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Authors

Kim, Hyungkyoo
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Wind and the city: An evaluation of San Francisco's planning approach since 1985

Hyungkyoo Kim
Department of Urban Design and Planning, Hongik University, 94 Wausan-ro, Mapo-gu, Seoul 121-791, South Korea; e-mail: gusailsang@gmail.com

Elizabeth Macdonald
Department of City and Regional Planning and Department of Landscape Architecture and Environmental Planning, College of Environmental Design, University of California, Berkeley, 228 Wurster Hall #1850, Berkeley, CA 94720-1850, USA; e-mail: emacdon@berkeley.edu

Abstract
In 1985, San Francisco adopted a downtown plan on ground-level wind currents intended to mitigate the negative effects of wind on pedestrians' perceived comfort in public open spaces. The plan mandates that new buildings in designated parts of the city associated with high density or development potential be designed or adopt measures to not cause wind in excess of accepted comfort levels. This study examines whether and to what degree the plan has successfully shaped an urban form that mitigates wind by comparing the ground-level wind environment in 1985 and 2013. A series of wind tunnel tests found that during San Francisco's windiest season when the westerly winds are prevalent, the overall mean wind speed ratio measured at 318 locations in four areas of the city dropped by 22 percent. However, there still exist many excessively windy places that are associated with specific urban form conditions, including streets oriented to have direct exposure to westerly winds, flat façades on high-rise buildings, and horizontal street walls where building façades align. Recommendations based on the findings include incorporating more tangible guidance on the built form conditions, expanding the plan's reach to cover more parts of the city, and learning from strategies used elsewhere. By evaluating the urban form impacts of a wind mitigation policy that has been in place for 30 years, the research offers insights for other cities that have implemented or plan to adopt similar approach and sheds light on issues related to wind comfort in high-density urban areas.

Keywords
urban form, wind, outdoor comfort, San Francisco, wind tunnel simulation

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1 Introduction

Spurred by the residents' strong interest in the quality of the built environment and securing comfort in public open spaces, in 1985, San Francisco became one of the first cities in North America to adopt a downtown plan on ground-level wind currents, supplemented by planning codes. The intention has been to mitigate the adverse effects of wind on pedestrians by securing acceptable comfort in areas of public seating and walking (City and County of San Francisco, 1985). The plan focuses on the downtown area and four additional parts of the city, all associated with high density or development potential and substantial pedestrian activities. It has mandated that all new developments or additions to existing buildings located in these areas be designed or adopt measures so as to not cause ground-level wind current in excess of certain wind speed levels. Developers are required to provide in their Environmental Impact Review (EIR) process an in-depth wind tunnel study that examines the effect of the proposed project on the ground-level wind environment in adjacent public open spaces, including streets and plazas. Similar attempts to mitigate the negative impacts of building-induced wind have been enacted in other North American cities, notably Toronto, which benchmarked San Francisco's approach (Bosselmann et al, 1990), as well as New York City, Boston, and Chicago (American Society of Civil Engineers, 2004). Attempts have also been made in Wellington, New Zealand, which introduced wind regulations (Donn, 2011) and Tokyo, Japan, which requires that all projects over a gross floor area of 100,000 square meters be subjected to wind study (Ng, 2009).

San Francisco's wind planning approach is discussed in numerous studies. Arens et al (1989) and Arens and Bosselmann (1989) presented how the plan's wind speed criteria were established. A number of planners (Bosselmann, 1998; Gehl and Svarre, 2013; Gehl, 2010;

Loukaitou-Sideris and Banerjee, 1993; Marcus and Francis, 1998; Punter, 1999) and building scientists and urban climatologists (Brown and DeKay, 2001; Donn, 2011) noted the significance of the plan in promoting more comfortable public spaces, but proceeded no further. Others attempted empirical analysis of the relationship between wind and comfort in San Francisco (Bosselmann et al, 1988; Zacharias et al, 2004) but without reference to the city's planning approaches to ground-level wind currents.

Despite San Francisco's wind planning having been in effect for 30 years, there have been no studies to our knowledge that have empirically evaluated its effectiveness in making the city less windy, thus promoting comfort in public open spaces. We suspect one reasons is because it usually requires at least several decades to witness significant changes in a city's physical form, especially in the American context. Another reason is that collaboration between planning and urban climatology or building science fields, which is crucial to carrying out such research, has been relatively difficult to achieve. Critics comment that this is mainly due to communication problems between planners and scientists and lack of consensus of the role and importance of climate knowledge in planning (Eliasson, 2000; Hebbert, 2014; Willemsen and Wisse, 2007). Recently, the relationship between urban form and wind has garnered academic interest with respect to pedestrian comfort and activity (Lenzholzer and van der Wulp, 2010; Szűcs, 2013), air ventilation of urban areas (Ng et al, 2011; Ng, 2009), and mitigation of the urban heat island (Middel et al, 2014). As climate-responsiveness and resilience of cities are becoming key tasks of planning today, it is time to revisit the plan and examine whether or not such an approach has been successful in accomplishing its primary goal.

This study examines whether and to what degree the plan changed San Francisco's urban form so as to provide a less windy environment, thereby providing more wind comfort in a city with a relatively cool climate and high wind speed levels and where wind is often regarded as an element of discomfort. It compares the wind environments in 1985 and 2013 generated by the changes in the urban form conditions of the two years. Based on the findings, this study identifies urban form conditions commonly found in the windy places and presents policy suggestions. The outcome of this study may provide useful insights for planners, designers, architects, and engineers concerned with creating livable and sustainable cities, and shed light on wind comfort issues in cities with a high-density urban core or new business districts.

2 San Francisco's Wind Planning

2.1 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, it is one of the best descriptions of San Francisco's unique climate. The city is famous for being windier in the summer than in the winter, which is different from many other U.S. cities where winters are usually considerably windier. Temperatures in San Francisco range between 50 and 70 °F in summer and 40 and 60 °F in winter, but with summer winds, averaging above 11 mph as compared to winter winds of 6 mph, it can feel very cool in summer.

San Francisco is not the windiest city in the U.S. According to the annual wind speed data between 1971 and 2000 provided by the National Climatic Data Center (2005), San

Francisco’s annual average wind speed is 8.7 mph, substantially lower than that of major U.S. cities that are notorious for fierce winds such as Boston (12.3 mph), Oklahoma City (12.2 mph), Wichita (12.2 mph), and Chicago (10.3 mph). However, the monthly average wind speed of San Francisco in July (11.2 mph), the windiest month, is similar to that of winter winds in Chicago (11.9 mph), which is known as “the windy city”, and higher than that in New York (10.8 mph). San Francisco’s cool summer temperatures and tall buildings accelerate winds are important contributing factors that make the residents of San Francisco feel windy and cold from mid-spring to mid-fall (Null, 1995).

The Central Valley east of San Francisco plays a key role in increasing the city’s wind speed. Mountains of the Coastal and Sierra Nevada ranges ring this 22,500 square mile plain with the only break in the Coastal Range occurring at San Francisco. The Valley’s daytime temperatures usually reach 100 °F on summer days, and heat waves frequently bring temperatures above 115 °F, generating extensive updrafts. Cool air from the Pacific Ocean rushes in through the gap at San Francisco to fill the void created by the updrafts, resulting in high westerly winds in the city.

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

San Francisco’s approach to dealing with wind issues was shaped by the city’s unique planning history. Beginning in the mid-1960s when suburbanization was accelerating flight out of many U.S. cities, San Francisco was one of the few cities that saw uninterrupted downtown growth (Vettel, 1985). The amount of downtown office space doubled between 1965 and 1983, mostly accommodated in newly constructed high-rise office towers in the Financial District

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(Hartman, 2002). This resulted in the so-called "Manhattanization" of San Francisco (Keating and Krumholz, 1991).

Citizens became concerned about the adverse impacts of rapid downtown development and in the 1980s initiated the "Anti-High-Rise Movement" (Hartman, 2002). One concern was the deteriorating environmental quality of San Francisco's public open spaces. Critics argued that existing planning measures, including incentive zoning and design reviews, failed to provide outdoor spaces that made people feel welcome and comfortable (Loukaitou-Sideris and Banerjee, 1993; 1998). Although since the 1970s the city had required wind studies for new high-rise buildings as a part of the EIR process, many downtown open spaces became uncomfortable places for walking or gathering due to the excessive ground-level winds and shades produced by high-rise buildings (Arens et al, 1989).

In the early 1980s, researchers at the University of California, Berkeley examined the effects of new developments in downtown San Francisco on sun and wind conditions at the street level, evaluating their combined effects on outdoor thermal comfort (Bosselmann et al, 1983). Their findings pointed to many places where the wind environment produced a feeling of discomfort. They recommended that the ground-level wind conditions could be significantly improved through better building designs (Bosselmann et al, 1984).

The passage in 1984 of Proposition K, a voter referendum measure known as the "no new shadows" or "sunshine" rules, prevented the development of any structure over 40 feet tall that would cast a shadow on city-owned open spaces. It was followed in 1985 by the adoption of the Downtown Area Plan, enacted as part of the San Francisco General Plan (Lai, 1988). This was not only the first downtown plan in the U.S. to impose limitations on growth (Keating and

Krumholz, 1991) but also the first to include concrete planning objectives and policies related to wind and sunlight access, thus regulating the physical form of new developments.

2.3 Key Contents of San Francisco's Wind Planning

San Francisco's Downtown Area Plan includes planning objectives and implementation policies on ground-level wind currents and mitigating its adverse effects. Objective 10 and Policy 10.5, in the Open Space element of the Plan, emphasize that minimizing adverse wind is crucial to well-designed open spaces. Objective 14 and Policy 14.2, in the Urban Form element, present 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 surrounding streets and open spaces. Policy 14.2 also suggests several preferable approaches to building massing and detailing, such as narrow or complex façades and setbacks at various levels..

The Downtown Area Plan is supplemented by the San Francisco Planning Code, five sections of which present the wind planning details: §§ 148, 249.1, 243, 263, and 825. Collectively they provide technical guidelines on wind speed criteria for comfort and safety, preexisting conditions, exceptions, and documentation. They require that new buildings and additions to existing buildings should not cause ground-level wind currents to exceed on a year round basis the comfort level of 11 mph equivalent wind speed in areas of pedestrian use and 7 mph in areas with public seating for more than 10 percent of the time between 7 am and 6 pm. When pre-existing ambient wind speeds exceed the comfort levels, the codes require that new buildings be designed to reduce wind speeds. An exception may be granted, allowing the building or addition to produce excessive winds for a longer time, when the amount and time by which the comfort level is exceeded are limited, and when an unattractive or ungainly building form would result by applying the regulations to the letter. However, no exception is granted if the equivalent wind speeds reach or exceed the hazard level of 26 mph for a single hour of the year. The Planning Code stipulate that wind tunnel test procedures and results must be included in EIRs of all development projects.

The comfort and safety wind speed criteria were established based on research findings dating from the 1970s and 1980s that empirically examined the mechanical effect of wind on people's acceptable range of comfort and safety (Arens, 1981; Davenport, 1972; Hunt et al, 1976; Jackson, 1978; Lawson, 1978; Melbourne, 1978; Penwarden and Wise, 1975; Penwarden, 1973). A noteworthy point is the use of "equivalent wind speed," which is defined as a mean wind speed adjusted to incorporate the effects of the gustiness of wind on pedestrians. Equivalent wind speed and turbulence intensity are calculated, respectively, by Equations (1) and (2):

$$U_{eqv} = \overline{U} \times (1 + 3\,I) \tag{1}$$

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

where U_{eqv}: equivalent wind speed; $\overline{U}$: mean wind speed; I: turbulence intensity; and U_i: wind speed measured at location i.

Table 1. Adopted year, location, zoning information, and area of the five zoning districts.

Planning Code section	**Adopted year**	**Implemented zoning district**		**Permitted density (Floor area ratio)**	**Permitted height (feet)**	**Total area (acres)**	**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 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

Source: City and County of San Francisco (2013)
Notes: a. Applies to non-residential use only; b. Does not include Transbay DTR District; c. Applies to residential use only.

The Planning Code designates implementation of wind regulation in five zoning districts all located in the northeastern part of San Francisco, in and around the downtown, as shown in Figure 1: Downtown Commercial (C-3) Districts, the Van Ness Special Use District, the Folsom & Main Residential/Commercial Special Use District, the South of Market Residential/Service Mixed Use 40-X/85B Height District, and Downtown Residential Districts. As summarized in Table 1, areas currently contained within these districts include 479 parcels on 496 acres of land.

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Permitted densities and building heights in the five zones are generally high, implying that areas with high density or development potential are prone to high ground-level wind currents.

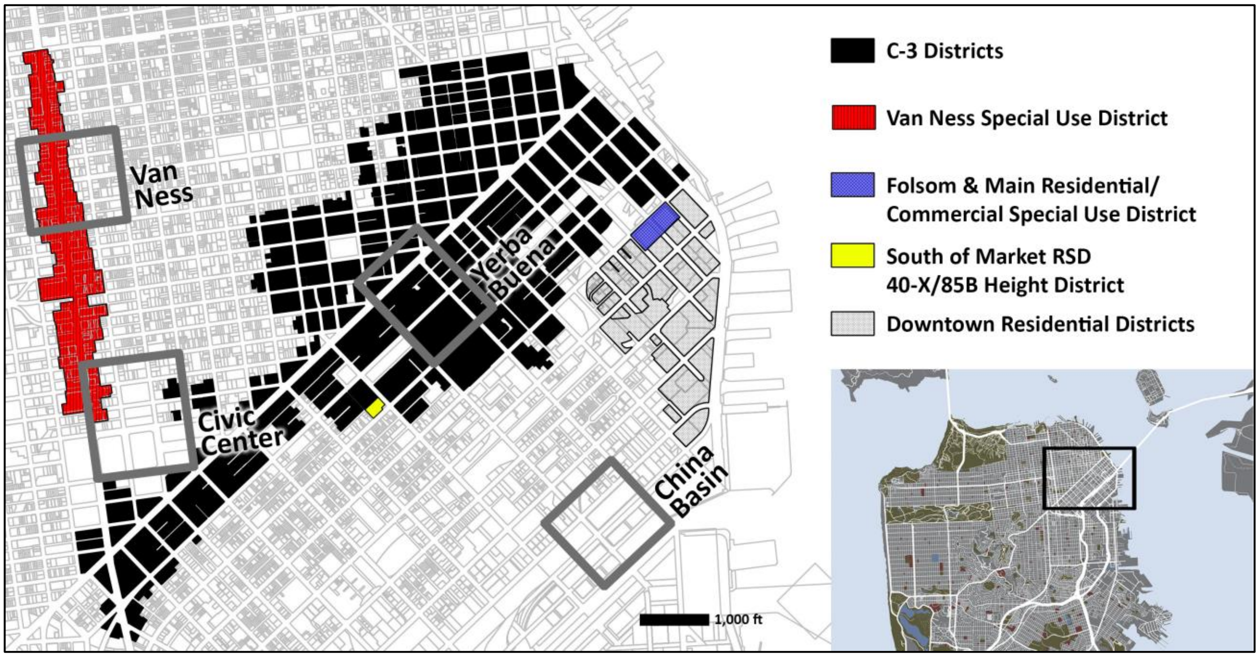

Figure 1. [In colour online.] Location of the five zoning districts subject to wind planning, and the four selected study areas (Yerba Buena, Van Ness, Civic Center, and Mission Bay North) for wind tunnel simulation.

3 Methods

3.1 Wind Tunnel Simulation

A series of wind tunnel simulations were carried out to comparatively study how the wind environment of 2013 differs from that of 1985, thus analyzing how effective the regulations have been at shaping urban form to improve wind comfort in San Francisco. Boundary layer wind tunnels are frequently used to study wind environments around buildings and structures in urban areas. They manipulate air flow to model wind near the earth's surface in a scaled fashion by generating relevant friction and turbulence (American Society of Civil Engineers, 1999). The method has been validated by comparing its simulation results with those from full-scale field measurements (Carpenter, 1990; Isyumov and Davenport, 1975; Isyumov, 1995). It has proven effective and reliable in predicting wind speeds at the pedestrian level and has become the industry standard (American Society of Civil Engineers, 2004).

In a typical boundary layer wind tunnel, a scale model of an urban area is placed on a turntable that is rotated as required to simulate the actual wind direction. To evaluate the wind environment, wind speeds at selected locations are measured with an anemometer. The wind speed ratio (WSR) of a location is calculated by dividing the wind speed measured there by the reference wind speed at the top of the boundary layer of wind. In theory, the WSR of any location will remain constant regardless of wind conditions as long as the surrounding physical setting stays the same and is used to estimate the actual wind speed. For example, if the WSR of a location is 0.5, then when the wind speed at the top of the boundary layer of wind (usually 1,700 feet above ground level in dense urban areas) is 20 mph, the wind speed at the location is estimated to be 10 mph.

A different method of analyzing wind flows involved simulation using computational fluid dynamics (CFD), which has the advantages of easier implementation and visualization. It is a branch of fluid mechanics that adopts numerical methods and algorithms to solve problems that involve fluid flows. Although researchers developing this method have made considerable progress towards accurately assessing urban wind environments (Reiter, 2010), CFD simulation was not used in this study. Their insufficient capability of fully addressing the complexity and uncertainty of turbulence in the real world raises concerns on reliability when applied to urban scale and may generate erroneous results (American Society of Civil Engineers, 2011).

3.2 Study Areas

Four areas of San Francisco were selected for wind tunnel simulation, referred to as Yerba Buena (YB), Van Ness (VN), Civic Center (CC), and Mission Bay North (MBN). The locations of each area are shown in Figure 1. They were chosen because they have high development density, high levels of ambient wind speed, and large volumes of pedestrian traffic. Each rectangular shaped study area covers approximately 45 acres, with sides ranging between 1,200 and 1,800 feet. Although the four areas comprise only a small subset of San Francisco's diverse urban forms and wind environments, they represent typical development characteristics in their vicinity and different conditions related to the number of parcels subject to the wind planning. All of YB and parts of VN and CC are within designated wind control districts. MBN is not in a wind control district but was included in this study because its urban form has changed significantly over the last 30 years, allowing comparison of wind levels in regulated versus non-regulated areas. Table 2 shows each study area's land use and wind conditions.

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Table 2. Land use and wind conditions of the four study areas.

Study area	Number of parcels	Number (%) of parcels subject to wind planning	Number (%) of parcels with urban form change since 1985	Land use types in 2013	Development density in 2013 (total floor area ratio)[a]	Average wind speed (mph)[b]
YB	68	68 (100%)	17 (25%)	Commercial, mixed-use, open space	8.0	6.4
VN	191	40 (21%)	24 (13%)	Commercial, residential, mixed-use	2.9	8.7
CC	92	9 (10%)	20 (22%)	Civic/institutional, commercial, mixed-use, open space	4.4	4.2
MBN	44	0 (0%)	11 (25%)	Commercial, residential, mixed-use, open space	2.4	4.2

Notes: a. Total floor area of existing buildings divided by total area of parcels in each study area; b. Data comes from field work measurements carried out in the four study areas.

3.3 Scale Models and Measurement Locations

Scale models representing urban form conditions in 1985 and 2013 were created for each of the four study areas. Information for the models was gathered from a variety of sources. For 1985, Sanborn Maps from the Earth Sciences and Map Library, University of California, Berkeley that provide information on block configurations, building footprints, and building stories were used. This data was cross-checked with satellite images, photographs, and documents from the mid-1980s. For 2013, GIS data on blocks, parcels, streets, and buildings and detailed information on parcels and buildings were downloaded from publicly available online resources provided by the City and County of San Francisco (City and County of San Francisco, n.d.; San Francisco Planning Department, n.d.). As an example, Figure 2 shows the changes in YB's urban form between 1985 and 2013. While little redevelopment or reconstruction occurred north of Market Street, the area south of Market Street saw major changes. Most notably, Yerba Buena Gardens was built on a block south of Mission Street, which had been a large surface parking area, and a number of high-density developments were built along Third Street.

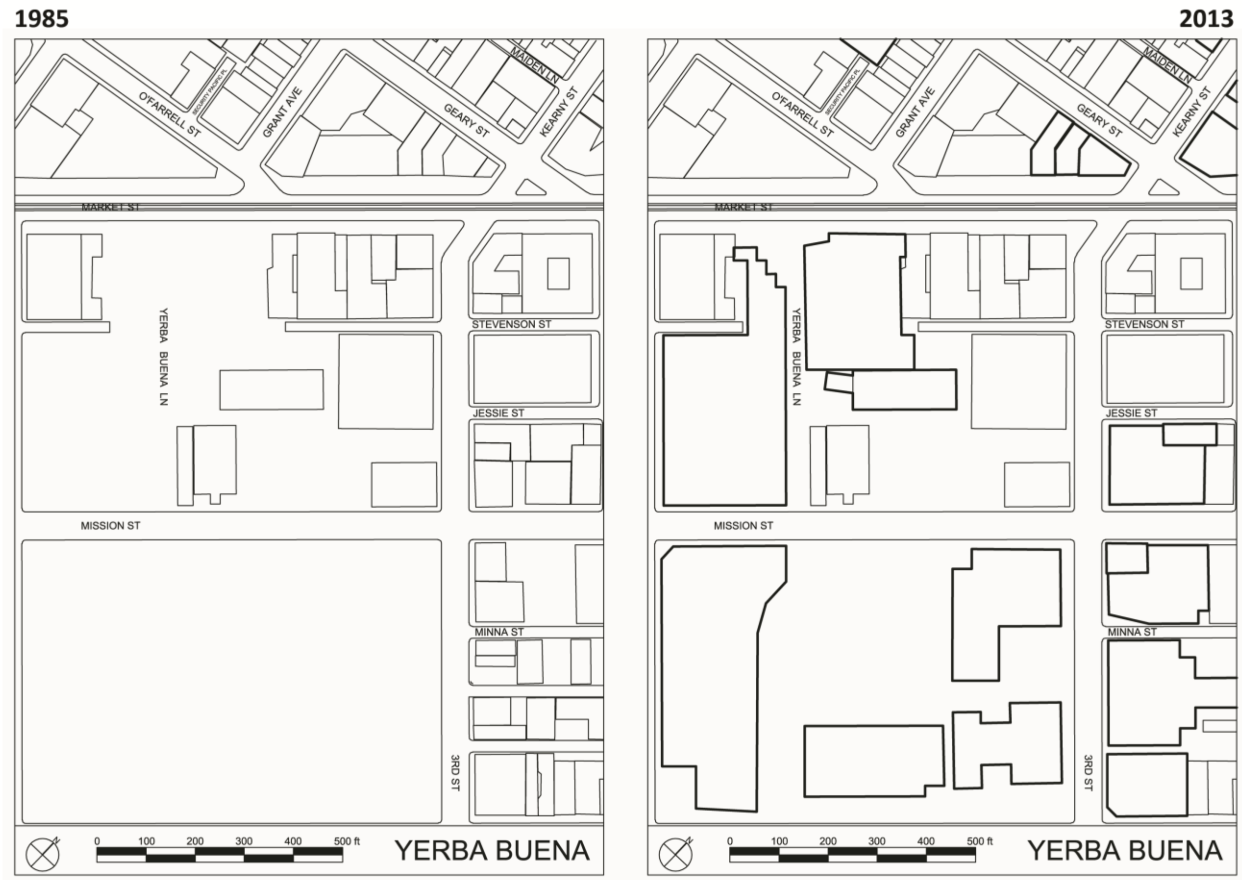

Figure 2. 1985 and 2013 urban form conditions of YB. Buildings constructed after 1985 are expressed in thicker lines.

Represented on the scale models were the physical configuration and location of blocks, parcels, streets, railroads, and buildings. Topography was not included since the four study areas are located on relatively flat parts of the city where slopes are not a significant factor. Small building elements (e.g., louvers, signboards, bay windows, and awnings), street furniture (e.g., benches, ledges, lamp posts, and utility poles), and vegetation (e.g., trees and landscaping) were

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not included because these features have relatively limited effect on the surrounding wind environment.

A scale of 1”= 30’ (1:360) was used for the models for several reasons. First, it is the scale used in the study by Bosselmann et al (1984) that provided the technical foundation for San Francisco’s wind planning, and so was selected for this study for reasons of consistency. Second, the scale meets accepted standards for wind tunnel study of urban areas, including that adopted by the American Society of Civil Engineers (1999). Lastly, many wind tunnel studies of proposed developments in San Francisco have used or similar scales, as indicated in their EIRs. White foam core boards were used to make building volumes, and chipboard sheets were used for the ground surface.

Wind speeds were measured, and WRS were calculated at locations corresponding to where people’s everyday outdoor activities tend to occur. The locations can be categorized into five types: street corners, mid-block points on sidewalks, transit stops, bicycle lanes, and open spaces. A total of 318 such locations were identified throughout the four study areas: 74 in YB, 72 in VN, 102 in CC, and 70 in MBN, as illustrated in Figure 3. The larger number of locations in CC than the other three is mainly because this area includes Civic Center Plaza, a large-scale public open space. The same measurement locations were used for 1985 and 2013 conditions. On the scale models, measurement locations were indicated with small white stickers. Figure 4 shows the scale models of the four study areas in their 1985 and 2013 urban form conditions.

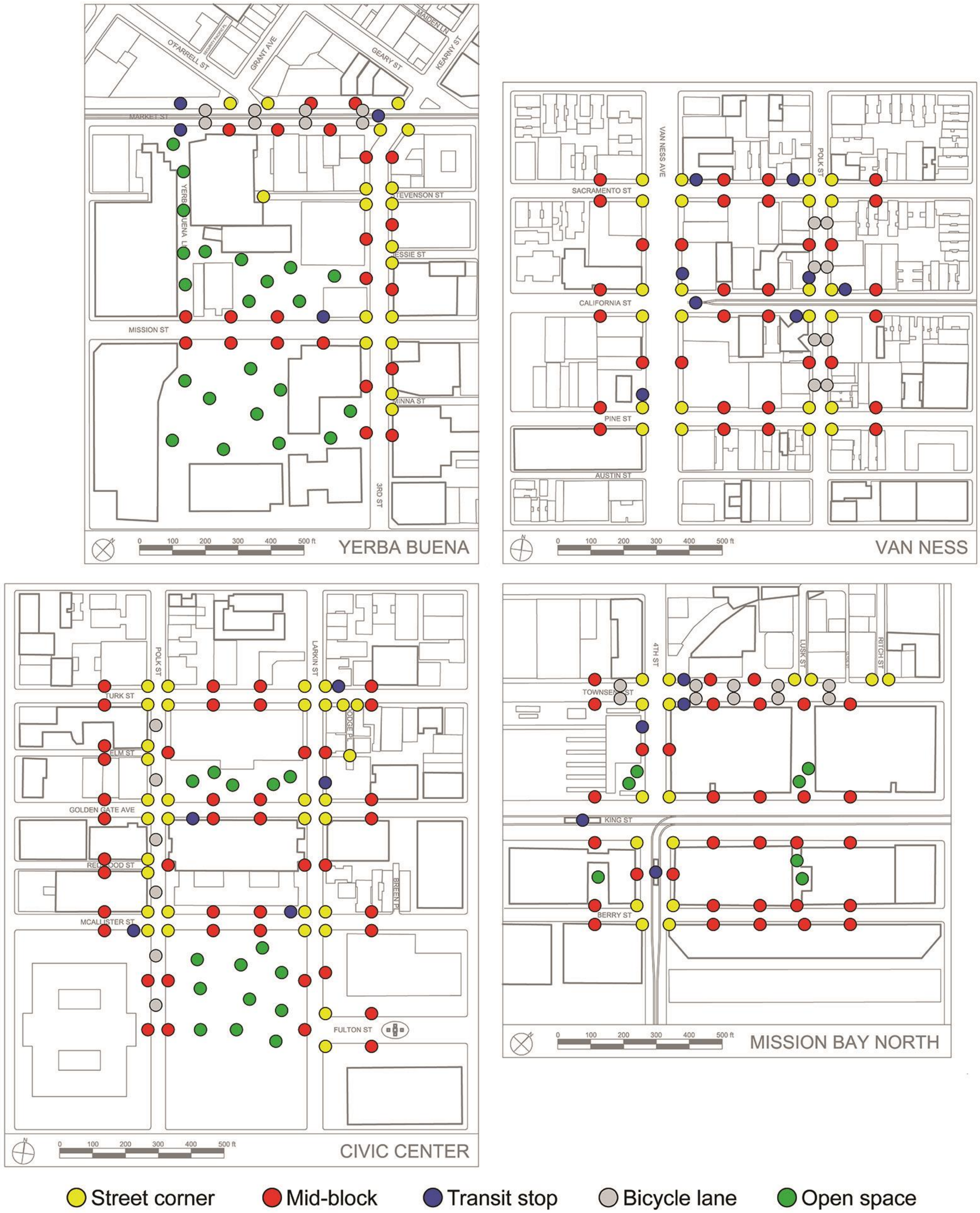

Figure 3. [In colour online.] Measurement locations of the four study areas. Buildings constructed after 1985 are expressed in thicker lines.

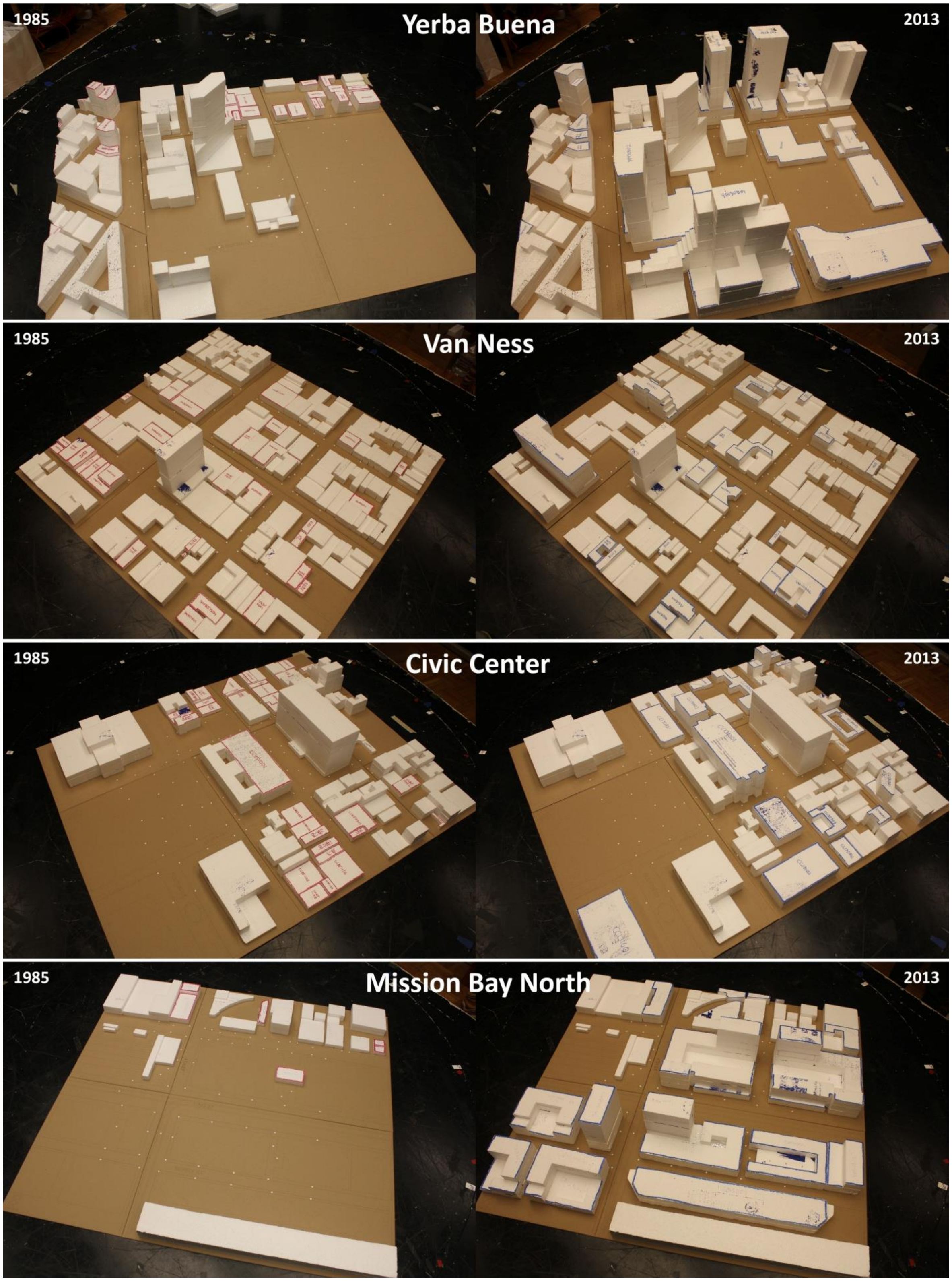

Figure 4. [In colour online.] Scale models of the four study areas representing their 1985 and 2013 urban form conditions. Small white stickers are placed at each measurement location.

3.4 Simulation Procedure

The same wind tunnel simulation used for the Bosselmann et al (1984) study was used for this study. The scale models were placed on a turntable that was rotated to simulate westerly winds. This wind direction was selected for the following reasons. First, not only statistically but also perceptually it is the most prevalent wind direction during the windiest period of the year in San Francisco, mid-spring to mid-fall (Gilliam, 2002; Null, 1995). Second, the vast majority of wind studies of proposed developments in San Francisco, as found in their EIRs (e.g., San Francisco Planning Department (2010a; 2010b; 2012)), are centered on analyzing the effect of westerly winds. Third, based on a series of interviews with local academics and planners, including those who participated in developing the 1985 wind regulations, it was evident that addressing adverse effects of westerly winds was the most critical concern.

Wind speed was measured at each location with an anemometer held in place for 20 seconds, a period long enough to generate a reliable mean wind speed value. The reference wind speed, based on which the WSR was calculated, was collected at the Pitot tube, a measurement instrument suspended from the ceiling of the wind tunnel above the model.

4 Results

An evaluation of overall changes in the wind environment generated by changes in the urban form conditions between 1985 and 2013 is presented below. Changes in the WSR at selected individual measurement locations and places within each area are also examined.

4.1 Overall Changes

As shown in Table 3, the mean WSR measured at 318 locations in the four study areas was 0.279 in 1985 and decreased by 22 percent to 0.218 in 2013. Among the 318 locations, 212 experienced a decrease in WSR, and 106 went through an increase. All four areas had a lower overall mean WSR value in 1985 than 2013. The 1985 YB and MBN models showed the highest overall mean WSR levels, 0.308 and 0.310 respectively, while the VN and CC models showed 0.244 and 0.262 respectively. In 2013, YB and MBN showed the lowest WSR levels. The mean WSR in YB dropped 34 percent, from 0.308 to 0.202, and that in MBN dropped 41 percent, from 0.310 to 0.184. VN and CC experienced a relatively small decrease, 8 percent and 6 percent respectively. Table 4 presents that among the five location types, open spaces and mid-block points had the highest overall WSR in both 1985 and 2013. Bicycle lanes and street corners registered the lowest WSR in 1985, while bicycle lanes and transit stops did so in 2013.

Table 3. Wind speed ratio statistics of the four study areas.

Study 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.

Table 4. Wind speed ratio statistics of the five location types.

Location type	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
Street corner	91	0.063	0.588	0.249	0.063	0.541	0.217	-13*	41	50	+266	-82
Mid-block	129	0.049	0.800	0.307	0.056	0.649	0.235	-23*	36	93	+347	-83
Transit stop	22	0.074	0.508	0.281	0.056	0.419	0.183	-35*	2	20	+37	-69
Bicycle lane	32	0.063	0.450	0.166	0.063	0.038	0.144	-13	13	19	+225	-78
Open space	44	0.066	0.599	0.341	0.060	0.567	0.240	-30*	14	30	+105	-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 big drop in the overall mean WSR within YB, where every single parcel is subject to wind planning requirements and 25 percent of the parcels experienced new development between 1985 and 2013, suggests that the goal of reducing ground-level wind currents has been well achieved in spite of large-scale new developments. Both VN and CC, where respectively only 21 and 10 percent of parcels are subject to wind planning, and development has been mostly in the form of small-scale infill rather than large-scale redevelopment projects involving consolidation of parcels, experienced relatively small overall decreases.

While MBN showed the biggest overall drop among the four areas, the location with the highest rate increase (347%) is in this area. MBN has no parcels subject to wind planning. In 1985, this area was a rail yard with few buildings or structures, but by 2013, as the result of redevelopment, many large-scale residential buildings had been erected. One plausible interpretation of the results is that the new buildings, which are situated in blocks whose long sides face northwest, operate as wind breaks along some streets. However, had the buildings in

MBN been subject to wind planning restrictions, the WSRs may have been further reduced and locations with very high wind levels could have been minimized through better design.

It is unclear how much of the decrease in overall wind speed is attributable to the wind regulations and how much to there simply being more buildings, especially in the cases of YB and MBN. Nevertheless, the findings indicate that streets and open spaces in the four study areas generally experience lower wind levels in 2013 than in 1985. Because of urban form changes San Francisco has become more wind-comfortable during its windiest season, mid-spring to mid-fall, when the westerly winds are prevalent.

4.2 Changes in Individual Places

For a closer analysis, the 318 locations in the four study areas were grouped into 21 sub-areas, such as all the locations along a particular street or within a particular open space. By way of example, the findings related to four of the sub-areas, one from each study area, are discussed below.

Figure 5 shows WSRs at locations on public sidewalks, bicycle lanes, and transit stops along Market Street in YB. In 1985, this place was generally well sheltered from westerly winds. WSRs at most locations remained below 0.250 but higher ratios existed at the Market Street and Grant Avenue intersection. The westerly wind that ran along Market Street was induced into the large vacant parcel south of the intersection, which had been cleared for new construction, resulting in several locations with WSRs exceeding 0.450. By 2013, large buildings such as the Four Seasons Hotel San Francisco were constructed on the vacant parcel. The westerly wind that runs along Market Street leaves several locations between Grant Avenue and Geary Street, especially on bicycle lanes, with higher ratios than in 1985. However, the ratios at most locations remain below 0.250.

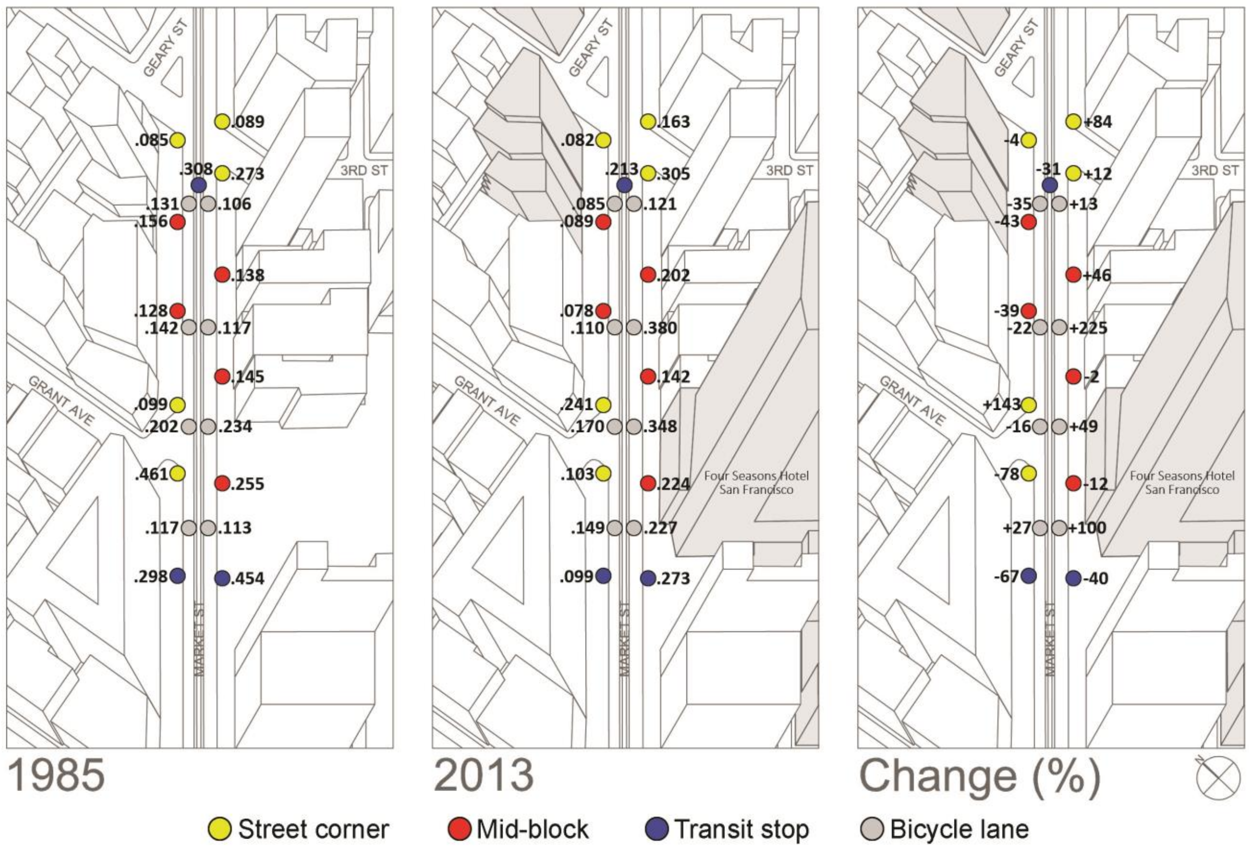

Figure 5. [In colour online.] WSRs in 1985 and 2013 and their changes in Market Street in YB.

Figure 6 presents Pine Street in VN. This street showed the highest level of WSRs within the VN study area in both 1985 and 2013. In 1985, the westerly wind that runs along the street was accelerated as it passed the 25-story Holiday Inn Golden Gateway located at the northeastern corner of the Pine Street and Van Ness Avenue intersection. The ratios rose up to 0.662 and gradually slowed down at Polk Street. In 2013, the 13-story San Francisco Towers, built in 1997 at the southwestern corner of the same intersection, serves to decrease WSRs at several locations.

The building also increases them elsewhere, especially street corners along the street, including ones that had relatively low WSRs in 1985. It can be interpreted that even though wind planning has been implemented in this sub-area to secure wind comfort, many locations that used to be less windy have evolved in the opposite direction to the extent permitted by the wind planning.

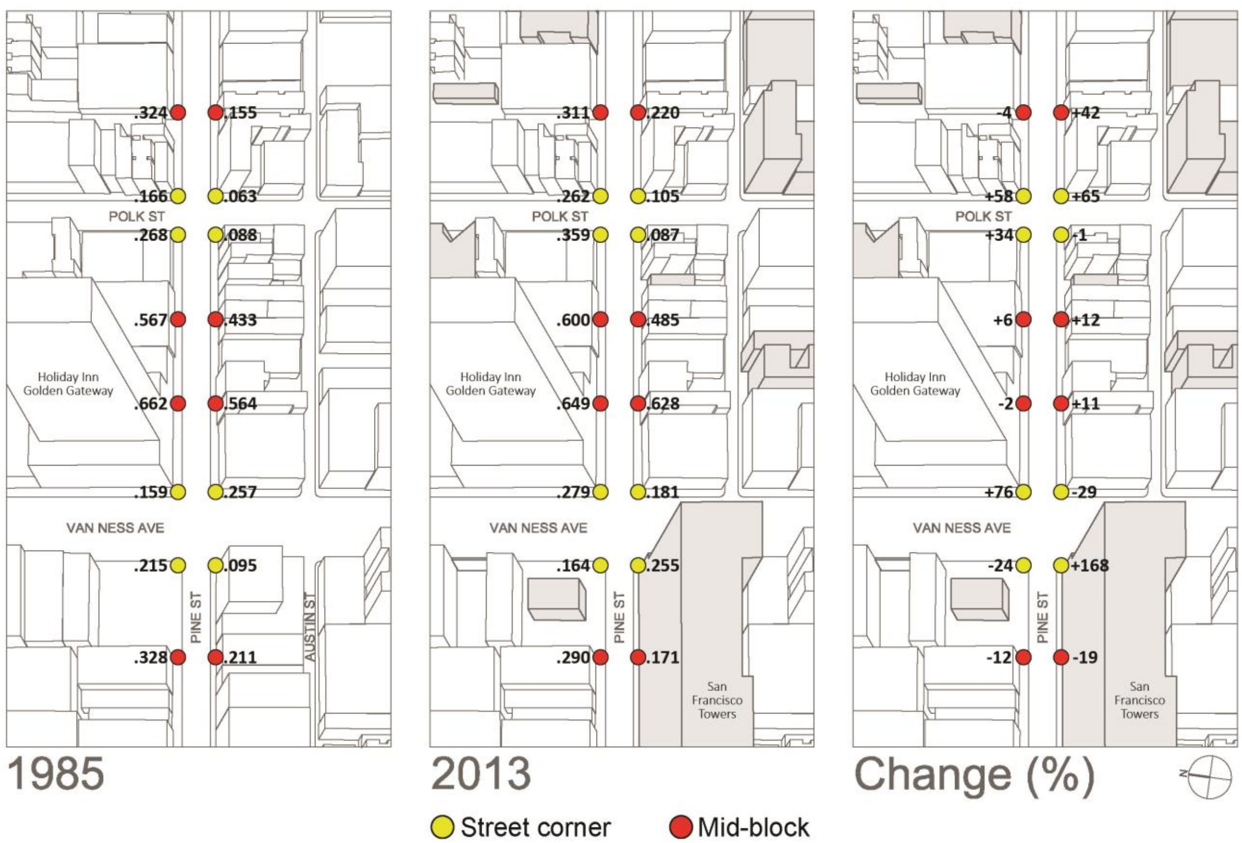

Figure 6. [In colour online.] WSRs in 1985 and 2013 and their changes in Pine Street in VN.

Figure 7 illustrates Larkin Street in CC. A clear difference is observed in WSRs 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 did not exceed 0.130, those at street corners were generally higher, some of which reaching 0.483. By 2013, the biggest ratio increases are at street corner locations, especially at the two southern intersections where the ratios soared 84 percent. On the other hand, WSRs at the Larkin Street and Turk Street intersection are considerably lower than in 1985. Several new buildings such as the State of California Building located on the west seem to have influenced the wind environment in both positive and negative ways.

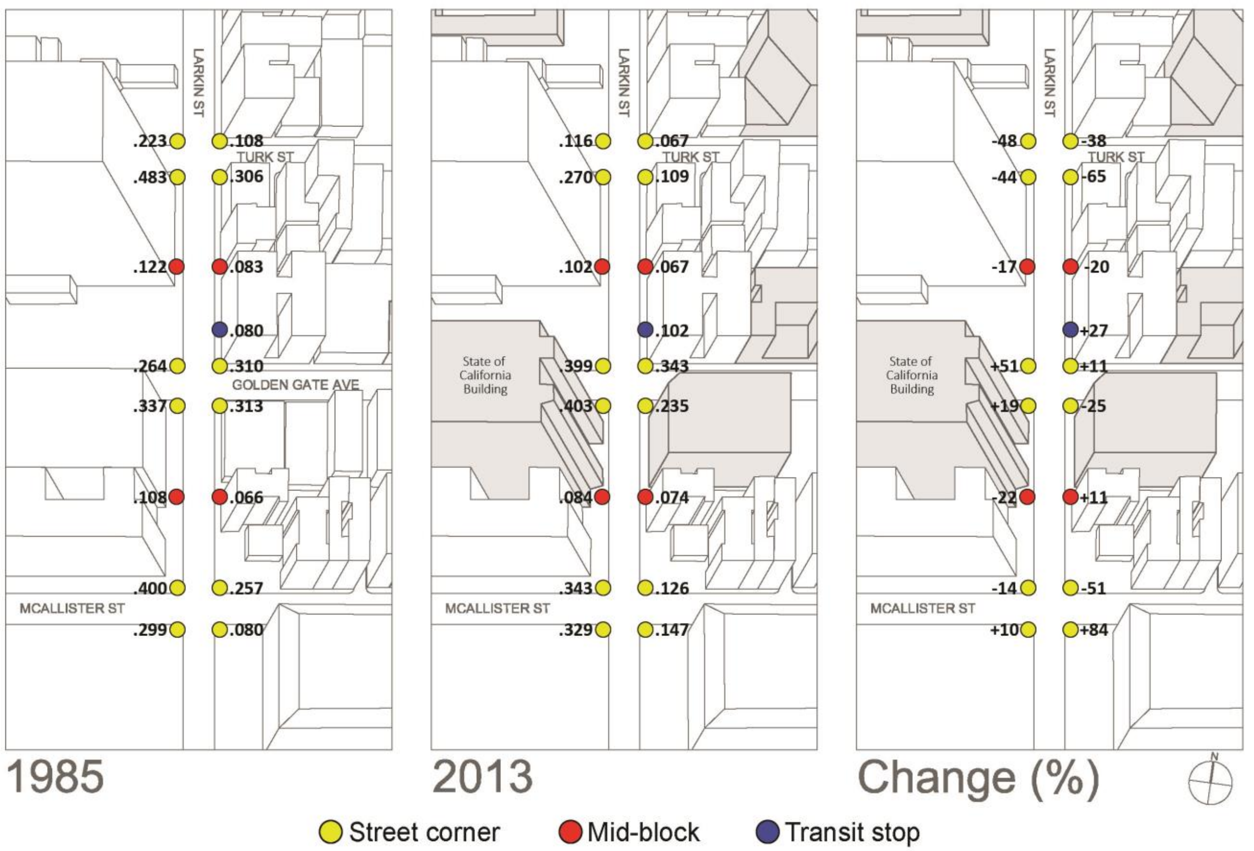

Figure 7. [In colour online.] WSRs in 1985 and 2013 and their changes in Larkin Street in CC.

Figure 8 depicts the wind conditions and their changes along King Street and two adjacent open spaces in MBN. In 1985, there were few buildings to block westerly winds. All measurement locations, except for two located directly in front of the Caltrain Station sheltered by the station building, experienced relatively high WSRs ranging between 0.301 and 0.564. However in 2013, the new buildings on both sides of King Street have generally decreased the WSRs. WSRs in the small open spaces between the high-rise residential towers have decreased by up to 84 percent. However, several locations on the southeastern side of King Street experience higher WSRs, up to 0.474. Also, the high ratios existing in 1985 at the King Street and 4th Street intersection remain in 2013.

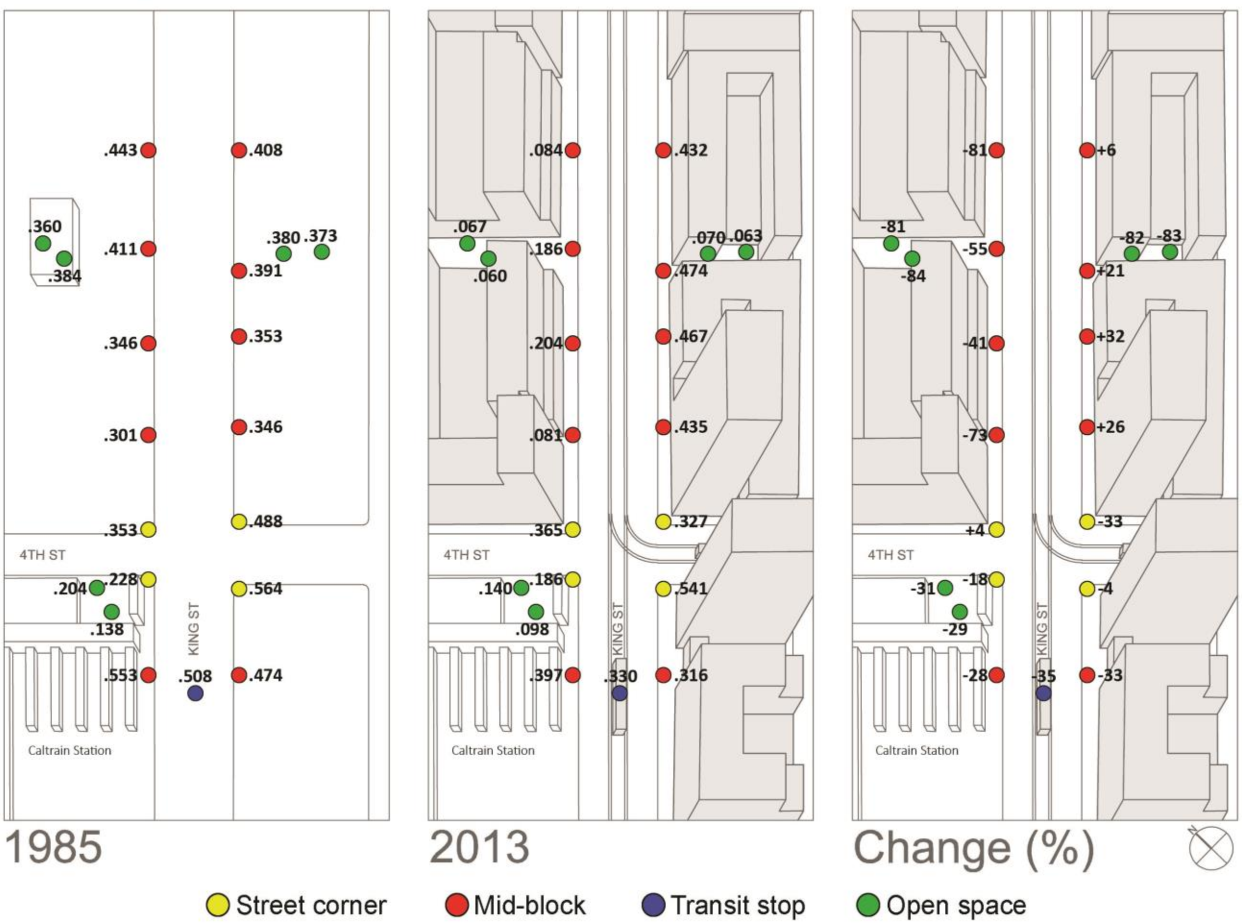

Figure 8. [In colour online.] WSRs in 1985 and 2013 and changes in King Street in MBN.

4.3 Urban Form Conditions of Windy Places

In order to study and understand how particular building forms affect WSRs, eight sub-areas among the 21 were selected for the further examination. These include sub-areas with the highest WSRs at particular locations and that also have concentrations of locations where the WSRs exceed 0.350 in 2013, which corresponds to the 80th percentile of the overall WSR distribution measured at 318 locations. The eight places are Yerba Buena Lane and Yerba Buena Gardens in YB; California Street and Pine Street in VN; Golden Gate Avenue, and McAllister Street and Fulton Street in Civic Center Plaza in CC; and King Street in MBN.

Figure 9 shows a sectional diagram and street view of the most representative sub-areas in each area – Yerba Buena Lane in YB, California Street in VN, Golden Gate Avenue in CC, and King Street in MBN – whose wind conditions in 2013 are discussed below.

Yerba Buena Lane experiences a concentration of WSRs that range from 0.373 to 0.554, especially in the narrow space between the 42-story Four Seasons Hotel and 38-story Marriot Marquis Hotel. Although this place is not directly exposed to the westerly wind, the flat façades of these two buildings are inducing the faster winds that exist at higher altitudes to slide down to the ground level. On California Street between Van Ness Avenue and Polk Street, the highest WSRs range between 0.419 and 0.492. Winds are accelerated by both the continuous street walls, which let the wind flow smoothly without any obstacle on both sides of the street, and the 25-story Holiday Inn Golden Gateway Hotel located on the south side of the street, which induces the faster wind at higher altitude down to the street level. Along Golden Gate Avenue, clusters of WSRs ranging from 0.375 to 0.567 are found along a 175 foot-wide open space fronted on its north side by the 22-story Phillip Burton Federal Building and on its south side by the 15-story State of California Building. Not only is this place directly exposed to the westerly wind, but the

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high-rise buildings' flat façades draw the faster winds at higher altitudes down to the pedestrian environment. Finally, along the southeastern edge of King Street, a 160 foot-wide thoroughfare running southwest-northeast, a concentration of WSRs exists that range between 0.432 and 0.541. This place is both directly and indirectly exposed to the westerly wind. It is fairly wide, and no obstacles to its west block the prevalent wind patterns as continuous street walls rise up to 17 stories on both sides of the street.

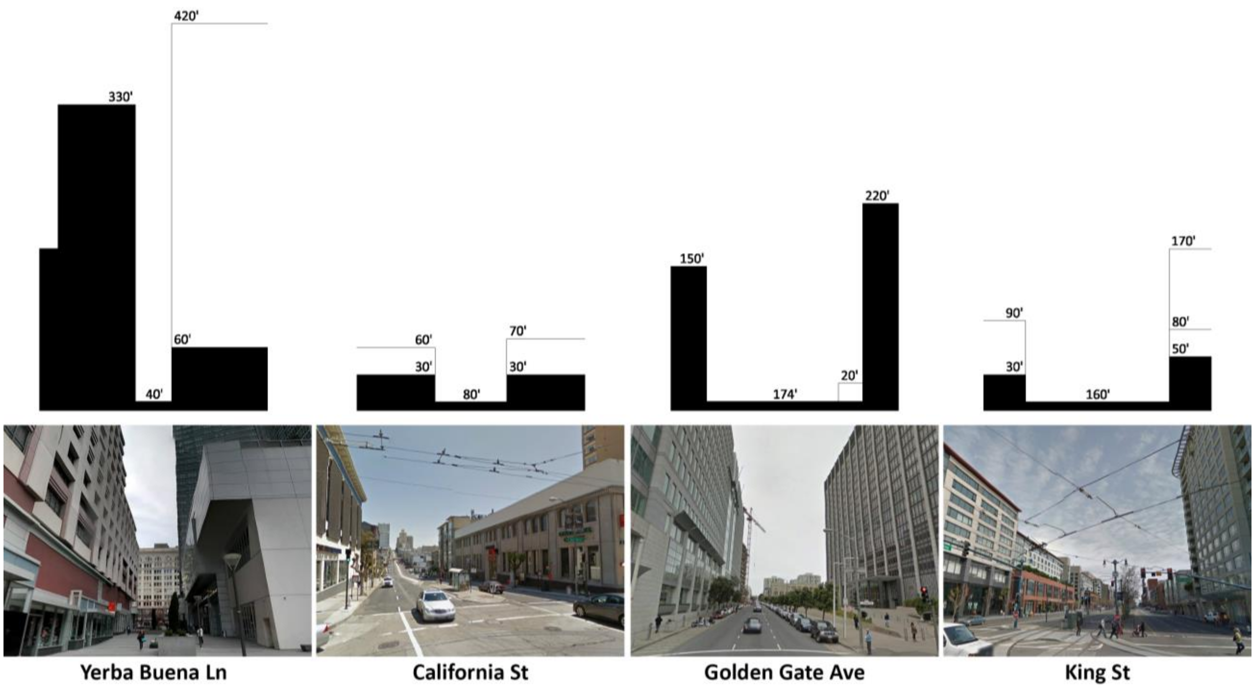

Figure 9. [In colour online.] Sectional diagram and © Google Maps street view of Yerba Buena Lane, facing northwest, California Street, facing east, Golden Gate Avenue, facing west, and King Street, facing northeast.

From this analysis, three common urban form conditions associated with concentrations of higher WSRs can be identified: (1) direct exposure of street orientation to the prevailing wind; (2) high-rise buildings with flat façades that extend directly to the street without any major surface changes such as setbacks; and (3) horizontal street walls where building façades align.

These findings are in line with findings of previous research that investigated the impact of street configuration and orientation on urban wind environment (Brown and DeKay, 2001; Givoni, 1998), as well as some of the design elements introduced in the Downtown Area Plan. At the same time, they suggest the need for further improvement and amendment of the plan despite the positive changes it has made since 1985.

5 Concluding Remarks

In sum, San Francisco's wind planning, in place since 1985, seems to have had the intended effect of providing a less windy environment. It has generated increased wind comfort in public open spaces during the city's windiest months, between mid-spring and mid-fall, when westerly winds prevail. The overall mean WSR measured at 318 locations in scale models of four areas of the city dropped by 22 percent between 1985 and 2013, suggesting that the actual ground-level wind speeds in those areas 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 streets oriented to have direct exposure to westerly winds, flat façades of high-rise buildings, and horizontal street walls where building façades align.

Three policy suggestions result from this research. The first derives directly from the urban form conditions mentioned above. San Francisco's wind planning should be revised to incorporate more tangible guidance on the built form conditions associated windy places and how to design buildings that mitigate ground-level wind currents, perhaps in the form of form-based codes. The Downtown Area Plan and related Planning Codes should proceed further and address the wind impacts of various block and street typologies, open space forms, and building masses and details.

Second, San Francisco should consider expanding the extent of its wind planning to cover more parts of the city. While the city's wind regulations appear to have successfully reduced overall wind ratios in the areas subject to them, this study suggest that many places in the city still experience excessive ground-level wind currents. These places should be identified, and appropriate wind mitigation policies should be implemented. The work of identification for better decision making could be accomplished via citywide wind monitoring and collaboration between planners and urban climatologists.

Lastly, San Francisco might improve its wind planning approach by learning from strategies used elsewhere. For example, Wellington, New Zealand, which also has had wind planning in effect since 1985, has made the city more wind-comfortable and safer (Donn, 2011). Urban designers and architects are provided with a guide that shows building forms that should be avoided or promoted. Recommendations include designing tall buildings to have protruding lower-level podiums and deep canopies to block the downwash off the tower, and screens and fences are installed as windbreaks that alter horizontal wind (Carpenter, 2002). The city has also constructed 90 micro wind shelters for pedestrians in major downtown locations (Donn, 2011).

By evaluating the impacts of an urban policy that has been in effect in San Francisco for 30 years, this study provides important feedback to the city's decision makers that may encourage refinement of the plan or expansion of its implementation areas. The research findings should also be of interest to other cities that have implemented wind planning or are considering it. Just as important, the study reinforces the need to create interdisciplinary bridging between the fields of urban planning and urban climatology, as has been emphasized by other researchers for many years (Givoni, 1976; Jackson, 1978; Lynch, 1962; Olgyay, 1963; Penwarden, 1973) but largely unheeded.

This study provides useful lessons for cities that have cool climates where wind mitigation would improve pedestrian comfort. Conversely, the same knowledge may be useful to warm weather cities where ground-level wind may need to be encouraged rather than discouraged to promote comfort. For more climate-responsive and resilient cities, researchers should keep exploring and studying a wide range of solutions in varied climate regions, and planners should develop their own climate-based plans followed by vigorous evaluation of plan effectiveness.

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