2.21   0.027     .0412928     .678087
     out_min |   .0110974     .00424     2.62   0.009     .0027872    .0194075
         clo |   .2378448   .3179932     0.75   0.454    -.3854104    .8610999
  w_vel_e10s |  -.1114111   .0197788    -5.63   0.000    -.1501769   -.0726452
        temp |   .2531849   .0281372     9.00   0.000      .198037    .3083329
       solar |   .0009821   .0003422     2.87   0.004     .0003114    .0016529
      r_humd |  -.0032784   .0104389    -0.31   0.753    -.0237384    .0171815
-------------+----------------------------------------------------------------
       /cut1 |   12.74929     2.4114                      8.023032    17.47555
       /cut2 |    14.4039   2.412923                      9.674657    19.13314
       /cut3 |   16.68918   2.433663                      11.91929    21.45908
       /cut4 |   18.23813   2.451449                      13.43338    23.04288
       /cut5 |   19.64803   2.465757                      14.81523    24.48083
       /cut6 |   21.61658    2.49312                      16.73016    26.50301
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of W_FEEL (Section 6.1)

```
Iteration 0:   log likelihood = -830.63088
Iteration 1:   log likelihood = -705.37034
Iteration 2:   log likelihood =  -700.0667
Iteration 3:   log likelihood = -699.97027
```

```
Iteration 4:   log likelihood = -699.97021

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(18)     =     261.32
                                                Prob > chi2     =     0.0000
Log likelihood = -699.97021                     Pseudo R2       =     0.1573

------------------------------------------------------------------------------
      w_feel |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .2377077   .1549737     1.53   0.125    -.0660352    .5414507
      often1 |   .1759702   .2141025     0.82   0.411     -.243663    .5956034
      often2 |   .0171567    .244719     0.07   0.944    -.4624837    .4967971
      often3 |  -.1670835   .2336548    -0.72   0.475    -.6250385    .2908715
      purps1 |  -.2161942   .3878599    -0.56   0.577    -.9763857    .5439973
      purps2 |   .1923926   .5231266     0.37   0.713    -.8329167    1.217702
      purps3 |   .4260409   .2622712     1.62   0.104    -.0880012    .9400829
      purps4 |   .1188917   .1898493     0.63   0.531    -.2532061    .4909894
      locdyb |  -.1857286   .2497817    -0.74   0.457    -.6752917    .3038346
      locdvn |   .0070793   .2858575     0.02   0.980    -.5531912    .5673498
      locdcc |  -.8227589     .26315    -3.13   0.002    -1.338524   -.3069944
         met |  -.0829943   .1687691    -0.49   0.623    -.4137757    .2477871
     out_min |  -.0009051   .0044323    -0.20   0.838    -.0095922     .007782
         clo |  -.3543947   .3387202    -1.05   0.295    -1.018274    .3094847
  w_vel_e10s |   .2365854   .0225925    10.47   0.000     .1923048    .2808659
        temp |  -.0941266   .0287833    -3.27   0.001    -.1505408   -.0377125
       solar |   .0005445   .0003588     1.52   0.129    -.0001587    .0012478
      r_humd |  -.0050612   .0111598    -0.45   0.650     -.026934    .0168116
-------------+----------------------------------------------------------------
       /cut1 |  -8.924959   2.564233                   -13.95076   -3.899156
       /cut2 |  -5.061866   2.536454                   -10.03322    -.090507
       /cut3 |  -2.410299    2.52997                   -7.368949    2.548351
       /cut4 |   .8222759   2.540427                    -4.15687    5.801422
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of W_PREF (Section 6.1)

```
Iteration 0:   log likelihood = -578.13298
Iteration 1:   log likelihood = -514.09365
Iteration 2:   log likelihood =  -512.6685
Iteration 3:   log likelihood = -512.66121
Iteration 4:   log likelihood = -512.66121

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(18)     =     130.94
                                                Prob > chi2     =     0.0000
Log likelihood = -512.66121                     Pseudo R2       =     0.1132

------------------------------------------------------------------------------
      w_pref |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .5011011   .1672146     3.00   0.003     .1733665    .8288358
      often1 |   .0567258   .2317138     0.24   0.807    -.3974248    .5108765
      often2 |   .0321216   .2656495     0.12   0.904    -.4885419    .5527851
      often3 |   .1162549   .2559124     0.45   0.650    -.3853243    .6178341
      purps1 |   .2537277   .4290217     0.59   0.554    -.5871394    1.094595
      purps2 |  -1.098608   .5358099    -2.05   0.040    -2.148776     -.04844
      purps3 |   .2891956   .2845363     1.02   0.309    -.2684853    .8468765
      purps4 |  -.1619606   .2003078    -0.81   0.419    -.5545567    .2306355
      locdyb |   .1600983    .273768     0.58   0.559    -.3764772    .6966738
      locdvn |  -.6954544   .3180868    -2.19   0.029    -1.318893   -.0720156
```

```
      locdcc |  -1.009367   .2838349    -3.56   0.000    -1.565673    -.453061
         met |   -.448836   .1833633    -2.45   0.014    -.8082214   -.0894506
     out_min |  -.0049961   .0047789    -1.05   0.296    -.0143625    .0043703
         clo |   .1313324   .3628473     0.36   0.717    -.5798352    .8425001
  w_vel_e10s |   .1222656   .0236623     5.17   0.000     .0758884    .1686429
        temp |  -.0905847   .0303984    -2.98   0.003    -.1501645   -.0310049
       solar |   .0007418   .0003881     1.91   0.056    -.0000189    .0015025
      r_humd |   .0126983   .0116668     1.09   0.276    -.0101683    .0355649
-------------+----------------------------------------------------------------
       /cut1 |  -7.851156   2.687734                     -13.11902   -2.583294
       /cut2 |  -4.238499   2.671937                     -9.475399    .9984009
------------------------------------------------------------------------------
```

Simple Logistic Regression Estimation of COMFD (Section 6.1)

```
Iteration 0:   log likelihood =  -360.0052
Iteration 1:   log likelihood = -297.99111
Iteration 2:   log likelihood = -292.01017
Iteration 3:   log likelihood =   -291.815
Iteration 4:   log likelihood = -291.81457

Logistic regression                                     Number of obs   =        701
                                                        LR chi2(18)     =     136.38
                                                        Prob > chi2     =     0.0000
Log likelihood = -291.81457                             Pseudo R2       =     0.1894

------------------------------------------------------------------------------
       comfd |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -.7837834   .2183811    -3.59   0.000    -1.211802   -.3557643
      often1 |   .3103805   .2910146     1.07   0.286    -.2599977    .8807587
      often2 |     .24899   .3302306     0.75   0.451    -.3982501    .8962301
      often3 |   .0631822   .3177135     0.20   0.842    -.5595248    .6858893
      purps1 |  -.2729248   .4943311    -0.55   0.581    -1.241796    .6959464
      purps2 |   1.120019   .8624684     1.30   0.194    -.5703881    2.810426
      purps3 |  -.2608107   .3465359    -0.75   0.452    -.9400086    .4183873
      purps4 |   .1808456   .2720802     0.66   0.506    -.3524218     .714113
      locdyb |  -.4976913    .375378    -1.33   0.185    -1.233419     .238036
      locdvn |   .1415134   .4032491     0.35   0.726    -.6488402     .931867
      locdcc |   .2122627   .4017186     0.53   0.597    -.5750912    .9996166
         met |    .649194   .2690054     2.41   0.016     .1219532    1.176435
     out_min |   .0017192   .0063829     0.27   0.788    -.0107911    .0142295
         clo |   .5668909   .4847352     1.17   0.242    -.3831727    1.516954
  w_vel_e10s |  -.1450976   .0299097    -4.85   0.000    -.2037195   -.0864757
        temp |   .1756338   .0451148     3.89   0.000     .0872105    .2640571
       solar |   .0010772   .0005895     1.83   0.068    -.0000782    .0022326
      r_humd |   .0060351   .0164468     0.37   0.714    -.0262001    .0382703
       _cons |  -9.883374   3.909958    -2.53   0.011    -17.54675   -2.219997
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of FEEL if EW_SPD < 11 (Section 6.2)

```
Iteration 0:   log likelihood = -530.87378
Iteration 1:   log likelihood = -467.17506
Iteration 2:   log likelihood = -464.39392
Iteration 3:   log likelihood = -464.36894
Iteration 4:   log likelihood = -464.36894
```

```
Ordered logistic regression                     Number of obs   =        334
                                                LR chi2(18)     =     133.01
                                                Prob > chi2     =     0.0000
Log likelihood = -464.36894                     Pseudo R2       =     0.1253

------------------------------------------------------------------------------
       feel2 |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -.5027477   .2141517    -2.35   0.019    -.9224774    -.083018
      often1 |    .185902   .3082778     0.60   0.546    -.4183114    .7901154
      often2 |   .5291824   .3590787     1.47   0.141    -.1745989    1.232964
      often3 |   .2449485   .3575213     0.69   0.493    -.4557804    .9456774
      purps1 |   .6215046   .4825687     1.29   0.198    -.3243127    1.567322
      purps2 |  -.4123587   .7539749    -0.55   0.584    -1.890122    1.065405
      purps3 |  -.3161954   .3906105    -0.81   0.418    -1.081778    .4493872
      purps4 |   .3175855   .2602615     1.22   0.222    -.1925177    .8276886
      locdyb |   -.506353   .3224279    -1.57   0.116      -1.1383     .125594
      locdvn |   1.008275   .4785779     2.11   0.035     .0702799    1.946271
      locdcc |   .6847806   .3278159     2.09   0.037     .0422732    1.327288
         met |    .284426   .2194989     1.30   0.195     -.145784     .714636
     out_min |   .0170726   .0061928     2.76   0.006     .0049349    .0292103
         clo |    .225412   .4928494     0.46   0.647    -.7405551    1.191379
  w_vel_e10s |    -.09916    .052642    -1.88   0.060    -.2023363    .0040164
        temp |   .2088872   .0368805     5.66   0.000     .1366027    .2811717
       solar |   .0009088   .0004525     2.01   0.045      .000022    .0017957
      r_humd |  -.0220205   .0138323    -1.59   0.111    -.0491313    .0050902
-------------+----------------------------------------------------------------
       /cut1 |    8.69302   3.124179                      2.569741     14.8163
       /cut2 |   10.13509   3.118071                      4.023787     16.2464
       /cut3 |   12.65929   3.138524                      6.507896    18.81068
       /cut4 |   14.19703   3.159404                      8.004709    20.38935
       /cut5 |   15.67683   3.179031                      9.446046    21.90762
       /cut6 |   17.88714   3.221855                      11.57242    24.20186
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of FEEL if EW_SPD ≥ 11 (Section 6.2)

```
Iteration 0:   log likelihood =  -585.7808
Iteration 1:   log likelihood = -508.25249
Iteration 2:   log likelihood = -502.86234
Iteration 3:   log likelihood = -502.80417
Iteration 4:   log likelihood = -502.80415

Ordered logistic regression                     Number of obs   =        367
                                                LR chi2(18)     =     165.95
                                                Prob > chi2     =     0.0000
Log likelihood = -502.80415                     Pseudo R2       =     0.1417

------------------------------------------------------------------------------
       feel2 |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -.5452335   .2057831    -2.65   0.008     -.948561   -.1419059
      often1 |   .5956365   .2847836     2.09   0.036     .0374709    1.153802
      often2 |   .1189472   .3108166     0.38   0.702    -.4902421    .7281365
      often3 |   .5445265   .2947773     1.85   0.065    -.0332265    1.122279
      purps1 |   .2920167   .5663738     0.52   0.606    -.8180555    1.402089
      purps2 |   .3156522   .6775877     0.47   0.641    -1.012395      1.6437
      purps3 |   .3255905   .3338619     0.98   0.329    -.3287669    .9799479
      purps4 |    .047114   .2524855     0.19   0.852    -.4477486    .5419765
      locdyb |  -.3618693   .3827028    -0.95   0.344    -1.111953    .3882145
```

```
      locdvn |    .405597   .3715535     1.09   0.275    -.3226344    1.133829
      locdcc |   .5705334   .4284975     1.33   0.183    -.2693063    1.410373
         met |   .4029131   .2448495     1.65   0.100    -.0769832    .8828094
     out_min |   .0067387   .0059074     1.14   0.254    -.0048396     .018317
         clo |   .3595216   .4254298     0.85   0.398    -.4743055    1.193349
  w_vel_e10s |  -.0920445   .0347368    -2.65   0.008    -.1601274   -.0239617
        temp |   .3411329   .0473248     7.21   0.000     .2483779    .4338878
       solar |    .001412   .0005627     2.51   0.012     .0003092    .0025148
      r_humd |   .0295664   .0177328     1.67   0.095    -.0051892     .064322
-------------+------------------------------------------------------------------
       /cut1 |   20.91283   4.173491                      12.73294    29.09272
       /cut2 |    22.6802   4.181761                       14.4841     30.8763
       /cut3 |   24.90668   4.221115                      16.63344    33.17991
       /cut4 |   26.52271   4.251716                       18.1895    34.85592
       /cut5 |   27.81847   4.269947                      19.44953    36.18741
       /cut6 |   29.38767   4.297496                      20.96473    37.81061
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of W_FEEL if EW_SPD < 11 (Section 6.2)

```
Iteration 0:   log likelihood = -362.57017
Iteration 1:   log likelihood = -317.05033
Iteration 2:   log likelihood = -315.70983
Iteration 3:   log likelihood = -315.69435
Iteration 4:   log likelihood = -315.69435

Ordered logistic regression                     Number of obs   =        334
                                                LR chi2(18)     =      93.75
                                                Prob > chi2     =     0.0000
Log likelihood = -315.69435                     Pseudo R2       =     0.1293

------------------------------------------------------------------------------
      w_feel |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .3745903   .2315459     1.62   0.106    -.0792313     .828412
      often1 |   .0904933   .3259856     0.28   0.781    -.5484267    .7294133
      often2 |  -.1655167   .3832169    -0.43   0.666    -.9166081    .5855746
      often3 |  -.1375888   .3784274    -0.36   0.716    -.8792928    .6041152
      purps1 |  -.3080224   .5324404    -0.58   0.563    -1.351586    .7355415
      purps2 |  -.4709867   .8474651    -0.56   0.578    -2.131988    1.190014
      purps3 |   .3220656   .4024702     0.80   0.424    -.4667615    1.110893
      purps4 |  -.1511264   .2826296    -0.53   0.593    -.7050701    .4028174
      locdyb |  -.0512403   .3531977    -0.15   0.885    -.7434951    .6410146
      locdvn |  -.5969341   .5082668    -1.17   0.240    -1.593119    .3992506
      locdcc |  -1.186572   .3604825    -3.29   0.001    -1.893104   -.4800387
         met |   .0906916   .2386197     0.38   0.704    -.3769944    .5583775
     out_min |  -.0122984   .0067982    -1.81   0.070    -.0256227    .0010258
         clo |  -.9587476   .5416901    -1.77   0.077    -2.020441    .1029454
  w_vel_e10s |   .4334941   .0636451     6.81   0.000      .308752    .5582363
        temp |  -.1160726   .0388874    -2.98   0.003    -.1922905   -.0398547
       solar |   .0011308   .0004897     2.31   0.021     .0001709    .0020906
      r_humd |   .0105304   .0150302     0.70   0.484    -.0189282    .0399891
-------------+----------------------------------------------------------------
       /cut1 |   -8.55054   3.395194                      -15.205   -1.896082
       /cut2 |  -4.532079   3.365941                     -11.1292    2.065044
       /cut3 |  -1.803902   3.355896                    -8.381337    4.773533
       /cut4 |   1.335661   3.412162                    -5.352054    8.023377
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of W_FEEL if EW_SPD ≥ 11 (Section 6.2)

```
Iteration 0:   log likelihood = -408.87466
Iteration 1:   log likelihood = -362.88039
Iteration 2:   log likelihood = -361.46164
Iteration 3:   log likelihood =  -361.4484
Iteration 4:   log likelihood =  -361.4484

Ordered logistic regression                       Number of obs   =        367
                                                  LR chi2(18)     =      94.85
                                                  Prob > chi2     =     0.0000
Log likelihood =  -361.4484                       Pseudo R2       =     0.1160

------------------------------------------------------------------------------
      w_feel |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .1345313   .2171267     0.62   0.536    -.2910292    .5600918
      often1 |   .2547094   .3004597     0.85   0.397    -.3341807    .8435996
      often2 |     .09863   .3283743     0.30   0.764    -.5449718    .7422318
      often3 |   -.336228   .3082627    -1.09   0.275    -.9404117    .2679557
      purps1 |  -.0598941   .6098966    -0.10   0.922    -1.255269    1.135481
      purps2 |   .7481526   .7021598     1.07   0.287    -.6280553    2.124361
      purps3 |   .6083495   .3662604     1.66   0.097    -.1095077    1.326207
      purps4 |   .5599257   .2701915     2.07   0.038       .03036    1.089491
      locdyb |  -.6368389    .409064    -1.56   0.120     -1.43859    .1649119
      locdvn |    .385869   .4003686     0.96   0.335    -.3988391    1.170577
      locdcc |   -.786947   .4621797    -1.70   0.089    -1.692802    .1189085
         met |  -.1936072    .255639    -0.76   0.449    -.6946504    .3074361
     out_min |   .0090079   .0061834     1.46   0.145    -.0031114    .0211272
         clo |   .1112204    .456834     0.24   0.808    -.7841578    1.006599
  w_vel_e10s |   .1668444   .0382554     4.36   0.000     .0918651    .2418237
        temp |   -.133163   .0483474    -2.75   0.006    -.2279222   -.0384037
       solar |  -.0005037   .0005812    -0.87   0.386    -.0016428    .0006353
      r_humd |  -.0376059   .0192614    -1.95   0.051    -.0753576    .0001458
-------------+----------------------------------------------------------------
       /cut1 |   -10.4745   4.391846                     -19.08236   -1.866642
       /cut2 |  -7.682788   4.368986                     -16.24584    .8802668
       /cut3 |  -4.543426   4.376796                     -13.12179    4.034937
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of W_PREF if EW_SPD < 11 (Section 6.2)

```
Iteration 0:   log likelihood =  -297.5438
Iteration 1:   log likelihood = -262.62112
Iteration 2:   log likelihood = -261.83466
Iteration 3:   log likelihood = -261.82809
Iteration 4:   log likelihood = -261.82809

Ordered logistic regression                       Number of obs   =        334
                                                  LR chi2(18)     =      71.43
                                                  Prob > chi2     =     0.0000
Log likelihood = -261.82809                       Pseudo R2       =     0.1200

------------------------------------------------------------------------------
      w_pref |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .5914437   .2382578     2.48   0.013      .124467     1.05842
      often1 |   .0316059    .343202     0.09   0.927    -.6410575    .7042694
      often2 |    -.06846   .4036731    -0.17   0.865    -.8596448    .7227248
      often3 |  -.0162937   .3949738    -0.04   0.967    -.7904281    .7578407
```

```
      purps1 |   .0781447   .5678873     0.14   0.891    -1.034894    1.191183
      purps2 |  -1.052052   .7969259    -1.32   0.187    -2.613998    .5098945
      purps3 |  -.1256927   .4275423    -0.29   0.769    -.9636602    .7122747
      purps4 |  -.1726535   .2893933    -0.60   0.551    -.7398539     .394547
      locdyb |   .1043482   .3629921     0.29   0.774    -.6071033    .8157997
      locdvn |  -1.663903   .5357689    -3.11   0.002    -2.713991   -.6138151
      locdcc |  -1.501211    .374822    -4.01   0.000    -2.235849   -.7665732
         met |  -.5951272   .2448419    -2.43   0.015    -1.075009   -.1152458
     out_min |  -.0038653   .0069044    -0.56   0.576    -.0173976    .009667
         clo |   .4433069   .5614588     0.79   0.430    -.6571322    1.543746
  w_vel_e10s |   .2010463   .0602661     3.34   0.001      .082927    .3191657
        temp |  -.0733743   .0398386    -1.84   0.066    -.1514565    .0047078
       solar |   .0013622    .000524     2.60   0.009     .0003352    .0023892
      r_humd |   .0406309   .0152481     2.66   0.008     .0107452    .0705165
-------------+----------------------------------------------------------------
       /cut1 |  -4.318834      3.446                     -11.07287    2.435202
       /cut2 |   -.905204   3.440126                     -7.647726    5.837318
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of W_PREF if EW_SPD ≥ 11 (Section 6.2)

```
Iteration 0:   log likelihood = -263.32441
Iteration 1:   log likelihood = -236.13262
Iteration 2:   log likelihood = -235.52662
Iteration 3:   log likelihood = -235.52412
Iteration 4:   log likelihood = -235.52412

Ordered logistic regression                     Number of obs   =        367
                                                LR chi2(18)     =      55.60
                                                Prob > chi2     =     0.0000
Log likelihood = -235.52412                     Pseudo R2       =     0.1056

------------------------------------------------------------------------------
      w_pref |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .4435913   .2436681     1.82   0.069    -.0339894     .921172
      often1 |  -.1177755   .3342646    -0.35   0.725    -.7729221     .537371
      often2 |   .0066303   .3632609     0.02   0.985     -.705348    .7186086
      often3 |    .158681   .3487991     0.45   0.649    -.5249527    .8423147
      purps1 |   .7079252   .7219234     0.98   0.327    -.7070186    2.122869
      purps2 |  -1.301165   .7732059    -1.68   0.092    -2.816621    .2142908
      purps3 |   .6474884   .4132845     1.57   0.117    -.1625343    1.457511
      purps4 |   .0146444   .2907727     0.05   0.960    -.5552596    .5845484
      locdyb |     .35265   .4679308     0.75   0.451    -.5644775    1.269778
      locdvn |   .0860927   .4596788     0.19   0.851    -.8148612    .9870465
      locdcc |  -.2829056   .5098525    -0.55   0.579    -1.282198    .7163869
         met |  -.1674949   .2863525    -0.58   0.559    -.7287355    .3937457
     out_min |  -.0085056   .0068509    -1.24   0.214    -.0219332     .004922
         clo |   .1631386   .5000638     0.33   0.744    -.8169685    1.143246
  w_vel_e10s |   .1332849   .0447658     2.98   0.003     .0455456    .2210243
        temp |  -.1749811   .0527016    -3.32   0.001    -.2782743   -.0716879
       solar |  -.0001063   .0006475    -0.16   0.870    -.0013753    .0011628
      r_humd |  -.0387773   .0208335    -1.86   0.063    -.0796102    .0020555
-------------+----------------------------------------------------------------
       /cut1 |  -16.87148    4.84485                     -26.36721   -7.375751
       /cut2 |  -12.15425   4.778372                     -21.51969   -2.788816
------------------------------------------------------------------------------
```

Simple Logistic Regression Estimation of COMFD if EW_SPD < 11 (Section 6.2)

```
Iteration 0:   log likelihood = -124.37406
Iteration 1:   log likelihood = -105.72124
Iteration 2:   log likelihood = -102.54717
Iteration 3:   log likelihood = -102.44112
Iteration 4:   log likelihood = -102.44075
Iteration 5:   log likelihood = -102.44075

Logistic regression                                     Number of obs   =        334
                                                        LR chi2(18)     =      43.87
                                                        Prob > chi2     =     0.0006
Log likelihood = -102.44075                             Pseudo R2       =     0.1763

------------------------------------------------------------------------------
       comfd |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -1.159981   .3915063    -2.96   0.003    -1.927319   -.3926425
      often1 |    .027689    .515449     0.05   0.957    -.9825725     1.03795
      often2 |   .8538838   .7015415     1.22   0.224    -.5211122     2.22888
      often3 |  -.0739835   .6130596    -0.12   0.904    -1.275558    1.127591
      purps1 |  -.9429335   .7962437    -1.18   0.236    -2.503543    .6176755
      purps2 |  -.2078994   1.298986    -0.16   0.873    -2.753865    2.338067
      purps3 |   .2227917    .640035     0.35   0.728    -1.031654    1.477237
      purps4 |  -.0786748   .4754901    -0.17   0.869    -1.010618    .8532688
      locdyb |  -.1314457   .6192703    -0.21   0.832    -1.345193    1.082302
      locdvn |   .4490479   .8857987     0.51   0.612    -1.287086    2.185182
      locdcc |    .354537   .6068843     0.58   0.559    -.8349343    1.544008
         met |   .7813107   .4910065     1.59   0.112    -.1810444    1.743666
     out_min |   .0011356   .0123113     0.09   0.927     -.022994    .0252653
         clo |   -.397297   .9674308    -0.41   0.681    -2.293426    1.498832
  w_vel_e10s |  -.2538534   .1129674    -2.25   0.025    -.4752655   -.0324413
        temp |   .1209049   .0668992     1.81   0.071    -.0102152     .252025
       solar |   .0004082   .0008869     0.46   0.645      -.00133    .0021464
      r_humd |  -.0185054   .0242432    -0.76   0.445    -.0660212    .0290104
       _cons |  -2.823132   5.791838    -0.49   0.626    -14.17492    8.528661
------------------------------------------------------------------------------
```

Simple Logistic Regression Estimation of COMFD if EW_SPD ≥ 11 (Section 6.2)

```
Iteration 0:   log likelihood = -220.60343
Iteration 1:   log likelihood = -183.76568
Iteration 2:   log likelihood = -180.97553
Iteration 3:   log likelihood = -180.87266
Iteration 4:   log likelihood = -180.87243

Logistic regression                                     Number of obs   =        367
                                                        LR chi2(18)     =      79.46
                                                        Prob > chi2     =     0.0000
Log likelihood = -180.87243                             Pseudo R2       =     0.1801

------------------------------------------------------------------------------
       comfd |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -.6235927   .2801483    -2.23   0.026    -1.172673    -.074512
      often1 |   .5338703   .3750039     1.42   0.155    -.2011238    1.268864
      often2 |   .0583429   .3930192     0.15   0.882    -.7119605    .8286463
      often3 |   .0811259   .3835976     0.21   0.833    -.6707116    .8329634
      purps1 |   .0285351   .6638876     0.04   0.966    -1.272661    1.329731
      purps2 |   1.997925   1.209154     1.65   0.098    -.3719743    4.367824
      purps3 |  -.3636843   .4588248    -0.79   0.428    -1.262964    .5355958
```

```
      purps4 |   .2287032   .3527318     0.65   0.517    -.4626384    .9200448
      locdyb |  -.4989446   .5213898    -0.96   0.339     -1.52085    .5229606
      locdvn |   .0668484   .5095352     0.13   0.896    -.9318222    1.065519
      locdcc |   .2935965   .6352854     0.46   0.644      -.95154    1.538733
         met |   .5531486   .3421156     1.62   0.106    -.1173856    1.223683
     out_min |   .0042954   .0079414     0.54   0.589    -.0112694    .0198602
         clo |   .9605628   .5988462     1.60   0.109    -.2131542     2.13428
   w_vel_e10s |   -.165747   .0473586    -3.50   0.000    -.2585682   -.0729258
        temp |   .2332694   .0686458     3.40   0.001     .0987262    .3678127
       solar |    .001892    .000857     2.21   0.027     .0002123    .0035717
      r_humd |   .0297145   .0256545     1.16   0.247    -.0205675    .0799965
       _cons |  -15.32562   6.128768    -2.50   0.012    -27.33779    -3.31346
------------------------------------------------------------------------------
```

ANOVA Comparison of EW_SPD and WAIT_TR (Section 7.2)

```
                    Number of obs =     701     R-squared     =  0.0348
                    Root MSE      = 4.29909     Adj R-squared =  0.0320

    Source |  Partial SS    df       MS           F     Prob > F
-----------+----------------------------------------------------
     Model |  465.029397     2  232.514698      12.58     0.0000
           |
   wait_tr |  465.029397     2  232.514698      12.58     0.0000
           |
  Residual |  12900.5693   698  18.4821909
-----------+----------------------------------------------------
     Total |  13365.5987   700  19.0937124
```

ANOVA Comparison of EW_SPD and BIKE (Section 7.2)

```
                    Number of obs =     701     R-squared     =  0.0344
                    Root MSE      = 4.30001     Adj R-squared =  0.0316

    Source |  Partial SS    df       MS           F     Prob > F
-----------+----------------------------------------------------
     Model |  459.507759     2   229.75388      12.43     0.0000
           |
      bike |  459.507759     2   229.75388      12.43     0.0000
           |
  Residual |  12906.0909   698  18.4901016
-----------+----------------------------------------------------
     Total |  13365.5987   700  19.0937124
```

ANOVA Comparison of EW_SPD and WALK_O (Section 7.2)

```
                    Number of obs =     701     R-squared     =  0.0348
                    Root MSE      = 4.29897     Adj R-squared =  0.0321

    Source |  Partial SS    df       MS           F     Prob > F
-----------+----------------------------------------------------
     Model |  465.786635     2  232.893318      12.60     0.0000
           |
    walk_o |  465.786635     2  232.893318      12.60     0.0000
           |
  Residual |   12899.812   698   18.481106
-----------+----------------------------------------------------
```

```
       Total |  13365.5987   700  19.0937124
```

ANOVA Comparison of EW_SPD and WIT_O (Section 7.2)

```
                          Number of obs =     701     R-squared     =  0.0555
                          Root MSE      = 4.25268     Adj R-squared =  0.0528

      Source |  Partial SS    df       MS           F     Prob > F
-------------+----------------------------------------------------
       Model |  742.065508     2  371.032754      20.52     0.0000
             |
       sit_o |  742.065508     2  371.032754      20.52     0.0000
             |
    Residual |  12623.5331   698   18.085291
-------------+----------------------------------------------------
       Total |  13365.5987   700  19.0937124
```

Ordinal Logistic Regression Estimation of WAIT_TR (Section 7.2)

```
Iteration 0:   log likelihood = -710.06372
Iteration 1:   log likelihood = -684.87667
Iteration 2:   log likelihood = -684.74485
Iteration 3:   log likelihood = -684.74481

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(15)     =      50.64
                                                Prob > chi2     =     0.0000
Log likelihood = -684.74481                     Pseudo R2       =     0.0357

------------------------------------------------------------------------------
     wait_tr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .2847567    .153435     1.86   0.063    -.0159703    .5854838
      locdyb |  -.0536328   .2427387    -0.22   0.825    -.5293919    .4221262
      locdvn |  -.5679953   .2835604    -2.00   0.045    -1.123763   -.0122272
      locdcc |  -.2780617   .2599193    -1.07   0.285    -.7874942    .2313707
         met |   .1932666   .1680673     1.15   0.250    -.1361393    .5226724
     out_min |  -.0049095   .0043527    -1.13   0.259    -.0134407    .0036218
         clo |  -.1550292   .3341977    -0.46   0.643    -.8100447    .4999862
  w_vel_e10s |   .0787067   .0203471     3.87   0.000     .0388271    .1185862
        temp |  -.0603876   .0283073    -2.13   0.033    -.1158689   -.0049063
       solar |    .000192   .0003526     0.54   0.586    -.0004991    .0008832
      r_humd |   .0017233   .0109996     0.16   0.876    -.0198356    .0232822
    trnst_so |  -.4192098   .2353211    -1.78   0.075    -.8804307    .0420111
    trnst_fr |  -.2620711   .2082791    -1.26   0.208    -.6702907    .1461485
     bikg_so |   .1151477   .1881826     0.61   0.541    -.2536833    .4839788
     bikg_fr |  -.4134167   .2115146    -1.95   0.051    -.8279777    .0011442
-------------+----------------------------------------------------------------
       /cut1 |  -3.031306   2.492272                   -7.916071    1.853458
       /cut2 |  -1.433895   2.490164                   -6.314528    3.446737
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of BIKE (Section 7.2)

```
Iteration 0:   log likelihood = -743.47521
Iteration 1:   log likelihood = -724.12597
```

```
Iteration 2:   log likelihood =  -724.0778
Iteration 3:   log likelihood = -724.07779

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(15)     =      38.79
                                                Prob > chi2     =     0.0007
Log likelihood = -724.07779                     Pseudo R2       =     0.0261

------------------------------------------------------------------------------
        bike |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .1880511   .1507798     1.25   0.212    -.1074719    .4835742
      locdyb |   .0892857   .2370575     0.38   0.706    -.3753384    .5539098
      locdvn |  -.3486877   .2756542    -1.26   0.206    -.8889601    .1915846
      locdcc |  -.1583383   .2507403    -0.63   0.528    -.6497803    .3331037
         met |   .0263483   .1673128     0.16   0.875    -.3015788    .3542754
     out_min |  -.0018655    .004293    -0.43   0.664    -.0102796    .0065486
         clo |    .076727   .3262197     0.24   0.814    -.5626519    .7161058
  w_vel_e10s |   .0803364   .0205504     3.91   0.000     .0400583    .1206145
        temp |  -.0344431   .0273701    -1.26   0.208    -.0880875    .0192012
       solar |   .0001941   .0003465     0.56   0.575     -.000485    .0008732
      r_humd |   .0054446   .0106744     0.51   0.610    -.0154768     .026366
    trnst_so |  -.0116077   .2277506    -0.05   0.959    -.4579906    .4347753
    trnst_fr |   .0784369   .2016977     0.39   0.697    -.3168833    .4737572
     bikg_so |   .0865565   .1818174     0.48   0.634    -.2697991    .4429122
     bikg_fr |  -.2757434    .200241    -1.38   0.168    -.6682085    .1167218
-------------+----------------------------------------------------------------
       /cut1 |  -.9541501   2.407025                     -5.671832    3.763532
       /cut2 |    .504814   2.406721                     -4.212273    5.221901
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of WALK_O (Section 7.2)

```
Iteration 0:   log likelihood = -620.94846
Iteration 1:   log likelihood = -599.11811
Iteration 2:   log likelihood = -598.96612
Iteration 3:   log likelihood = -598.96608

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(15)     =      43.96
                                                Prob > chi2     =     0.0001
Log likelihood = -598.96608                     Pseudo R2       =     0.0354

------------------------------------------------------------------------------
      walk_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .2696247   .1612645     1.67   0.095    -.0464479    .5856973
      locdyb |  -.0602392   .2532482    -0.24   0.812    -.5565966    .4361182
      locdvn |  -.2932857   .2881593    -1.02   0.309    -.8580676    .2714962
      locdcc |  -.3675777   .2707992    -1.36   0.175    -.8983344     .163179
         met |   .0355637   .1761806     0.20   0.840     -.309744    .3808714
     out_min |   .0004581   .0045407     0.10   0.920    -.0084415    .0093578
         clo |   .6516556   .3474647     1.88   0.061    -.0293627    1.332674
  w_vel_e10s |   .0540196   .0209094     2.58   0.010     .0130379    .0950014
        temp |  -.0475904   .0298807    -1.59   0.111    -.1061555    .0109747
       solar |  -.0001681   .0003857    -0.44   0.663    -.0009241    .0005879
      r_humd |   .0072956   .0115687     0.63   0.528    -.0153786    .0299697
    trnst_so |  -.1262194   .2516029    -0.50   0.616     -.619352    .3669133
    trnst_fr |   .1877202   .2211438     0.85   0.396    -.2457136    .6211541
     bikg_so |  -.1599076   .2056325    -0.78   0.437      -.56294    .2431247
     bikg_fr |   -.064637   .2158303    -0.30   0.765    -.4876567    .3583827
```

```
-------------+----------------------------------------------------------------
       /cut1 |  -.8947446   2.601578                      -5.993744    4.204255
       /cut2 |   1.159766   2.603393                       -3.94279    6.262322
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of SIT_O (Section 7.2)

```
Iteration 0:   log likelihood = -749.97932
Iteration 1:   log likelihood =  -689.9848
Iteration 2:   log likelihood = -689.36649
Iteration 3:   log likelihood = -689.36512

Ordered logistic regression                     Number of obs   =        701
                                                LR chi2(15)     =     121.23
                                                Prob > chi2     =     0.0000
Log likelihood = -689.36512                     Pseudo R2       =     0.0808

------------------------------------------------------------------------------
       sit_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |    .524086   .1547151     3.39   0.001       .22085     .827322
      locdyb |   -.266878   .2440894    -1.09   0.274    -.7452844    .2115284
      locdvn |  -.4733392   .2892782    -1.64   0.102    -1.040314    .0936357
      locdcc |  -.8296198   .2597643    -3.19   0.001    -1.338748   -.3204912
         met |  -.2168394   .1717435    -1.26   0.207    -.5534505    .1197717
     out_min |  -.0105246   .0043727    -2.41   0.016    -.0190949   -.0019543
         clo |  -.3294626   .3292976    -1.00   0.317     -.974874    .3159488
  w_vel_e10s |   .0716654   .0210828     3.40   0.001     .0303438    .1129869
        temp |  -.1178761   .0279272    -4.22   0.000    -.1726124   -.0631398
       solar |  -.0001911   .0003465    -0.55   0.581    -.0008702     .000488
      r_humd |   .0080507   .0105443     0.76   0.445    -.0126157    .0287171
    trnst_so |  -.2997851   .2343571    -1.28   0.201    -.7591167    .1595464
    trnst_fr |  -.2168383   .2065669    -1.05   0.294    -.6217019    .1880253
     bikg_so |  -.2375978   .1909348    -1.24   0.213    -.6118231    .1366274
     bikg_fr |  -.0946924   .2046756    -0.46   0.644    -.4958493    .3064645
-------------+----------------------------------------------------------------
       /cut1 |  -8.895942   2.437098                     -13.67257   -4.119318
       /cut2 |  -7.037572   2.427426                     -11.79524   -2.279904
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of WAIT_TR if EW_SPD < 11 (Section 7.3)

```
Iteration 0:   log likelihood = -322.63809
Iteration 1:   log likelihood = -309.33514
Iteration 2:   log likelihood = -309.20919
Iteration 3:   log likelihood = -309.20913

Ordered logistic regression                     Number of obs   =        334
                                                LR chi2(15)     =      26.86
                                                Prob > chi2     =     0.0299
Log likelihood = -309.20913                     Pseudo R2       =     0.0416

------------------------------------------------------------------------------
     wait_tr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .3840729    .231431     1.66   0.097    -.0695236    .8376694
      locdyb |   .3393555   .3304404     1.03   0.304    -.3082958    .9870069
      locdvn |  -.6292912   .5225572    -1.20   0.228    -1.653485    .3949022
```

```
      locdcc |   -.246036   .3455198    -0.71   0.476    -.9232424    .4311704
         met |   .0052005   .2399543     0.02   0.983    -.4651014    .4755023
     out_min |  -.0074692   .0066838    -1.12   0.264    -.0205693    .0056309
         clo |  -.2293349   .5245564    -0.44   0.662    -1.257446    .7987767
  w_vel_e10s |   .0745934   .0587466     1.27   0.204    -.0405478    .1897347
        temp |  -.0509099   .0382869    -1.33   0.184    -.1259509    .0241311
       solar |   .0003497   .0004686     0.75   0.455    -.0005686    .0012681
      r_humd |   .0067907   .0145444     0.47   0.641    -.0217158    .0352971
    trnst_so |  -.9757933   .3512962    -2.78   0.005    -1.664321   -.2872655
    trnst_fr |  -.5483687   .3014769    -1.82   0.069    -1.139253    .0425152
     bikg_so |   .0162369   .2885219     0.06   0.955    -.5492556    .5817295
     bikg_fr |  -.5759496   .3005858    -1.92   0.055    -1.165087    .0131877
-------------+----------------------------------------------------------------
       /cut1 |  -2.773878   3.341419                     -9.322939    3.775183
       /cut2 |  -1.233177   3.337944                     -7.775427    5.309073
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of WAIT_TR if EW_SPD ≥ 11 (Section 7.3)

```
Iteration 0:   log likelihood = -383.31013
Iteration 1:   log likelihood = -367.44042
Iteration 2:   log likelihood =  -367.3402
Iteration 3:   log likelihood = -367.34016

Ordered logistic regression                     Number of obs   =        367
                                                LR chi2(15)     =      31.94
                                                Prob > chi2     =     0.0066
Log likelihood = -367.34016                     Pseudo R2       =     0.0417

------------------------------------------------------------------------------
     wait_tr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .2610518   .2123398     1.23   0.219    -.1551265    .6772301
      locdyb |  -.5098182   .3943253    -1.29   0.196    -1.282682    .2630452
      locdvn |  -.8089618   .3864607    -2.09   0.036    -1.566411   -.0515128
      locdcc |  -.4348766   .4374723    -0.99   0.320    -1.292307    .4225534
         met |   .4706655   .2486991     1.89   0.058    -.0167759    .9581068
     out_min |  -.0024879   .0059332    -0.42   0.675    -.0141168    .0091411
         clo |  -.1993884   .4471575    -0.45   0.656    -1.075801    .6770242
  w_vel_e10s |   .1009997   .0346657     2.91   0.004     .0330561    .1689433
        temp |  -.0787112   .0454129    -1.73   0.083    -.1677188    .0102963
       solar |  -.0002205   .0005707    -0.39   0.699     -.001339     .000898
      r_humd |  -.0039118   .0183048    -0.21   0.831    -.0397886     .031965
    trnst_so |  -.0326089   .3309254    -0.10   0.922    -.6812108     .615993
    trnst_fr |  -.0014721   .2952112    -0.00   0.996    -.5800754    .5771312
     bikg_so |   .1575705   .2522112     0.62   0.532    -.3367544    .6518954
     bikg_fr |  -.3363609   .3106605    -1.08   0.279    -.9452443    .2725225
-------------+----------------------------------------------------------------
       /cut1 |  -3.816361   4.077815                     -11.80873    4.176009
       /cut2 |  -2.124037   4.074939                     -10.11077    5.862697
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of BIKE if EW_SPD < 11 (Section 7.3)

```
Iteration 0:   log likelihood = -340.05671
Iteration 1:   log likelihood =  -322.1446
Iteration 2:   log likelihood = -321.98398
Iteration 3:   log likelihood = -321.98388
```

```
Ordered logistic regression                     Number of obs   =        334
                                                LR chi2(15)     =      36.15
                                                Prob > chi2     =     0.0017
Log likelihood = -321.98388                     Pseudo R2       =     0.0531

------------------------------------------------------------------------------
        bike |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .0695991     .22781     0.31   0.760    -.3769003    .5160986
      locdyb |   .0488671   .3271158     0.15   0.881     -.592268    .6900022
      locdvn |  -.7402226   .4970401    -1.49   0.136    -1.714403    .2339581
      locdcc |  -.5767332   .3399178    -1.70   0.090     -1.24296    .0894934
         met |   .3064877   .2373214     1.29   0.197    -.1586537     .771629
     out_min |  -.0128528   .0066977    -1.92   0.055      -.02598    .0002744
         clo |   1.273119   .5314474     2.40   0.017     .2315007    2.314736
  w_vel_e10s |    .181178   .0591688     3.06   0.002     .0652093    .2971467
        temp |   .0029616   .0372622     0.08   0.937    -.0700709    .0759942
       solar |   .0004876   .0004774     1.02   0.307    -.0004481    .0014233
      r_humd |   .0310935   .0144147     2.16   0.031     .0028412    .0593459
    trnst_so |  -.0820042   .3470679    -0.24   0.813    -.7622448    .5982364
    trnst_fr |   .4079701   .3051885     1.34   0.181    -.1901884    1.006129
     bikg_so |  -.0629129   .2818323    -0.22   0.823     -.615294    .4894683
     bikg_fr |  -.2133088    .281004    -0.76   0.448    -.7640666     .337449
-------------+----------------------------------------------------------------
       /cut1 |   5.183056   3.276101                    -1.237984     11.6041
       /cut2 |   6.686325   3.284821                     .2481953    13.12446
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of BIKE if EW_SPD ≥ 11 (Section 7.3)

```
Iteration 0:   log likelihood = -398.19935
Iteration 1:   log likelihood = -388.92281
Iteration 2:   log likelihood = -388.90231
Iteration 3:   log likelihood = -388.90231

Ordered logistic regression                     Number of obs   =        367
                                                LR chi2(15)     =      18.59
                                                Prob > chi2     =     0.2327
Log likelihood = -388.90231                     Pseudo R2       =     0.0233

------------------------------------------------------------------------------
        bike |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |    .217655   .2088893     1.04   0.297    -.1917605    .6270705
      locdyb |    .045597   .3887223     0.12   0.907    -.7162848    .8074788
      locdvn |  -.2142689   .3772786    -0.57   0.570    -.9537215    .5251836
      locdcc |  -.0478664   .4214076    -0.11   0.910    -.8738101    .7780773
         met |  -.1904095   .2456747    -0.78   0.438     -.671923     .291104
     out_min |   .0062377   .0058708     1.06   0.288    -.0052689    .0177443
         clo |  -.6632517   .4331201    -1.53   0.126    -1.512151    .1856481
  w_vel_e10s |   .0712461   .0358208     1.99   0.047     .0010387    .1414535
        temp |  -.0863976   .0444372    -1.94   0.052     -.173493    .0006978
       solar |  -.0000475     .00056    -0.08   0.932     -.001145      .00105
      r_humd |  -.0189927   .0179576    -1.06   0.290    -.0541888    .0162035
    trnst_so |   .1098592   .3166436     0.35   0.729    -.5107508    .7304692
    trnst_fr |  -.0296617   .2817633    -0.11   0.916    -.5819075    .5225842
     bikg_so |   .2124907   .2438798     0.87   0.384    -.2655049    .6904864
     bikg_fr |  -.3635603   .2983227    -1.22   0.223     -.948262    .2211414
-------------+----------------------------------------------------------------
       /cut1 |  -6.851276   3.991361                    -14.6742    .9716474
```

```
       /cut2 |  -5.353081   3.984799                      -13.16314    2.456981
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of WALK_O if EW_SPD < 11 (Section 7.3)

```
Iteration 0:   log likelihood = -286.85085
Iteration 1:   log likelihood = -280.46679
Iteration 2:   log likelihood = -280.42413
Iteration 3:   log likelihood = -280.42412

Ordered logistic regression                     Number of obs   =        334
                                                LR chi2(15)     =      12.85
                                                Prob > chi2     =     0.6136
Log likelihood = -280.42412                     Pseudo R2       =     0.0224

------------------------------------------------------------------------------
      walk_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .2422722   .2396673     1.01   0.312    -.2274671    .7120114
      locdyb |   .1139608   .3376432     0.34   0.736    -.5478077    .7757293
      locdvn |  -.5133987   .5316862    -0.97   0.334    -1.555485    .5286872
      locdcc |   -.424421   .3532343    -1.20   0.230    -1.116747    .2679054
         met |   .0331772   .2420792     0.14   0.891    -.4412893    .5076437
     out_min |  -.0049971   .0068522    -0.73   0.466    -.0184271     .008433
         clo |   .8429527   .5609069     1.50   0.133    -.2564047     1.94231
  w_vel_e10s |   .0142054   .0603141     0.24   0.814    -.1040081    .1324189
        temp |  -.0066893    .040112    -0.17   0.868    -.0853073    .0719287
       solar |   .0001022   .0005064     0.20   0.840    -.0008903    .0010948
      r_humd |    .018731   .0152302     1.23   0.219    -.0111196    .0485815
    trnst_so |   -.384567   .3701839    -1.04   0.299    -1.110114      .34098
    trnst_fr |   .0657024   .3188764     0.21   0.837    -.5592839    .6906888
     bikg_so |  -.1033724   .3150122    -0.33   0.743     -.720785    .5140401
     bikg_fr |   -.000353    .297809    -0.00   0.999     -.584048     .583342
-------------+----------------------------------------------------------------
       /cut1 |    2.12112   3.474059                     -4.68791     8.93015
       /cut2 |   3.769792   3.478309                     -3.047568    10.58715
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of WALK_O if EW_SPD ≥ 11 (Section 7.3)

```
Iteration 0:   log likelihood = -328.04078
Iteration 1:   log likelihood =  -309.1713
Iteration 2:   log likelihood =  -308.9999
Iteration 3:   log likelihood =  -308.9997

Ordered logistic regression                     Number of obs   =        367
                                                LR chi2(15)     =      38.08
                                                Prob > chi2     =     0.0009
Log likelihood =  -308.9997                     Pseudo R2       =     0.0580

------------------------------------------------------------------------------
      walk_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .3473004   .2252332     1.54   0.123    -.0941486    .7887494
      locdyb |  -.1316763   .4262828    -0.31   0.757    -.9671752    .7038226
      locdvn |  -.2617023   .4051288    -0.65   0.518     -1.05574    .5323356
      locdcc |  -.2825479   .4740247    -0.60   0.551    -1.211619    .6465235
         met |   .0927117    .265984     0.35   0.727    -.4286073    .6140307
```

```
     out_min |   .0052975   .0063098     0.84   0.401    -.0070695    .0176646
         clo |   .4876801   .4604259     1.06   0.290     -.414738    1.390098
  w_vel_e10s |   .0923702   .0362373     2.55   0.011     .0213463    .1633941
        temp |  -.0941211   .0486795    -1.93   0.053    -.1895312     .001289
       solar |  -.0006224   .0006318    -0.99   0.325    -.0018607    .0006159
      r_humd |  -.0036959   .0195426    -0.19   0.850    -.0419987    .0346069
    trnst_so |   .0718833   .3547288     0.20   0.839    -.6233724     .767139
    trnst_fr |   .3718087   .3142697     1.18   0.237    -.2441485     .987766
     bikg_so |  -.2237131   .2776188    -0.81   0.420    -.7678358    .3204097
     bikg_fr |  -.1966425   .3250908    -0.60   0.545    -.8338087    .4405237
-------------+----------------------------------------------------------------
       /cut1 |  -3.858146   4.328792                     -12.34242     4.62613
       /cut2 |  -1.384186   4.329387                     -9.869629    7.101258
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of SIT_O if EW_SPD < 11 (Section 7.3)

```
Iteration 0:   log likelihood = -365.00962
Iteration 1:   log likelihood =  -338.7919
Iteration 2:   log likelihood = -338.61145
Iteration 3:   log likelihood = -338.61116

Ordered logistic regression                     Number of obs   =        334
                                                LR chi2(15)     =      52.80
                                                Prob > chi2     =     0.0000
Log likelihood = -338.61116                     Pseudo R2       =     0.0723

------------------------------------------------------------------------------
       sit_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .5070363   .2237836     2.27   0.023     .0684286     .945644
      locdyb |  -.2386983   .3149234    -0.76   0.448    -.8559368    .3785402
      locdvn |  -.9315081   .4752223    -1.96   0.050    -1.862927   -.0000896
      locdcc |   -.994247   .3291156    -3.02   0.003    -1.639302   -.3491922
         met |  -.1212392    .232568    -0.52   0.602    -.5770641    .3345857
     out_min |  -.0178769   .0064345    -2.78   0.005    -.0304884   -.0052654
         clo |  -.0587598   .5005012    -0.12   0.907    -1.039724    .9222045
  w_vel_e10s |   .0856107   .0551038     1.55   0.120    -.0223908    .1936123
        temp |    -.07295   .0369905    -1.97   0.049      -.14545     -.00045
       solar |   .0002748    .000453     0.61   0.544     -.000613    .0011626
      r_humd |   .0277882   .0136845     2.03   0.042      .000967    .0546094
    trnst_so |  -.8471096   .3402011    -2.49   0.013    -1.513891   -.1803278
    trnst_fr |  -.4277228   .3012763    -1.42   0.156    -1.018214     .162768
     bikg_so |  -.3073737   .2792531    -1.10   0.271    -.8546997    .2399522
     bikg_fr |  -.3226631    .279597    -1.15   0.248    -.8706631    .2253368
-------------+----------------------------------------------------------------
       /cut1 |  -4.681063   3.167611                     -10.88947    1.527342
       /cut2 |  -2.895152   3.161785                     -9.092136    3.301832
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of SIT_O if EW_SPD ≥ 11 (Section 7.3)

```
Iteration 0:   log likelihood = -376.08764
Iteration 1:   log likelihood = -340.47785
Iteration 2:   log likelihood = -339.85983
Iteration 3:   log likelihood = -339.85751

Ordered logistic regression                     Number of obs   =        367
```

```
                                                  LR chi2(15)     =      72.46
                                                  Prob > chi2     =     0.0000
Log likelihood = -339.85751                       Pseudo R2       =     0.0963

------------------------------------------------------------------------------
       sit_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .6235592     .22204     2.81   0.005     .1883687     1.05875
      locdyb |  -.3641772    .437029    -0.83   0.405    -1.220738    .4923838
      locdvn |  -.2893186   .4350684    -0.66   0.506    -1.142037    .5633998
      locdcc |  -.7992907   .4796955    -1.67   0.096    -1.739477    .1408953
         met |  -.1994769   .2621926    -0.76   0.447     -.713365    .3144111
     out_min |  -.0053403   .0061501    -0.87   0.385    -.0173943    .0067136
         clo |  -.6638638   .4489646    -1.48   0.139    -1.543818    .2160907
  w_vel_e10s |   .0724473   .0385158     1.88   0.060    -.0030422    .1479369
        temp |  -.2052932   .0472866    -4.34   0.000    -.2979732   -.1126133
       solar |  -.0011129   .0005815    -1.91   0.056    -.0022526    .0000268
      r_humd |  -.0223969   .0183773    -1.22   0.223    -.0584158     .013622
    trnst_so |   .1187811   .3363354     0.35   0.724    -.5404243    .7779864
    trnst_fr |  -.0153263   .2907347    -0.05   0.958    -.5851558    .5545033
     bikg_so |  -.1938014   .2655617    -0.73   0.466    -.7142927    .3266899
     bikg_fr |   .1166949   .3144434     0.37   0.711    -.4996028    .7329926
-------------+----------------------------------------------------------------
       /cut1 |  -16.60368    4.24329                     -24.92037   -8.286984
       /cut2 |  -14.57077   4.217313                     -22.83656   -6.304993
------------------------------------------------------------------------------
```

Ordinal Logistic Regression Estimation of SIT_O if EW_SPD < 7 (Section 7.3)

```
Iteration 0:   log likelihood = -106.37031
Iteration 1:   log likelihood = -86.523197
Iteration 2:   log likelihood = -86.076107
Iteration 3:   log likelihood = -86.071004
Iteration 4:   log likelihood = -86.071003

Ordered logistic regression                       Number of obs   =         97
                                                  LR chi2(15)     =      40.60
                                                  Prob > chi2     =     0.0004
Log likelihood = -86.071003                       Pseudo R2       =     0.1908

------------------------------------------------------------------------------
       sit_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |  -1.013801   .4655086    -2.18   0.029    -1.926181   -.1014207
      locdyb |   .9074778   .5838171     1.55   0.120    -.2367827    2.051738
      locdvn |  -2.845526   1.145812    -2.48   0.013    -5.091276   -.5997764
      locdcc |  -1.352796   .6961789    -1.94   0.052    -2.717282     .011689
         met |   .1868621   .4034922     0.46   0.643    -.6039681    .9776922
     out_min |  -.0439929   .0138008    -3.19   0.001     -.071042   -.0169438
         clo |   1.228583   1.084169     1.13   0.257    -.8963484    3.353514
  w_vel_e10s |  -.1026648   .2147083    -0.48   0.633    -.5234854    .3181558
        temp |   .0032507   .0768675     0.04   0.966    -.1474069    .1539083
       solar |   .0001553   .0009589     0.16   0.871    -.0017241    .0020346
      r_humd |   .0645347   .0281722     2.29   0.022     .0093182    .1197512
    trnst_so |  -.5666369   .7102314    -0.80   0.425    -1.958665     .825391
    trnst_fr |  -.0043686   .6516629    -0.01   0.995    -1.281604    1.272867
     bikg_so |  -2.393218   .6779151    -3.53   0.000    -3.721907   -1.064529
     bikg_fr |   .0552578   .5887541     0.09   0.925    -1.098679    1.209195
-------------+----------------------------------------------------------------
       /cut1 |   2.041009   6.504676                     -10.70792    14.78994
       /cut2 |   3.932224   6.524736                     -8.856023    16.72047
```

Ordinal Logistic Regression Estimation of SIT_O if EW_SPD ≥ 7 (Section 7.3)

```
Iteration 0:   log likelihood =  -638.0218
Iteration 1:   log likelihood = -579.36255
Iteration 2:   log likelihood = -578.53744
Iteration 3:   log likelihood = -578.53475

Ordered logistic regression                     Number of obs   =        604
                                                LR chi2(15)     =     118.97
                                                Prob > chi2     =     0.0000
Log likelihood = -578.53475                     Pseudo R2       =     0.0932

------------------------------------------------------------------------------
       sit_o |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       sexid |   .7584451   .1707422     4.44   0.000     .4237965    1.093094
      locdyb |  -.4400704   .2818061    -1.56   0.118    -.9924001    .1122593
      locdvn |  -.5358126   .3196394    -1.68   0.094    -1.162294    .0906692
      locdcc |  -.9242249   .2961162    -3.12   0.002    -1.504602   -.3438478
         met |  -.3102282   .1961849    -1.58   0.114    -.6947435    .0742871
     out_min |  -.0069417   .0048287    -1.44   0.151    -.0164057    .0025223
         clo |  -.4050025   .3568005    -1.14   0.256    -1.104319    .2943137
  w_vel_e10s |   .0713807   .0261722     2.73   0.006      .020084    .1226774
        temp |  -.1522301   .0316545    -4.81   0.000    -.2142719   -.0901883
       solar |  -.0001572   .0003879    -0.41   0.685    -.0009174     .000603
      r_humd |   .0000429   .0122698     0.00   0.997    -.0240055    .0240913
    trnst_so |  -.2146024    .259037    -0.83   0.407    -.7223055    .2931007
    trnst_fr |  -.2536778   .2240831    -1.13   0.258    -.6928726     .185517
     bikg_so |   .0244173   .2080365     0.12   0.907    -.3833267    .4321614
     bikg_fr |  -.0980768   .2261165    -0.43   0.664     -.541257    .3451033
-------------+----------------------------------------------------------------
       /cut1 |   -11.7863   2.807846                     -17.28958   -6.283028
       /cut2 |  -9.815969    2.79334                     -15.29081   -4.341123
------------------------------------------------------------------------------
```

Goodman and Kruskal's Gamma Test of FEEL and WAIT_TR (Section 7.3)

```
           |                                feel2
   WAIT_TR |         1          2          3          4          5          6          7 |     Total
-----------+-------------------------------------------------------------------------------+----------
         1 |        10         33        136         93         55         25          5 |       357
         2 |        18         39         84         44         22         13          1 |       221
         3 |        15         28         39         26          9          3          3 |       123
-----------+-------------------------------------------------------------------------------+----------
     Total |        43        100        259        163         86         41          9 |       701

                  gamma =  -0.2608  ASE = 0.046
```

Goodman and Kruskal's Gamma Test of FEEL and BIKE (Section 7.3)

```
           |                                feel2
      BIKE |         1          2          3          4          5          6          7 |     Total
-----------+-------------------------------------------------------------------------------+----------
         1 |        17         31        123         74         46         21          6 |       318
         2 |         8         39         73         58         27         16          1 |       222
         3 |        18         30         63         31         13          4          2 |       161
```

```
-----------+-------------------------------------------------------------------------------+----------
     Total |        43        100        259        163         86         41          9 |       701

                   gamma =  -0.1756  ASE = 0.045
```

Goodman and Kruskal's Gamma Test of FEEL and WALK_O (Section 7.3)

```
           |                                feel2
    WALK_O |         1          2          3          4          5          6          7 |     Total
-----------+-------------------------------------------------------------------------------+----------
         1 |         9         47        155        111         60         30          5 |       417
         2 |        20         44         89         34         23         10          3 |       223
         3 |        14          9         15         18          3          1          1 |        61
-----------+-------------------------------------------------------------------------------+----------
     Total |        43        100        259        163         86         41          9 |       701

                   gamma =  -0.2917  ASE = 0.050
```

Goodman and Kruskal's Gamma Test of FEEL and SIT_O (Section 7.3)

```
           |                                feel2
     SIT_O |         1          2          3          4          5          6          7 |     Total
-----------+-------------------------------------------------------------------------------+----------
         1 |         0          6         44         50         37         16          5 |       158
         2 |         7         32        116         58         28         18          1 |       260
         3 |        36         62         99         55         21          7          3 |       283
-----------+-------------------------------------------------------------------------------+----------
     Total |        43        100        259        163         86         41          9 |       701

                   gamma =  -0.4245  ASE = 0.039
```

Goodman and Kruskal's Gamma Test of W_FEEL and WAIT_TR (Section 7.3)

```
           |                        W_FEEL
   WAIT_TR |         1          2          3          4          5 |     Total
-----------+--------------------------------------------------------+----------
         1 |         6        132        159         57          3 |       357
         2 |         2         47        116         52          4 |       221
         3 |         1         21         49         44          8 |       123
-----------+--------------------------------------------------------+----------
     Total |         9        200        324        153         15 |       701

                   gamma =   0.3440  ASE = 0.050
```

Goodman and Kruskal's Gamma Test of W_FEEL and BIKE (Section 7.3)

```
           |                        W_FEEL
      BIKE |         1          2          3          4          5 |     Total
-----------+--------------------------------------------------------+----------
         1 |         5        118        139         51          5 |       318
         2 |         1         58        116         43          4 |       222
         3 |         3         24         69         59          6 |       161
-----------+--------------------------------------------------------+----------
     Total |         9        200        324        153         15 |       701

                   gamma =   0.3106  ASE = 0.049
```

Goodman and Kruskal's Gamma Test of W_FEEL and WALK_O (Section 7.3)

```
           |                        W_FEEL
    WALK_O |         1          2          3          4          5 |     Total
```

```
-----------+---------------------------------------------------+----------
         1 |         4        152        192         64          5 |       417
         2 |         3         35        108         71          6 |       223
         3 |         2         13         24         18          4 |        61
-----------+---------------------------------------------------+----------
     Total |         9        200        324        153         15 |       701

                  gamma =   0.3515  ASE = 0.054
```

Goodman and Kruskal's Gamma Test of W_FEEL and SIT_O (Section 7.3)

```
           |                        W_FEEL
     SIT_O |         1          2          3          4          5 |     Total
-----------+---------------------------------------------------+----------
         1 |         3         76         61         16          2 |       158
         2 |         3         81        128         46          2 |       260
         3 |         3         43        135         91         11 |       283
-----------+---------------------------------------------------+----------
     Total |         9        200        324        153         15 |       701

                  gamma =   0.4239  ASE = 0.045
```

Goodman and Kruskal's Gamma Test of W_PREF and WAIT_TR (Section 7.3)

```
           |              W_PREF
   WAIT_TR |         1          2          3 |     Total
-----------+---------------------------------+----------
         1 |        21        207        129 |       357
         2 |         5         85        131 |       221
         3 |         0         28         95 |       123
-----------+---------------------------------+----------
     Total |        26        320        355 |       701

                  gamma =   0.5171  ASE = 0.049
```

Goodman and Kruskal's Gamma Test of W_ PREF and BIKE (Section 7.3)

```
           |              W_PREF
      BIKE |         1          2          3 |     Total
-----------+---------------------------------+----------
         1 |        19        163        136 |       318
         2 |         6        104        112 |       222
         3 |         1         53        107 |       161
-----------+---------------------------------+----------
     Total |        26        320        355 |       701

                  gamma =   0.2997  ASE = 0.056
```

Goodman and Kruskal's Gamma Test of W_ PREF and WALK_O (Section 7.3)

```
           |              W_PREF
    WALK_O |         1          2          3 |     Total
-----------+---------------------------------+----------
         1 |        23        240        154 |       417
         2 |         3         63        157 |       223
         3 |         0         17         44 |        61
-----------+---------------------------------+----------
     Total |        26        320        355 |       701

                  gamma =   0.5619  ASE = 0.051
```

Goodman and Kruskal's Gamma Test of W_ PREF and SIT_O (Section 7.3)

	W_PREF		
SIT_O	1	2	3	Total
1	18	114	26	158
2	7	131	122	260
3	1	75	207	283
Total	26	320	355	701

gamma = 0.6552 ASE = 0.038

Goodman and Kruskal's Gamma Test of COMFD and WAIT_TR (Section 7.3)

	COMFD		
WAIT_TR	0	1	Total
1	32	325	357
2	58	163	221
3	57	66	123
Total	147	554	701

gamma = -0.6141 ASE = 0.051

Goodman and Kruskal's Gamma Test of COMFD and BIKE (Section 7.3)

	COMFD		
BIKE	0	1	Total
1	38	280	318
2	54	168	222
3	55	106	161
Total	147	554	701

gamma = -0.4226 ASE = 0.063

Goodman and Kruskal's Gamma Test of COMFD and WALK_O (Section 7.3)

	COMFD		
WALK_O	0	1	Total
1	41	376	417
2	77	146	223
3	29	32	61
Total	147	554	701

gamma = -0.6375 ASE = 0.050

Goodman and Kruskal's Gamma Test of COMFD and SIT_O (Section 7.3)

	COMFD		
SIT_O	0	1	Total
1	3	155	158
2	34	226	260
3	110	173	283
Total	147	554	701

gamma = -0.7391 ASE = 0.045