Tall Building Climatology for British Columbia (Residential)

Overview and analyses of aggregated data

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Context and Take-away Message

Audience: Managers, analysts and forecasters concerned with effect of increasing numbers of tall residential buildings on the weather sensitivity of BC Hydro's distribution system.

BC Hydro Context

- At present there is sparse quantitative knowledge about weather sensitivity of suites in tall residential buildings; Need to know relationship between consumption and height
- Over and underestimating relationship between consumption and weather events (in terms of degree-days) has costs in BC Hydro's business model
- More accurate consumption forecasting is beneficial financially for BC Hydro

Take-away Message

- Weather sensitivity of electrically-heated suites increases with height in tall buildings (especially above the 12th storey) so weather sensitivity of Vancouver downtown grid will increase as more tall buildings are commissioned.
- Weather sensitivity of 2000's-built suites is higher than 1960's-built suites so improvements are possible.
- Opportunities exist for BC Hydro to work with tall building developers to incorporate design features to reduce impact of weather sensitivity on grid

Tall Building Climatology for BC

Introduction

Load analysis accuracy may be improved with a better understanding of tall building climatology in the context of the climate of BC's urban centres. BC Hydro's working definition of a tall building is that it has at least 12 storeys with at least 80 apartment suites.

This project used BC Hydro's electrical energy consumption data set from Apr 2004 to Sep 2009 for purely apartment buildings with common use.

Electra, 21 storeys, at 989 Nelson Street, Vancouver, BC. Before being converted into condominium suites in 1995, this historic building housed BC Electric and later, BC Hydro offices. Source: http://www.6717000.com/electra/

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Cover image source: http://www.shangri-la.com/en/property/vancouver/shangrila

Project and Data Set Specifications (1 of 4)

Project and Data Set Specifications were written by Harinder Bains, Sr. Energy Load Advisor

[The] Excel file contains **256 "tall"** residential apartment buildings. My criterion for a "tall" building is that the building has to be **at least 12 floors** (storeys) high with **at least 80 Apartment Suites**. I picked buildings that are at least 6 years old (based on our building age logic) and those that are quite clean with respect to data quality (pure apartment buildings with common use). Based on these criteria I was able to **obtain 256 buildings** (33,864 Apartment Suites in total) – majority of these buildings are from the Lower Mainland (Metro Vancouver) - breakdown by region/service town is as follows:

"The ASHRAE Technical Committee for Tall Buildings defines *tall buildings* as those higher than 91 m [30 stories]" (Ross, 2004; cited in Ellis and Torcellini, 2005)

Project and Data Set Specifications (2 of 4)

Lower Mainland (total of 244 buildings)

- Vancouver – 157 buildings
- Burnaby – 50 buildings
- Richmond – 9 buildings
- Surrey – 9 buildings
- North Vancouver – 6 buildings
- Coquitlam – 5 buildings
- Abbotsford – 4 buildings
- West Vancouver – 3 buildings
- Maple Ridge – 1 building

Vancouver Island (total of 11 buildings)

- Victoria – 9 buildings
- Nanaimo – 2 buildings

Northern (total of 1 building)

- Prince George – 1 building

Project and Data Set Specifications (3 of 4)

As mentioned above, the minimum number of floors (storeys) is 12 – and the maximum number of floors is 46. I have separated out the common/other use by the following "Floor Number" codes (fake floor numbers are created to capture common use consumption by rate/premise codes):

Floor Number = 90 shows consumption for common use (rate 1111 with premise code of 140)

Floor Number = 91 shows consumption for common use (rate 1220 with premise code of 140)

Floor Number = 92 shows consumption for common use (rate 1220 with premise code of 141)

Floor Number = 93 shows consumption for common use (rate 1200 with premise code of 140)

Floor Number = 94 shows consumption for common use (rate 1200 with premise code of 141)

Floor Number = 95 shows consumption for common use (rate 1210 with premise code of 140)

Floor Number = 96 shows consumption for common use (rate 1210 with premise code of 141)

Floor Number = 97 shows consumption for common use (rate 1211 with premise code of 140)

Floor Number = 98 shows consumption for common use (rate 1212 with premise code of 140/141)

Floor Number = 99 shows consumption for common use (rate 1101 with premise code of 020) – suites that are missing unit numbers (unable to place on Floor)

Project and Data Set Specifications (4 of 4)

The following rate and premise codes are important here:

Rate 1111 – residential common use rate

Rate 1220 – commercial (general under 35 kW) common use rate

Rates 1200/1210/1211 – commercial (general – 35 kW & over) common use rate

Rate 1212 – transformer discount rate

Premise 020 – Apartment Suite

Premise 140 – Apartment Building common use

Premise 141 – Apartment/Business Complex common use

Billing history is summarized, by Floor Number, for each of the 256 buildings. The apartment suite consumption is shown for each floor – by rate code 1101 and premise code 020. The number of apartment suites per floor is indicated by "N" for each month – typically, the N is fairly consistent across time (some months may show it lower by 1 due to no billing). The billing history is provided from April 2004 to September 2009 (5 ½ years). … bring in weather to ***see if there is any relationship between usage and height (floor) of the building.***

In this report, **one storey is equivalent to 3 m (10 ft),** in accordance with the *Fire Reporting Manual* issued by Office of the Fire Commissioner, Ministry of Public Safety and Solicitor General, Government of British Columbia (Source: http://www.pssg.gov.bc.ca/firecom/fire_reporting_manual/pdf/bh.pdf)

Weather data from YVR as representative of Vancouver's downtown climate

Weather data was in the form of heating and cooling degree-days. We used Environment Canada data from Vancouver International Airport (YVR) which had hourly temperature (dry bulb) data from April 1953 to June 2009.

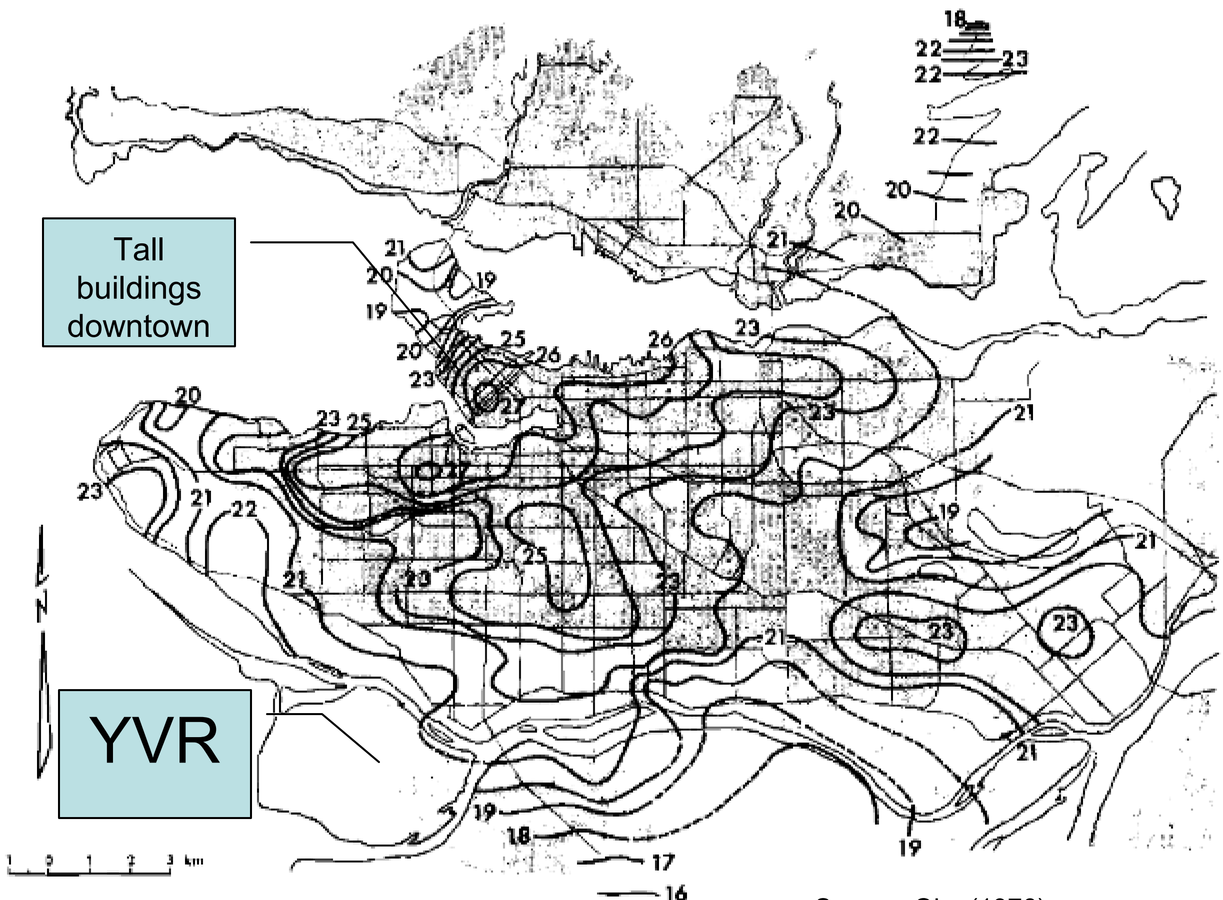
Temperature data was transformed to heating and cooling degree-days by the methods outlined in Wahlgren (2010). To keep the project and presentation manageable ***we decided to limit our analyses to using only heating degree-days.***

As far as we know, there was no temperature data recorded consistently by any level of government agency for the downtown Vancouver region with its concentration of residential tall buildings. Although Metro Vancouver does maintain an air quality monitoring station in Vancouver's downtown, it collects only data for concentrations of SO_2, NO_2, CO, O_3, COH, and precipitation (Metro Vancouver, 2008, p. 7) Inexplicably, temperature is not recorded.

The portion of downtown Vancouver occupied by most of the residential tall buildings in our data set does not, on the average, exhibit a strong enough urban heat island effect to make it necessary to adjust the YVR data to better represent downtown Vancouver's microclimate. The urban heat island for Vancouver has been discussed by Hay and Oke (1973, p. 30); Runnalls and Oke (1998); and Taylor and Langlois (2000).

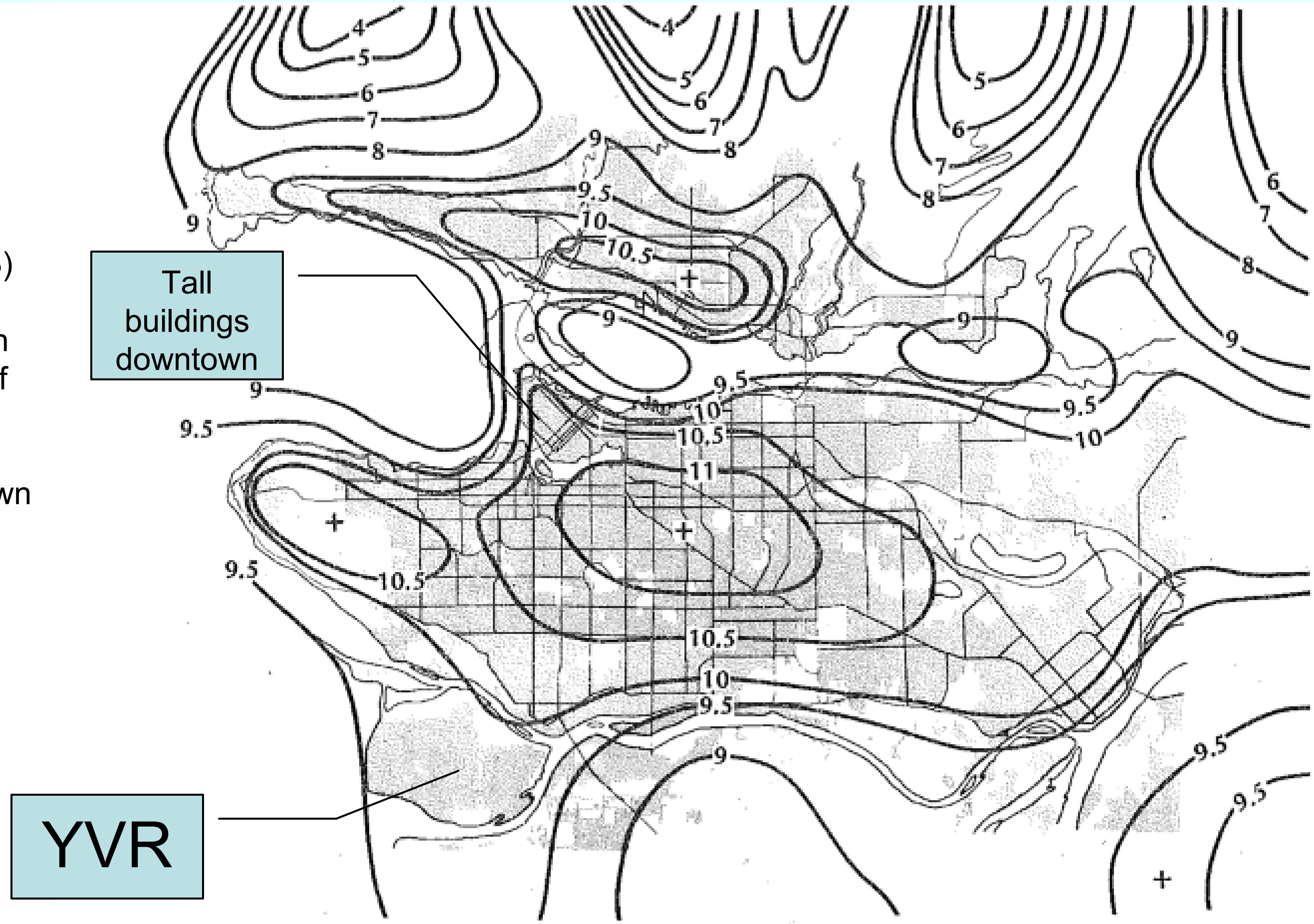
The discussion on the next four slides led us to decide the YVR-based degree-day data was representative of the climate in Vancouver's downtown.

A dramatic example of Vancouver's urban heat island occurred on July 4, 1972 (2100 local time).. Skies were clear and wind speed was 2 m s^{-1} from the west (Oke, 1976). YVR temperature was approx. 21°C while downtown Vancouver was 26°C, a difference of 5 K. This is, however, atypical. Processes that moderate the heat island effect in Vancouver include winds and cloudiness. ***Average urban heat island development in Vancouver is typified by the next three figures.***



Source: Oke (1976)

Mean annual temperatures (°C) define Metro Vancouver's urban heat island in the figure at right (from Hay and Oke, 1973) The **temperature difference** between the concentration of residential tall buildings in Vancouver downtown (10.7°C) and YVR (9.7 °C) is approximately **1 K**



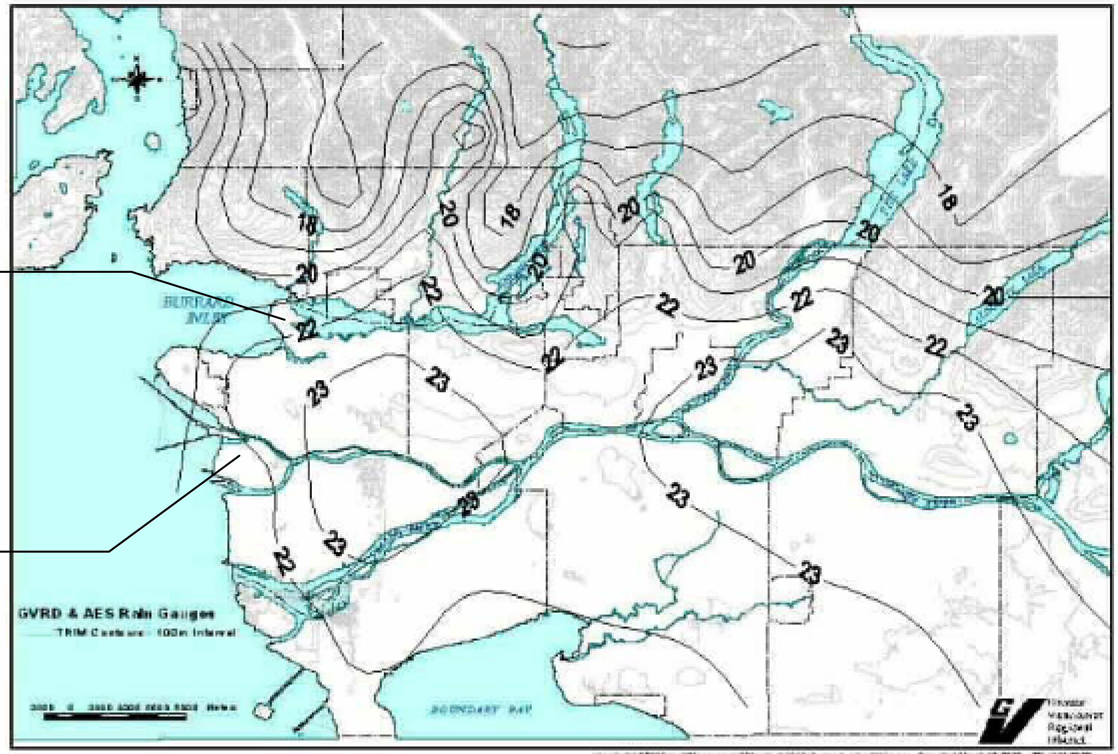
Source: Hay and Oke (1973)

Downtown Vancouver and YVR lie on the same isotherm for July mean maximum temperature (1961–1990; Taylor and Langlois (2000) so there is ***no difference in temperatures*** between the two locations.

GVRD July Mean Maximum Temperature 1961-90

Tall buildings downtown

YVR



Prepared by Aquatic & Atmospheric Sciences Division, Environment Canada, Pacific & Yukon Region. May 2000.
Note: Temperatures in degrees Celcius. Temperatures in the mountains are estimated.

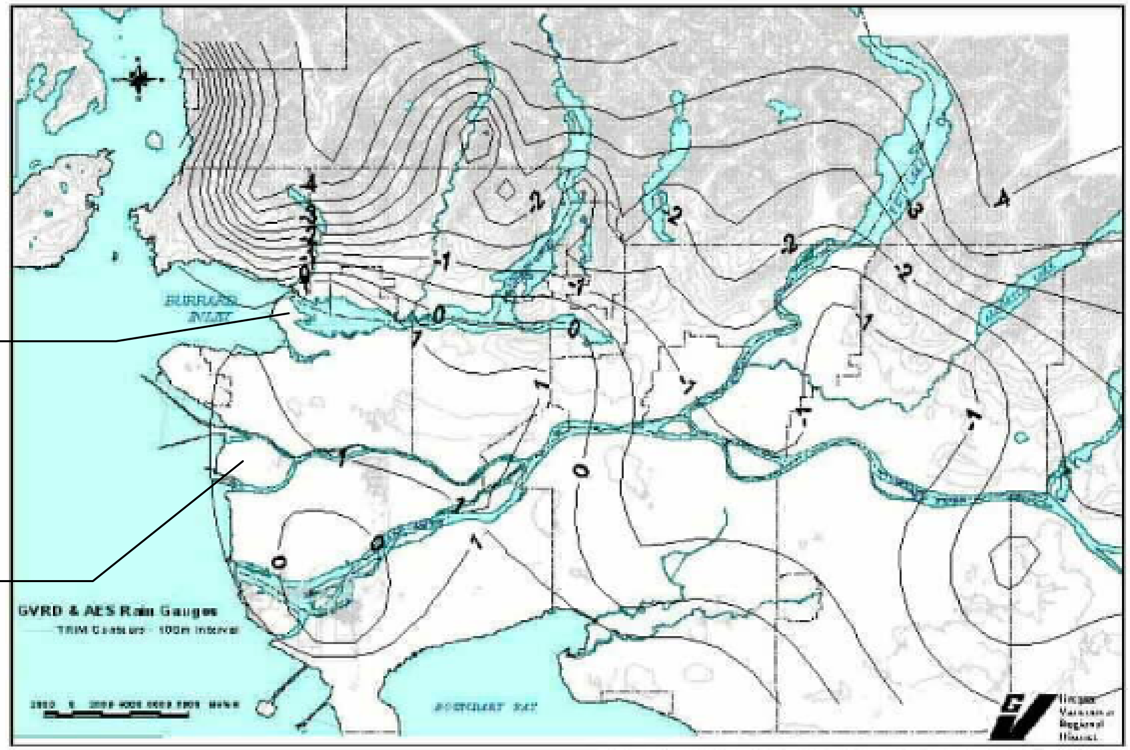
Source: Taylor and Langlois (2000)

January mean minimum temperatures ***differ by 0.5 K*** between Vancouver downtown and YVR (Taylor and Langlois, 2000)

Tall buildings downtown 1°C

YVR 0.5°C

GVRD January Mean Minimum Temperature 1961-90



Prepared by Aquatic & Atmospheric Sciences Division, Environment Canada, Pacific & Yukon Region. May 2000
Note: Temperatures in degrees Celcius. Temperatures in the mountains are estimated.

Source: Taylor and Langlois (2000)

Data Set

Microsoft Excel - Residential_TallBuildings_Consumption (modif by RVW).xls

	Max Floors Per Bldg	HB Building ID#	Building Street Address	Building City/Town	Floor #	Rate Code	Prem Code	Heat Type	APR04_Sum	MAY04_Sum	JUN04_Sum	JUL04_Sum	AUG04_Sum	SEP04_Sum	OCT04_Sum	NOV04_Sum	DEC04_Sum	JAN05_Sum	FEB05_Sum
1									Consumption units are kWh										
2			Monthly HDD	Lower Mainland					208	121	48	8	8	114	215	338	382	431	419
3			Monthly CDD	Lower Mainland					.	.	27.1	55.3	41.3	.	.	.	.	.	.
4			Monthly HDD	Vancouver Island					217	147	68	19	22	133	224	337	368	429	427
5			Monthly CDD	Vancouver Island					.	.	13.3	34.3	15.2	.	.	.	.	.	.
6			Monthly HDD	Northern Region					348	242	93	56	86	283	409	558	702	865	624
7			Monthly CDD	Northern Region					.	.	24.9	16.4	28	.	.	.	.	.	.
8	12	24512	1050 HARWOOD ST	VANCOUVER	1	1101	020	NONELEC	1,152	1,261	1,178	1,103	1,377	1,200	1,418	1,343	1,508	1,588	1,350
9	12	24512	1050 HARWOOD ST	VANCOUVER	2	1101	020	NONELEC	1,810	1,804	1,048	1,171	1,463	1,486	1,711	1,810	1,783	1,864	1,642
10	12	24512	1050 HARWOOD ST	VANCOUVER	3	1101	020	NONELEC	1,707	1,794	1,604	1,304	1,350	1,340	1,594	1,691	1,616	1,383	1,283
11	12	24512	1050 HARWOOD ST	VANCOUVER	4	1101	020	NONELEC	991	866	905	1,008	1,038	1,039	1,111	1,156	1,203	1,204	1,064
12	12	24512	1050 HARWOOD ST	VANCOUVER	5	1101	020	NONELEC	1,362	1,435	1,329	1,320	1,309	1,395	1,554	1,603	1,533	1,613	1,376
13	12	24512	1050 HARWOOD ST	VANCOUVER	6	1101	020	NONELEC	1,340	1,410	1,259	1,412	1,636	1,424	1,454	1,472	1,417	1,622	1,429
14	12	24512	1050 HARWOOD ST	VANCOUVER	7	1101	020	NONELEC	1,094	1,542	1,362	1,588	1,721	1,673	1,721	1,536	1,647	1,637	1,616
15	12	24512	1050 HARWOOD ST	VANCOUVER	8	1101	020	NONELEC	1,242	1,218	1,101	1,413	1,633	1,712	1,833	1,823	1,861	2,082	1,781
16	12	24512	1050 HARWOOD ST	VANCOUVER	9	1101	020	NONELEC	1,153	1,153	1,252	1,298	1,209	1,244	1,358	1,316	1,365	1,320	1,090
17	12	24512	1050 HARWOOD ST	VANCOUVER	10	1101	020	NONELEC	1,119	1,356	1,370	1,449	1,486	1,397	1,473	1,473	1,616	1,508	1,137
18	12	24512	1050 HARWOOD ST	VANCOUVER	11	1101	020	NONELEC	1,227	1,610	1,541	1,647	1,657	1,600	1,827	1,620	2,021	1,985	1,810
19	12	24512	1050 HARWOOD ST	VANCOUVER	12	1101	020	NONELEC	1,969	1,989	1,019	1,797	1,800	1,780	1,888	2,184	2,719	2,474	1,966
20	12	24512	1050 HARWOOD ST	VANCOUVER	90	1111	140	NONELEC	6,688	6,680	6,317	6,286	5,978	6,501	7,020	6,799	7,200	7,208	6,582
21	12	24512	1050 HARWOOD ST	VANCOUVER	99	1101	020	NONELEC	308	339	339	366	407	351	430	239	365	384	376
22	12	44421	1100 HARWOOD ST	VANCOUVER	1	1101	020	ELECTRIC	1,669	997	929	918	878	1,200	2,430	4,022	4,308	4,890	4,367
23	12	44421	1100 HARWOOD ST	VANCOUVER	2	1101	020	ELECTRIC	3,343	2,335	1,805	1,560	1,684	2,684	3,098	5,958	6,959	6,924	5,407
24	12	44421	1100 HARWOOD ST	VANCOUVER	3	1101	020	ELECTRIC	2,158	1,516	1,273	1,021	1,070	1,224	2,542	4,342	4,869	5,187	4,271
25	12	44421	1100 HARWOOD ST	VANCOUVER	4	1101	020	ELECTRIC	1,177	904	718	883	732	931	1,933	3,616	5,176	5,506	3,707
26	12	44421	1100 HARWOOD ST	VANCOUVER	5	1101	020	ELECTRIC	2,151	1,495	1,431	1,419	1,499	1,536	2,191	3,337	4,219	4,834	3,472
27	12	44421	1100 HARWOOD ST	VANCOUVER	6	1101	020	ELECTRIC	1,954	1,572	1,407	1,411	1,407	1,290	2,217	4,136	5,241	5,664	3,914
28	12	44421	1100 HARWOOD ST	VANCOUVER	7	1101	020	ELECTRIC	1,393	1,284	1,211	1,194	1,461	1,481	2,407	3,925	5,083	5,727	4,122
29	12	44421	1100 HARWOOD ST	VANCOUVER	8	1101	020	ELECTRIC	972	865	1,030	1,278	1,302	1,442	2,277	3,668	3,435	3,990	2,700
30	12	44421	1100 HARWOOD ST	VANCOUVER	9	1101	020	ELECTRIC	2,687	1,898	1,874	1,851	1,959	2,154	3,064	4,300	4,780	4,904	3,271
31	12	44421	1100 HARWOOD ST	VANCOUVER	10	1101	020	ELECTRIC	2,228	1,682	1,342	1,148	1,279	1,536	2,788	4,049	5,149	5,419	3,566
32	12	44421	1100 HARWOOD ST	VANCOUVER	11	1101	020	ELECTRIC	2,135	1,767	1,649	1,577	1,657	1,933	2,852	3,927	4,905	4,688	3,369
33	12	44421	1100 HARWOOD ST	VANCOUVER	12	1101	020	ELECTRIC	1,664	1,066	956	1,018	1,046	1,626	3,012	5,123	6,382	6,502	4,810
34	12	44421	1100 HARWOOD ST	VANCOUVER	91	1220	140	ELECTRIC	10,625	9,874	9,743	9,724	9,927	9,913	10,841	11,654	13,560	13,575	11,348
35	12	44421	1100 HARWOOD ST	VANCOUVER	99	1101	020	ELECTRIC	2,033	1,466	936	777	912	1,879	3,654	5,651	4,431	4,034	2,926
36	12	78359	11841 222 ST	MAPLE RIDGE	1	1101	020	NONELEC	484	501	491	507	492	375	560	542	553	551	445
37	12	78359	11841 222 ST	MAPLE RIDGE	2	1101	020	NONELEC	1,081	1,124	1,056	1,100	1,191	1,163	1,353	1,313	1,473	1,468	1,197
38	12	78359	11841 222 ST	MAPLE RIDGE	3	1101	020	NONELEC	1,142	1,180	1,237	1,271	1,162	1,168	1,383	1,340	1,460	1,456	1,229
39	12	78359	11841 222 ST	MAPLE RIDGE	4	1101	020	NONELEC	1,167	1,212	1,362	1,402	1,375	1,372	1,331	1,294	1,526	1,521	1,251
40	12	78359	11841 222 ST	MAPLE RIDGE	5	1101	020	NONELEC	1,006	1,040	1,019	1,057	1,096	1,072	1,273	1,234	1,336	1,332	1,102
41	12	78359	11841 222 ST	MAPLE RIDGE	6	1101	020	NONELEC	1,153	1,193	1,189	1,236	1,308	1,281	1,557	1,508	1,619	1,612	1,283
42	12	78359	11841 222 ST	MAPLE RIDGE	7	1101	020	NONELEC	1,499	1,549	1,537	1,594	1,627	1,582	1,746	1,689	1,740	1,737	1,500

Deg-day import | Residential_TallBuildings_Consu | Chart-Freq distr of floor #s | Floor consum prop Electri

Weather data added to residential tall building electrical energy consumption data set as monthly heating and cooling degree-days. Balance point temperature was 18°C for HDD and 20°C for CDD

Micro-climatological influences on tall buildings

In the first instance, buildings themselves modify these aspects of their environment (Oke, 1978):

- Radiative (shadow-casting, sunlit wall reflections, reduction of cooling of nearby surfaces)
- Thermal (warmer soil and air temperatures from building heat losses and wind shelter effect)
- Moisture (water balance altered by interception of precipitation and by shelter effect, soil drainage and evaporation affected by building)
- Aerodynamic (building causes airflow changes by being a wind obstacle)

These meteorological parameters change with elevation above the ground surface:

- Temperature
- Air pressure and density
- Wind-speed
- Radiation (short-wave and long-wave)
- Shading
- Reflection

Micro-climatological influences — Temperature

Temperature vs altitude

U.S. Standard Atmosphere

$H_z = E \times z / (E + z)$

$T_z = T_b + L (H_z - H_b)$

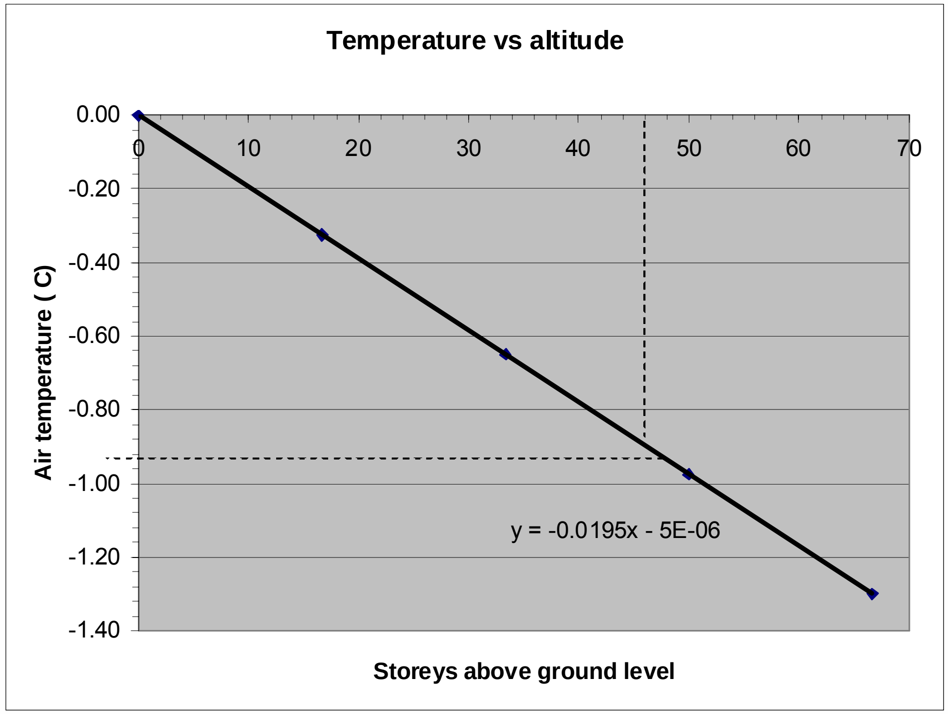
L =	-6.50E-03	K/m	moist adiabatic lapse rate
E =	6.36E+06	m	radius of Earth
H_b	0	m	for troposphere
T_b	0	°C	air temperature at ground level

Elevation (m) to	Storey
3	1

Elevation (m)	Storeys	L (K/m)	H_z (m)	T_z (°C)
0	0	-6.50E-03	0.00E+00	0.00
50	17	-6.50E-03	5.00E+01	-0.32
100	33	-6.50E-03	1.00E+02	-0.65
150	50	-6.50E-03	1.50E+02	-0.97
200	67	-6.50E-03	2.00E+02	-1.30

We viewed this as a negligible difference for the purpose of this study

The tallest building in our study has 46 storeys. The temperature at the 46th storey would by 0.9°C less than at ground level (dashed lines on chart)



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Micro-climatological influences — Air pressure and density, wind-speed, radiation

Because the data set does not have hourly values of air pressure, air density, wind-speed, and radiation corresponding to the BC Hydro sales regions we were forced to consider these variables as negligible,

Furthermore, the data set values for electrical energy consumption are monthly values. Monthly values of meteorological variables (other than monthly average temperature or degree-days) are not meaningful in the context of BC's weather patterns which cause changes in key variables day-to-day and even hour-by-hour.

Air pressure and temperature differences between a building's interior spaces and the outdoors cause a "stack effect" which creates zones of air inflow and outflow at various building levels. The exact nature of the stack effect for a particular building depends on design details such as presence of internal partitions and whether or not there is an airtight separation between floors (Hutcheon and Handegord, 1983).

Micro-climate can change from floor to floor in a tall building due to shading and reflections from surrounding buildings in the urban environment; lower floors are usually more shaded than upper floors (Ellis and Torcellini, 2005).

Micro-climatological influences: Wind speed

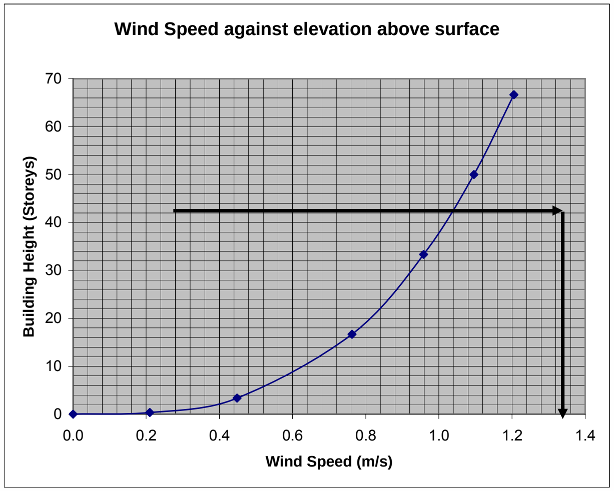
Wind speed vs altitude model

$U_H = U_{met} (\delta_{met} / H_{met})^{a_{met}} (H / \delta)^a$ from ASHRAE (2005)

U_{met} =	1.0 m/s	anemometer wind speed at height H_{met}
H_{met} =	10.0 m	anemometer height
δ_{met}	270 m	Boundary layer thickness at met station (typical)
a_{met} =	0.14	Exponent for met station site (ASHRAE, 2005)
H =		Wall height on building
δ	460 m	Boundary layer thickness at urban site (typical)
a =	0.33	Exponent for urban site (ASHRAE, 2005)

Elevation (m) to	Storey	
3	1	
Wall height, H (m)	**Storeys**	**U H**
0	0	0.0
1	0.3	0.2
10	3	0.4
50	17	0.8
100	33	1.0
150	50	1.1
200	67	1.2

The tallest building in our study has 46 storeys. The wind speed at the 46th storey would by 1.06 m/s more than at ground level (dashed lines on chart)

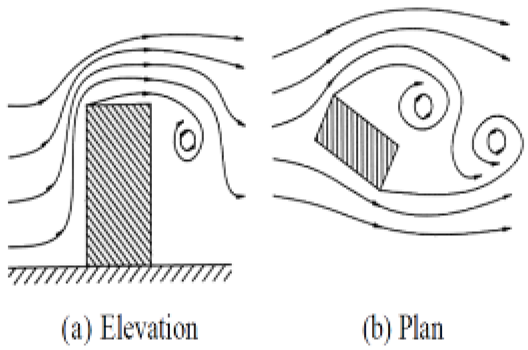


References

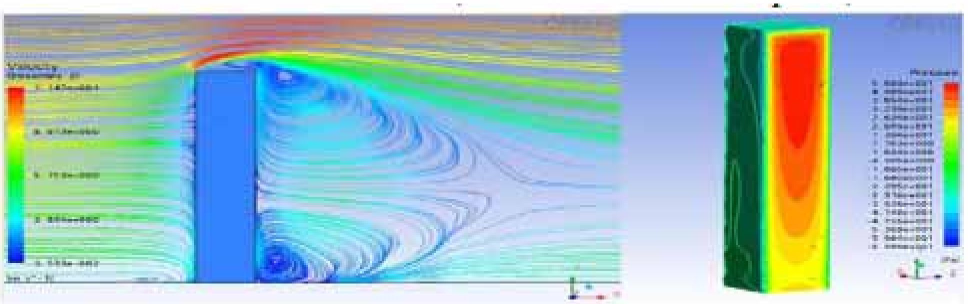
ASHRAE (2005) 2005 ASHRAE Handbook—Fundamentals (SI), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (Ch. 16)

Ellis, P. G. and Torcellini, P. A. (2005) Simulating Tall Buildings Using EnergyPlus, Building Simulation 2005, Ninth International IBPSA Conference, Montreal, Canada, August 15-18, 2005, pp. 279-286.

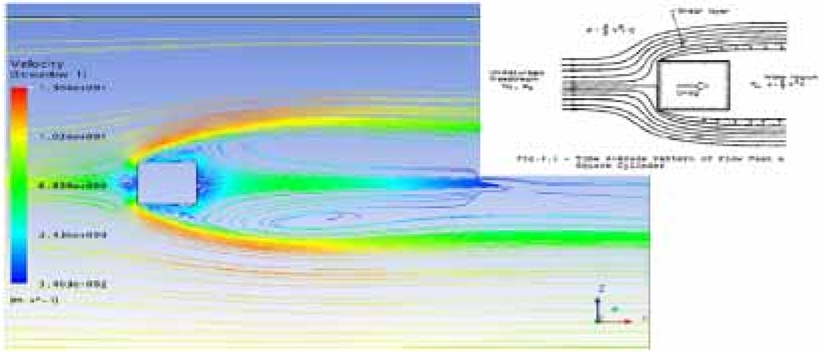
Tall Building Aerodynamics: Highlights (1 of 3)



Generation of eddies. Source: Mendis and others (2007)

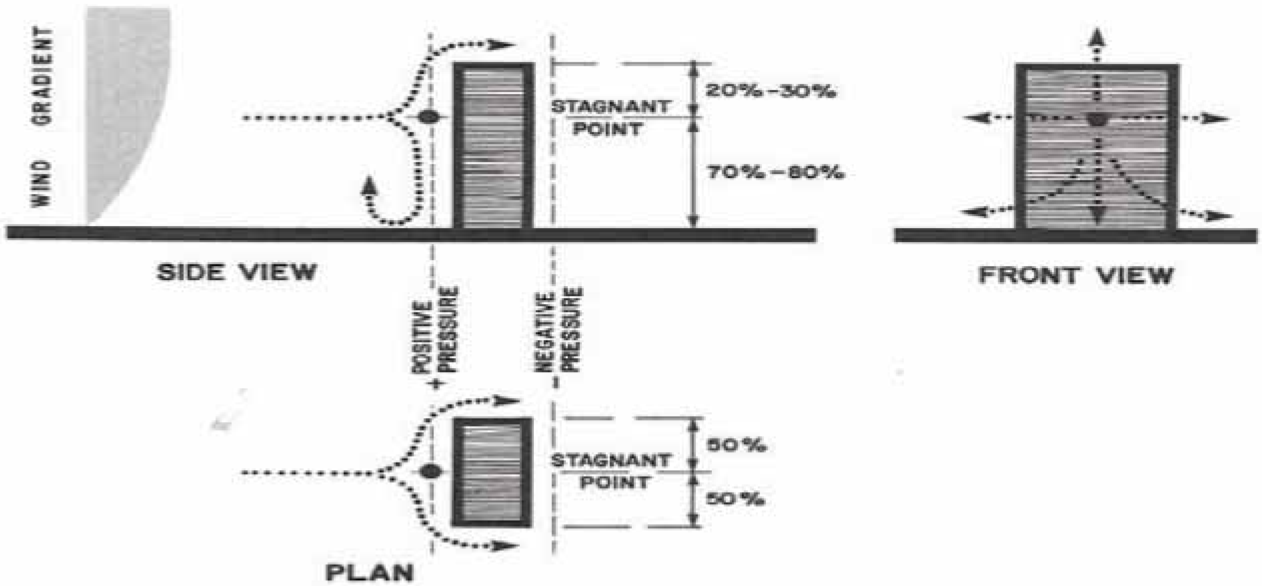


Stream line of a flow over a building model showing vertical view and pressure distribution. Source: Mendis and others (2007)



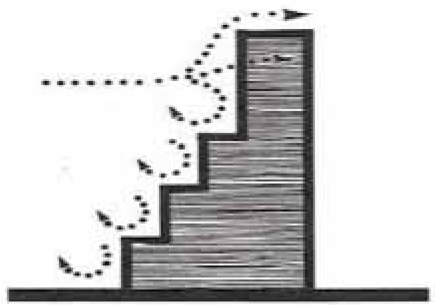
Plan view at ground level of flow streamlines over a building model. Source: Mendis and others (2007)

Tall Building Aerodynamics: Highlights (2 of 3)

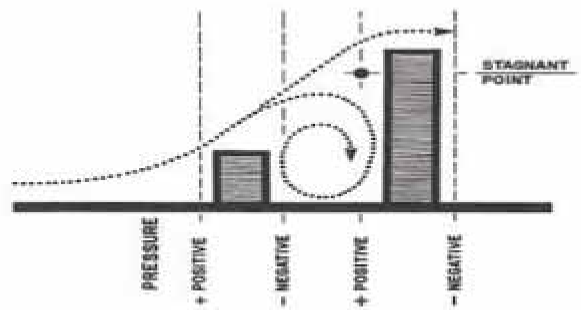


Aerodynamics of tall buildings. Source: http://www.hamilton.ca/NR/rdonlyres/53CD07BC-CBC9-464B-9063-19F319F87078/0/SitePlanGuidelinesSec4.pdf

Tall Building Aerodynamics: Highlights (3 of 3)



Stepped building facades reduce the impact of downdraft



Downdraft created between two buildings

Aerodynamics of tall buildings. Source: http://www.hamilton.ca/NR/rdonlyres/53CD07BC-CBC9-464B-9063-19F319F87078/0/SitePlanGuidelinesSec4.pdf

Tall Building Aerodynamics: Summary

- Building geometry affects weather sensitivity distribution of suites in our database
- Two wind regimes on a building are divided by a stagnant zone
- Adjacent buildings influence weather sensitivity due to wind
- Weather sensitivity due to wind is not constant over time
  - Affected by adding new buildings adjacent to existing buildings
  - Affected by wind speed and direction

Weather sensitivity influences from details of tall building designs

This list of tall building design details affecting weather sensitivity is based on Ge and Krpan (no date):

- Construction types
- Building geometries
- Surrounding topographies
- Roof overhangs; Overhang ratio (width of overhang divided by wall height)
- Sloped roof
- Flat roof
- East and southeast facing walls have highest wind-driven exposure in Lower Mainland but northeast and north exposures are comparable
- High rain deposition on upper parts of tall buildings
- Lower rain deposition on lower parts of tall buildings due to blocking effect

"…direct measurements of the rain impacting on building façades should be made wherever possible in southern BC, a region characterized by significant local variation of wind and rain conditions…When weather data from the Vancouver International Airport is used for buildings in the Vancouver region, significant errors could be introduced… (Ge and Krpan, no date)

Analyses

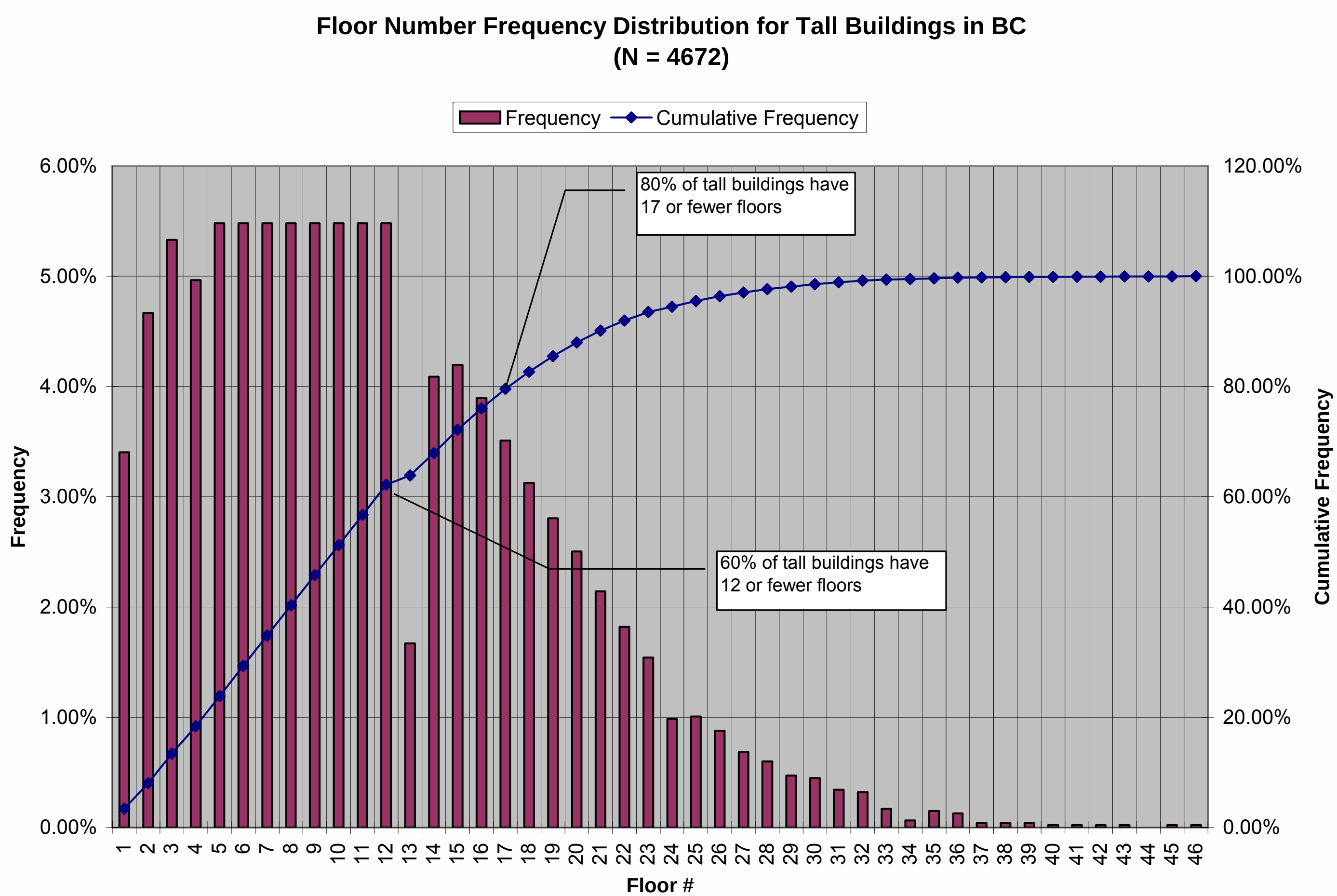
Two types of analyses were done using the data set:

- Electrical energy consumption against suite by floor to discover consumption patterns
- Electrical energy consumption by degree-days by suite by floor) to find weather sensitivity

Aggregate data, combining information from several buildings, was useful for understanding the vertical climate zones.

Tall buildings were analyzed from three out of the four BC Hydro Sales Regions. No tall building information was available from the South Interior Region.

On the next page is shown the floor number frequency distribution for tall residential buildings in BC. The distribution revealed 80% of tall residential buildings have 17 or fewer floors and 60% of the buildings have 12 or fewer floors (the minimum number of stories qualifying a building to be in our database was 12). The triskaidekaphobic anomaly of few floors numbered “13” is apparent. Many, but not all, floor 14’s are actually floor 13. Our analyses do not adjust for this anomaly. A discrepancy of one floor (3 m) was not judged to be significant in the context of our project.



Floor Number Frequency Distribution for Tall Buildings in BC
(N = 4672)
Frequency
Cumulative Frequency
80% of tall buildings have 17 or fewer floors
60% of tall buildings have 12 or fewer floors
Frequency
Cumulative Frequency
Floor #
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%

Urban canopy as defined by floor # distribution for tall residential buildings in Vancouver

The next slide shows the floor number distribution for tall residential buildings in Vancouver. Sixty percent of these buildings have 12 or fewer floors. The prevailing roof level may be conceptualized as an urban canopy within which the microclimate is determined by materials and geometry (Oke, 1976; see also figure below). We extended this concept to conjecture that the minority of tall buildings (40% of 157 tall buildings, or 63 tall buildings) projecting above the canopy will have their floors 13/14 and above exposed to the weather considerably more than the lower floors. ***This 13/14 storey urban canopy threshold will be marked, when relevant, in the slides that follow.***

Topography of an urban area could change the ideal model shown here

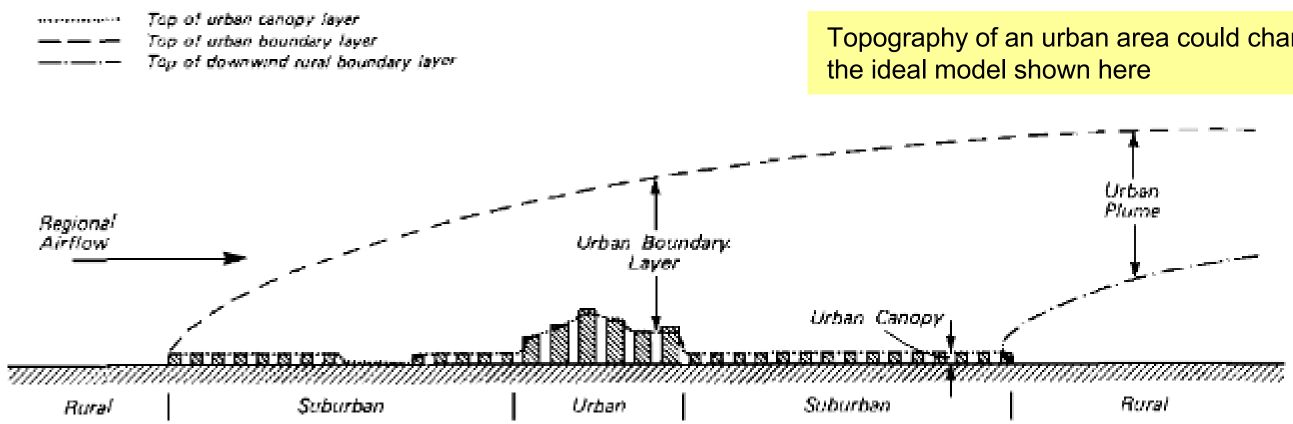
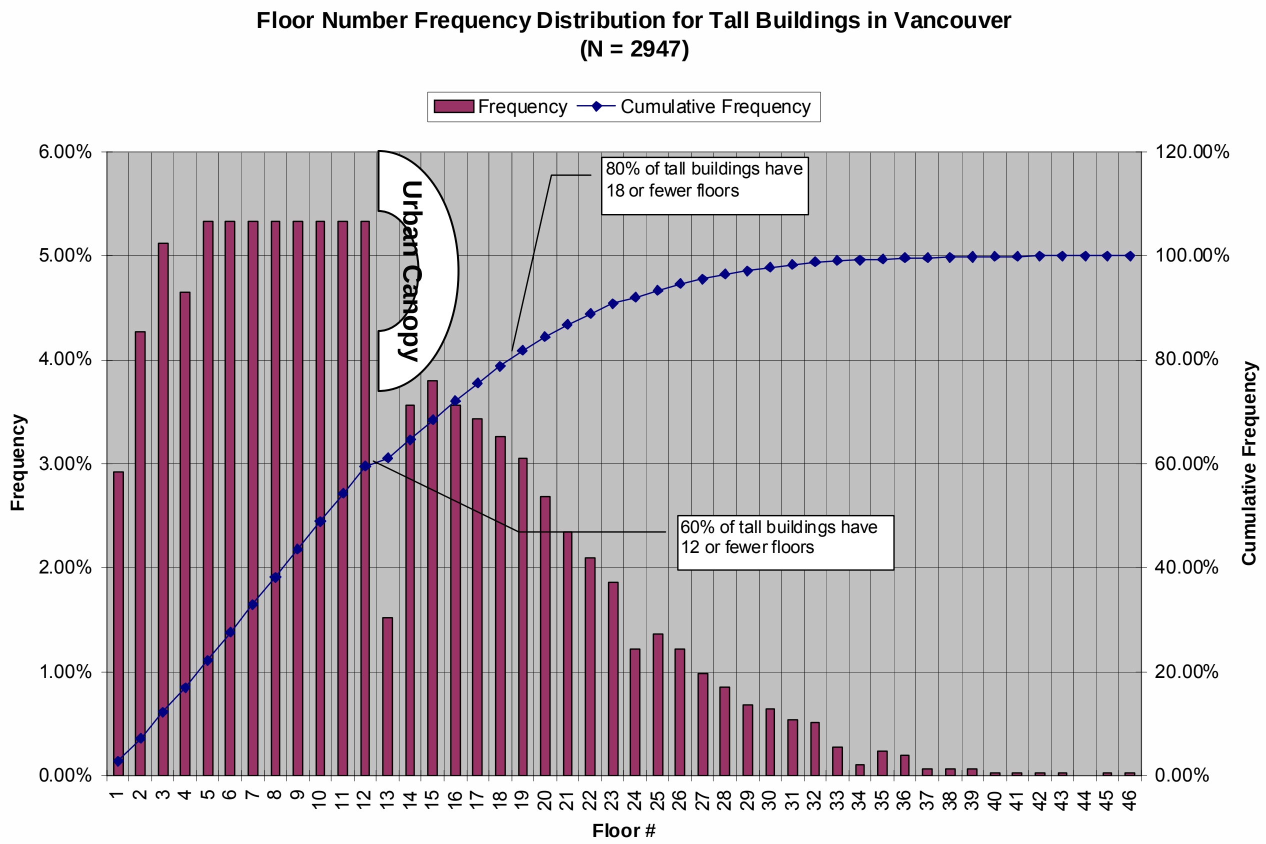


Figure (from Oke, 1976): Layers of the urban atmosphere in schematic form include the urban canopy and the urban boundary layer

BC hydro FOR GENERATIONS



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Urban Canopy Visualization – Yaletown area (1 of 2)

Yaletown from False Creek (Source of photo: http://www.pbase.ca/i/display.php?id=8562)

Urban Canopy Visualization – Yaletown area (2 of 2)

Source of photo: http://www.daapspace.daap.uc.edu/~larsongr/Larsonline/BldgIndx+76_files/OneWall.pdf

Proportion of building consumption by suite by floor for tall residential buildings in Vancouver

Floors contain different numbers of suites, both within the same building, and between different buildings. Therefore, looking at the data from the suite level is the most likely route for discovering relationships between electrical consumption and weather/climate.

As a first step, we analyzed, in aggregate, for the 157 buildings in Vancouver, the proportion of building electrical consumption by suite by floor by this method:

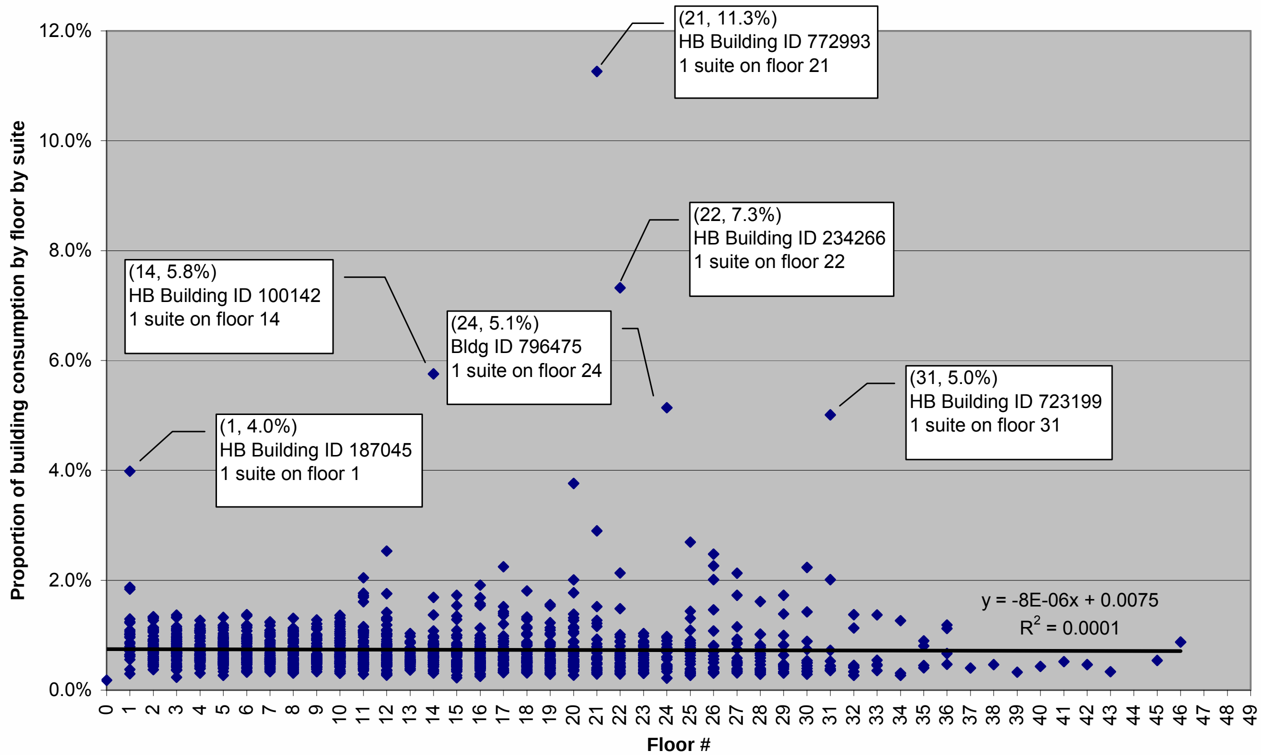
- Summed consumption of all floors to obtain total consumption of all floors with suites
- Divided each floor's consumption by number of suites on the floor
- Calculated proportion of total consumption by suites in building that a single suite on a floor would represent. Differing sizes of suites were not taken into account
- Made x-y scatter plots of this proportion against floor #
- Our data comprised 1441 electrically heated suites and 1507 non-electrically heated suites.

The scatter plots revealed that most suites, from both heating categories, used less than 2% of the total electrical energy consumed by all suites in their building. Notable anomalies with the proportion greater than or equal to 4% were identified as shown on the charts (next two slides) for further investigation as to causes of the anomalously high consumption.

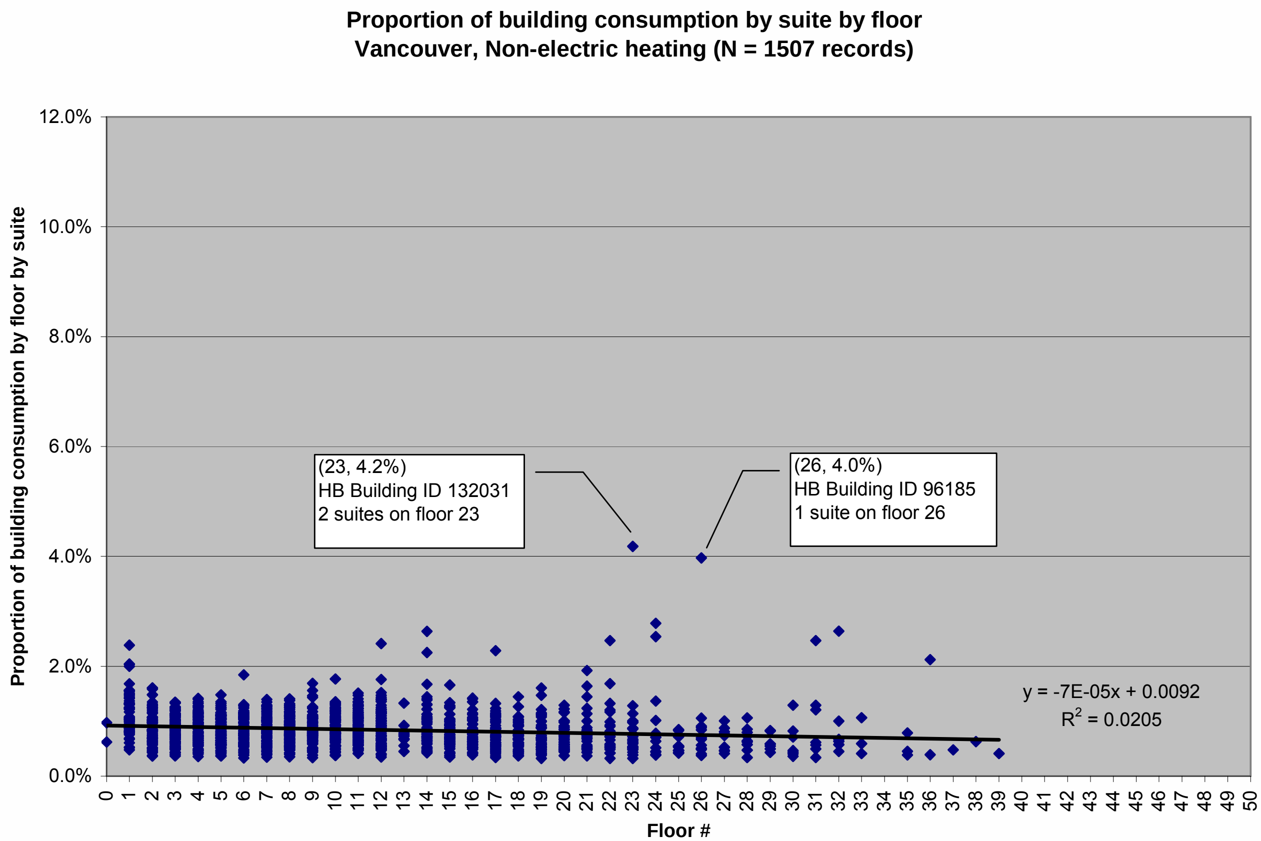
These analyses did not reveal a significant correlation between suite consumption proportion and floor #.

Electric Heat

Proportion of building consumption by suite by floor
Vancouver, Electric heating (N = 1441 records)



BC hydro FOR GENERATIONS



Non-electric heat

Weather sensitivity of suites by floor

Weather sensitivity is defined by the slope of the relationship between electrical consumption (kWh) and degree-days (K ·day). The information provided by the slope tells us how much additional electrical energy is consumed for each unit change of degree-day. Degree-days represent the likely demand for heating (or cooling) by people occupying an interior space.

We were interested in detecting and quantifying the weather sensitivity of suites as a function of their elevation above ground. To this end, we drew on the aggregate data for the 157 tall residential buildings in Vancouver to calculate the collective weather sensitivity of each floor level. The next 6 pages are examples of charts for floors 1, 2, 3, 12, 20, and 30. Total average suite consumption for each floor was plotted against heating degree-days (HDD) at Vancouver International Airport (YVR; observed from Apr 2004 to Jun 2009). The slope of each chart's linear regression line was tabulated against floor number to derive the chart titled "Weather sensitivity of suites relationship to floor #" for electrically-heated suites. A similar analysis was done for non-electrically heated suites.

For aggregated data: Electrically-heated suites above floor 12 (the urban canopy) were found usually to be increasingly weather sensitive with height in a tall building. Non-electrically-heated suites showed no significant weather sensitivity correlation with height (although individual non-electrically-heated suites may still exhibit some degree of weather sensitivity from thermostatically-controlled appliances such as refrigerators, freezers, water heaters, and air conditioners.

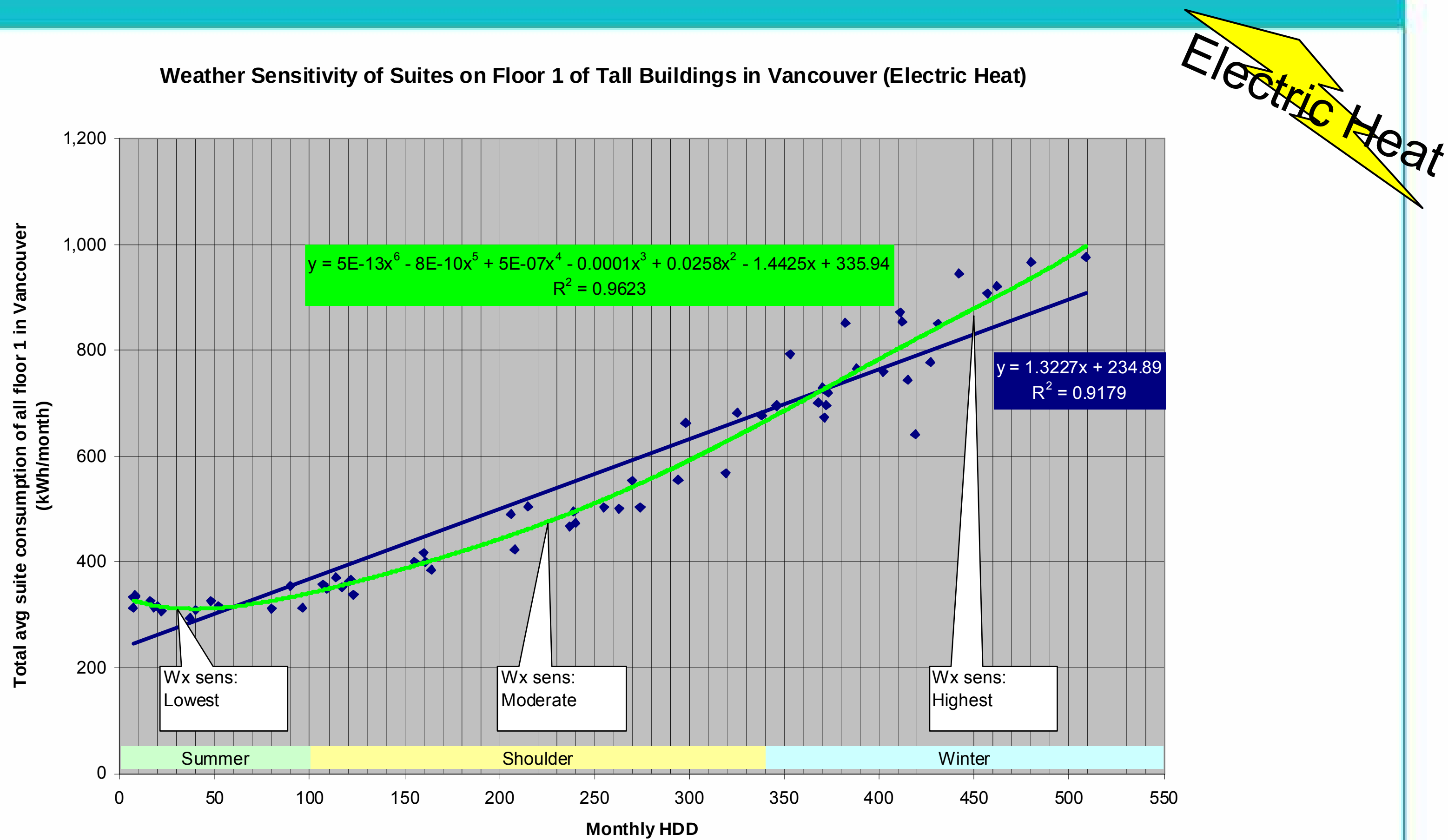
Weather sensitivity of suites by floor number — Seasonality

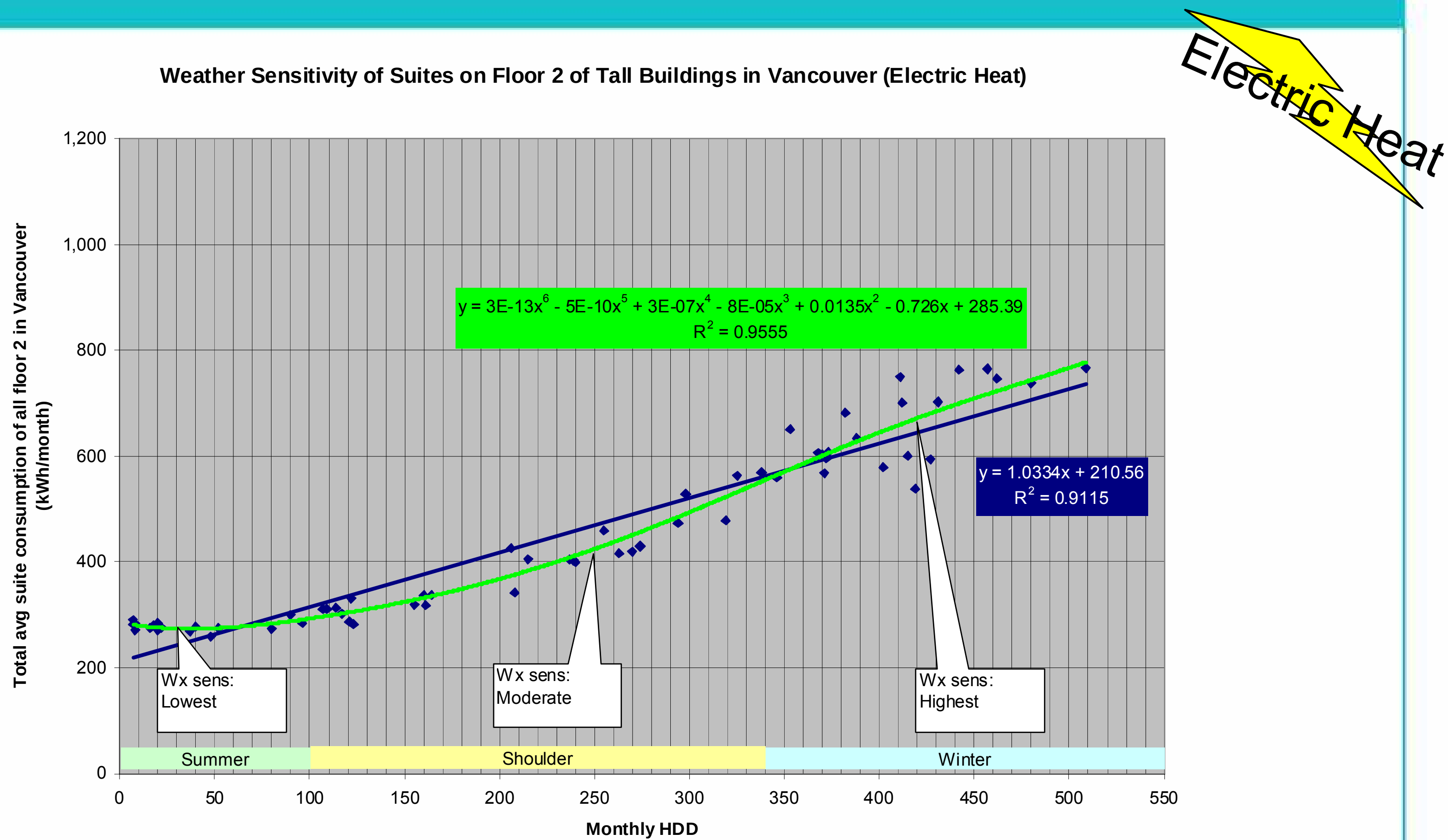
Seasonality is revealed on the charts for electrically-heated suites. Weather sensitivity is lowest in summer, moderate in shoulder months, and highest in winter. Months were allocated to seasons according to the findings by Wahlgren (2010). Winter always includes Nov to Mar. Summer always includes Jun to Aug. The balance of the months are included in the Shoulder Season. The following observations concerning seasonality were made, using a polynomial curve of order 6 as a visual aid:

• During **summer**, with a monthly HDD range of up to 100 HDD, consumption was relatively flat along the baseload value, varying little over the range of HDD. Suite occupants had little need for energy for heating or cooling;

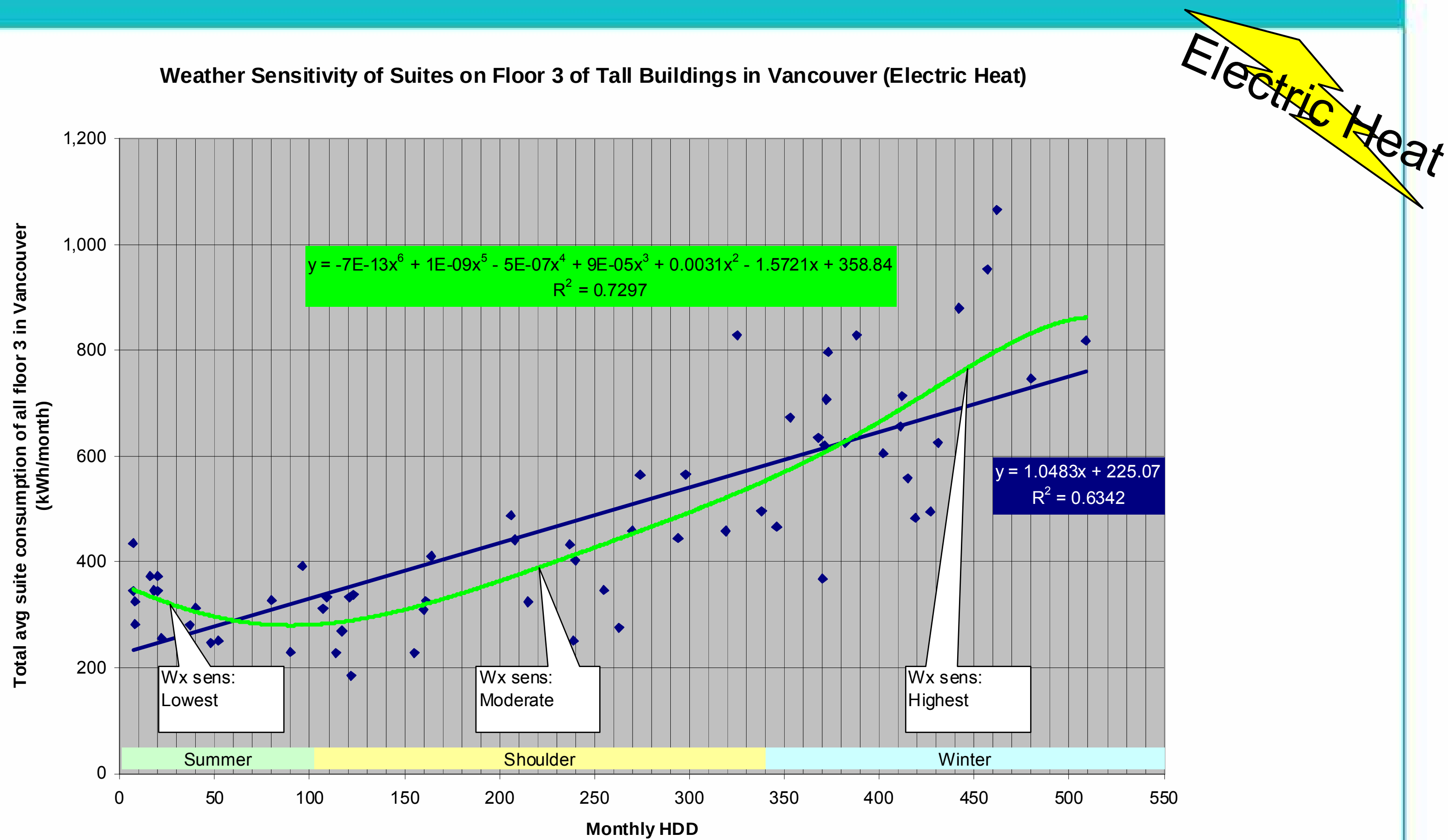
• During the **shoulder** months, consumption was sensitive in a linear fashion to HDD over the range 100 to 340 HDD as suite occupants used electrical energy to heat their living spaces;

• During **winter**, consumption was sharply sensitive to HDD over the range 340 to 450 HDD but above this value consumption was dampened, presumably because heating capacity of the suites in the data set reached its limit..


Weather Sensitivity of Suites on Floor 1 of Tall Buildings in Vancouver (Electric Heat)
Electric Heat
y = 5E-13x6 - 8E-10x5 + 5E-07x4 - 0.0001x3 + 0.0258x2 - 1.4425x + 335.94
R2 = 0.9623
y = 1.3227x + 234.89
R2 = 0.9179
Total avg suite consumption of all floor 1 in Vancouver (kWh/month)
1,200
1,000
800
600
400
200
0
Wx sens: Lowest
Wx sens: Moderate
Wx sens: Highest
Summer
Shoulder
Winter
0 50 100 150 200 250 300 350 400 450 500 550
Monthly HDD



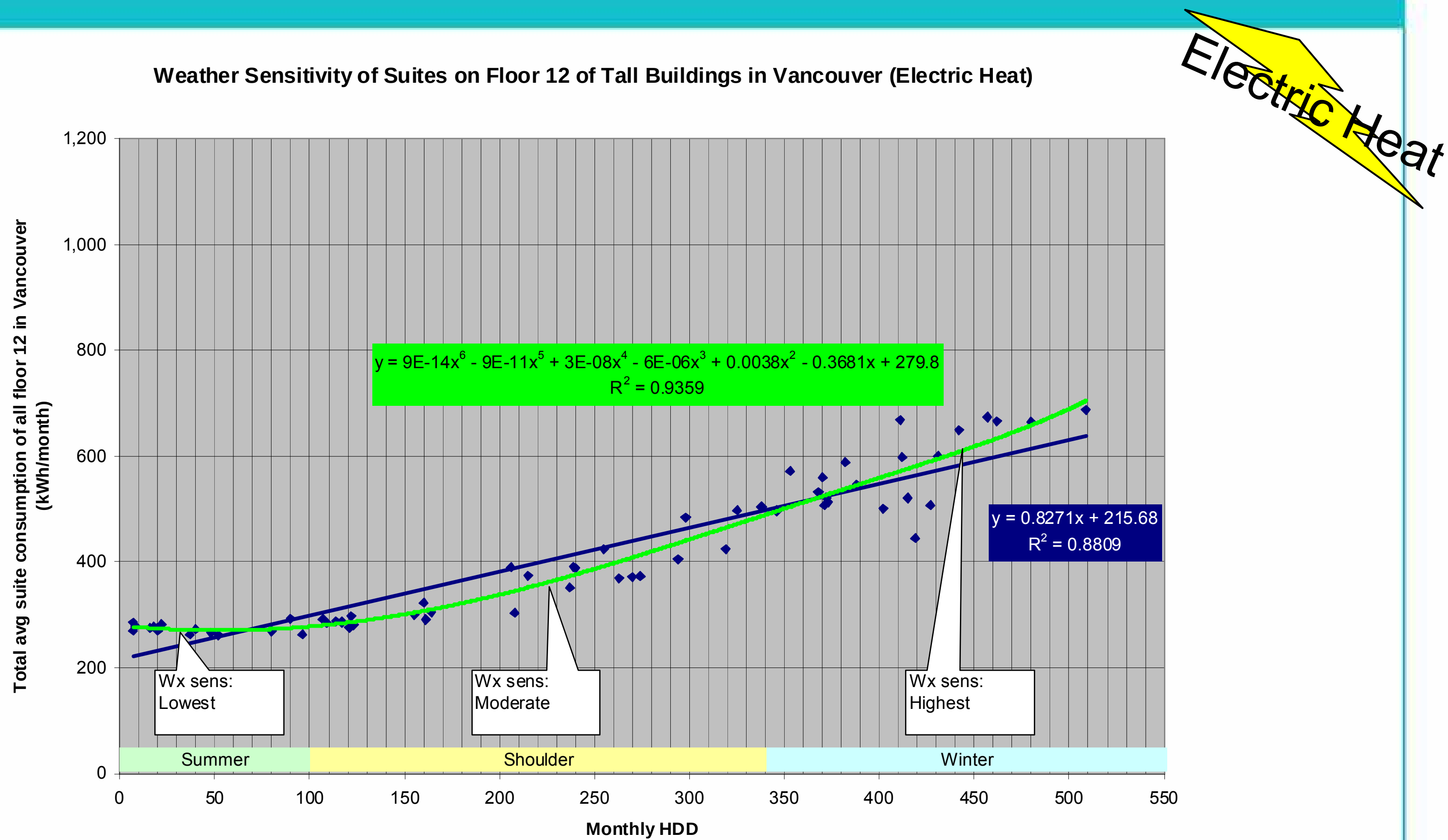
BC hydro FOR GENERATIONS



BC hydro FOR GENERATIONS

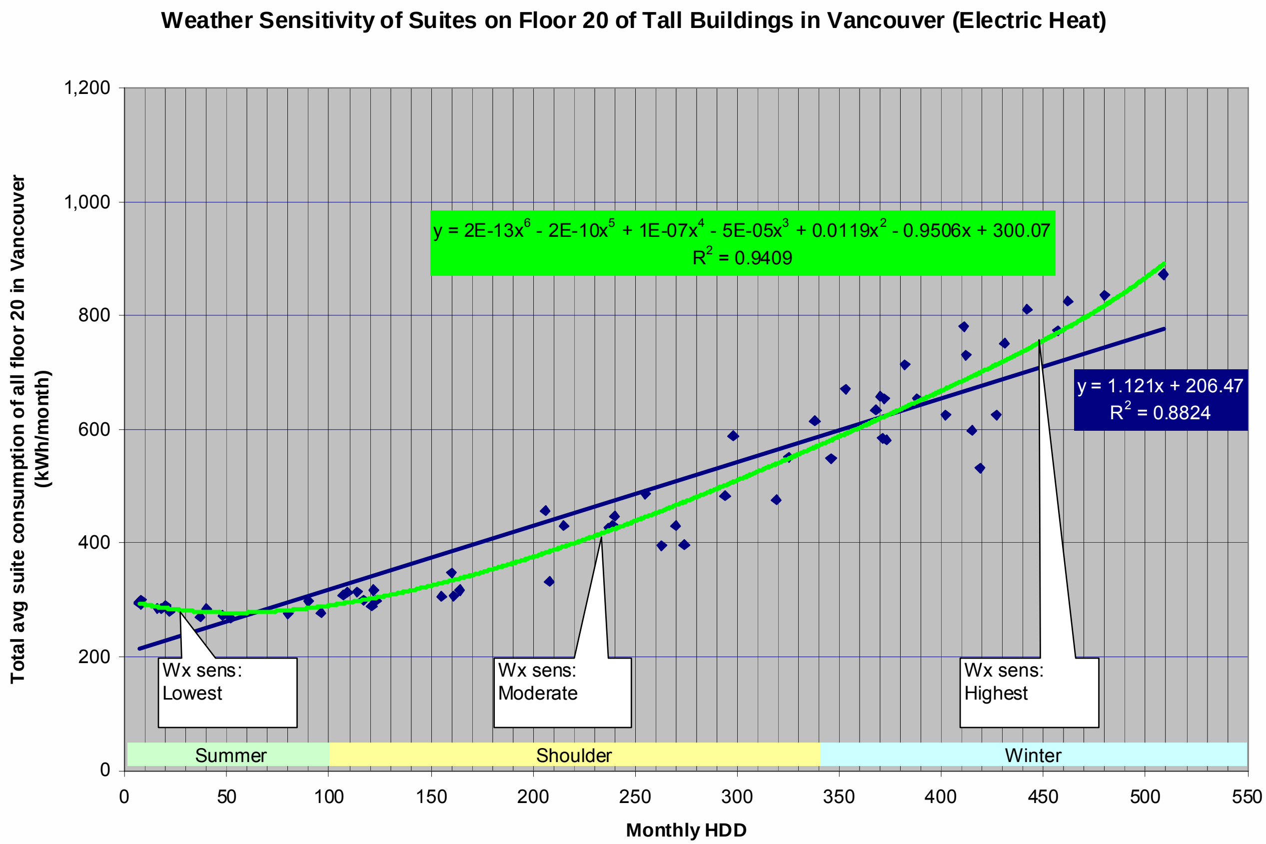
Roland Wahlgren and Harinder Bains
BC Hydro Customer Information Management—Load Analysis

Weather Sensitivity of Suites on Floor 12 of Tall Buildings in Vancouver (Electric Heat)



BC hydro FOR GENERATIONS

Electric Heat



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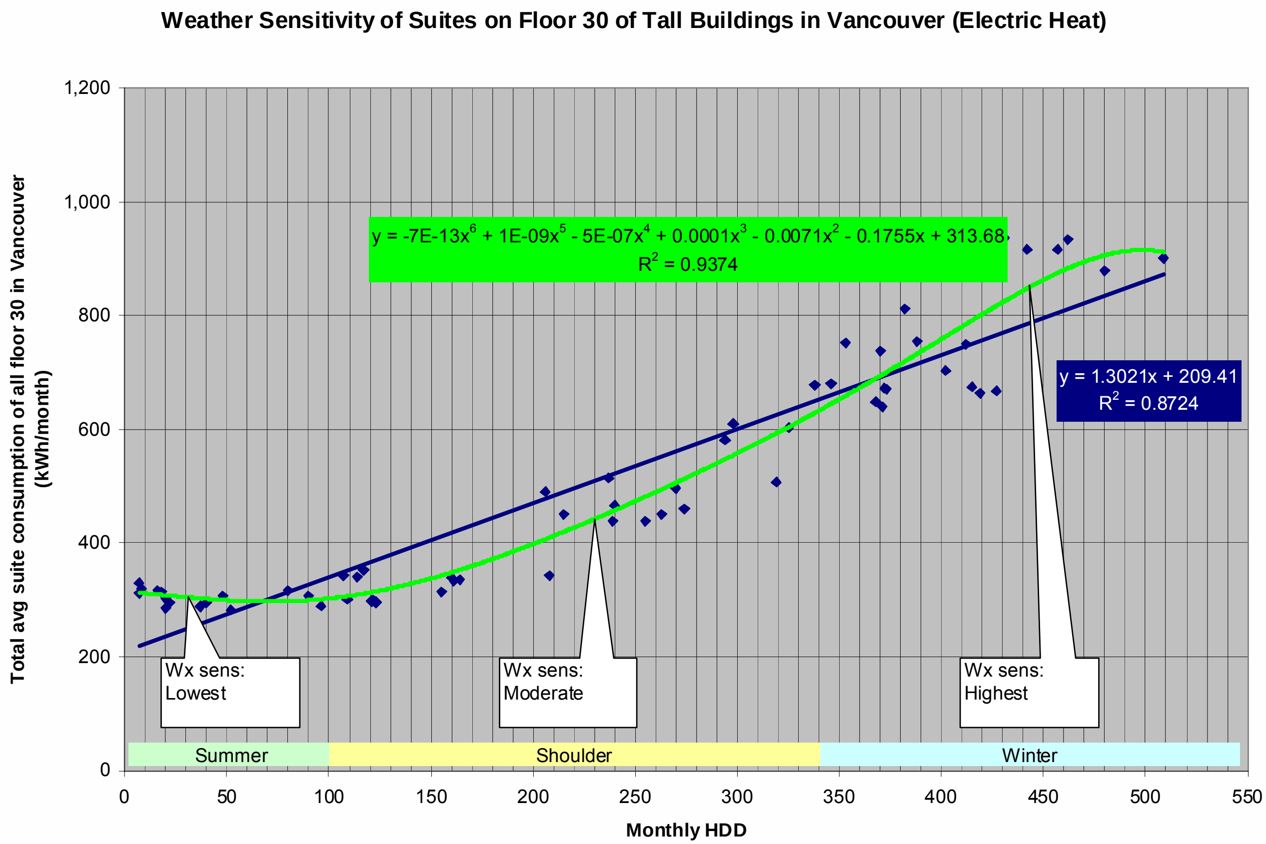
BC Hydro Customer Information Management—Load Analysis

Electric Heat



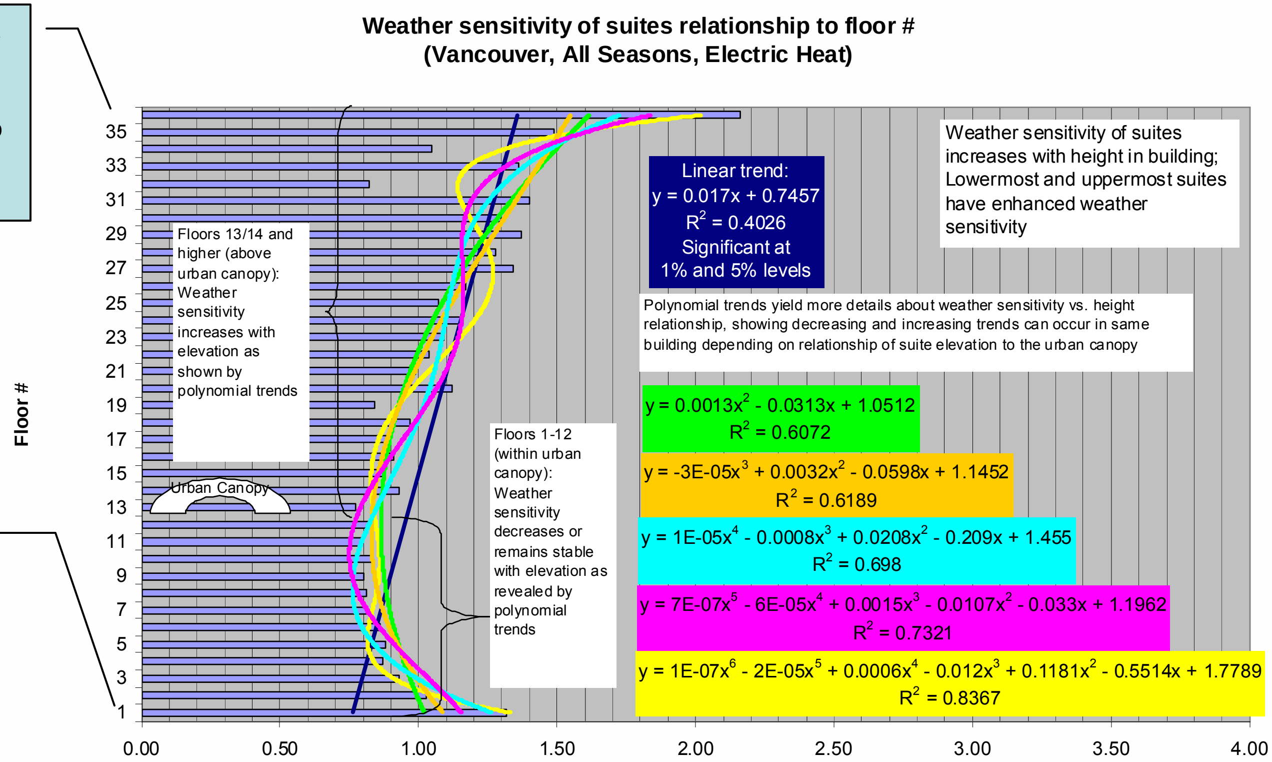
Roland Wahlgren and Harinder Bains
BC Hydro Customer Information Management—Load Analysis

Weather sensitivity of suites by floor number (Vancouver, Electric Heat)

Electric Heat

Top floor suites are more weather sensitive due to heat loss through roof

Suites on Floor # 1 are often more weather sensitive due to unheated parking garages situated below grade



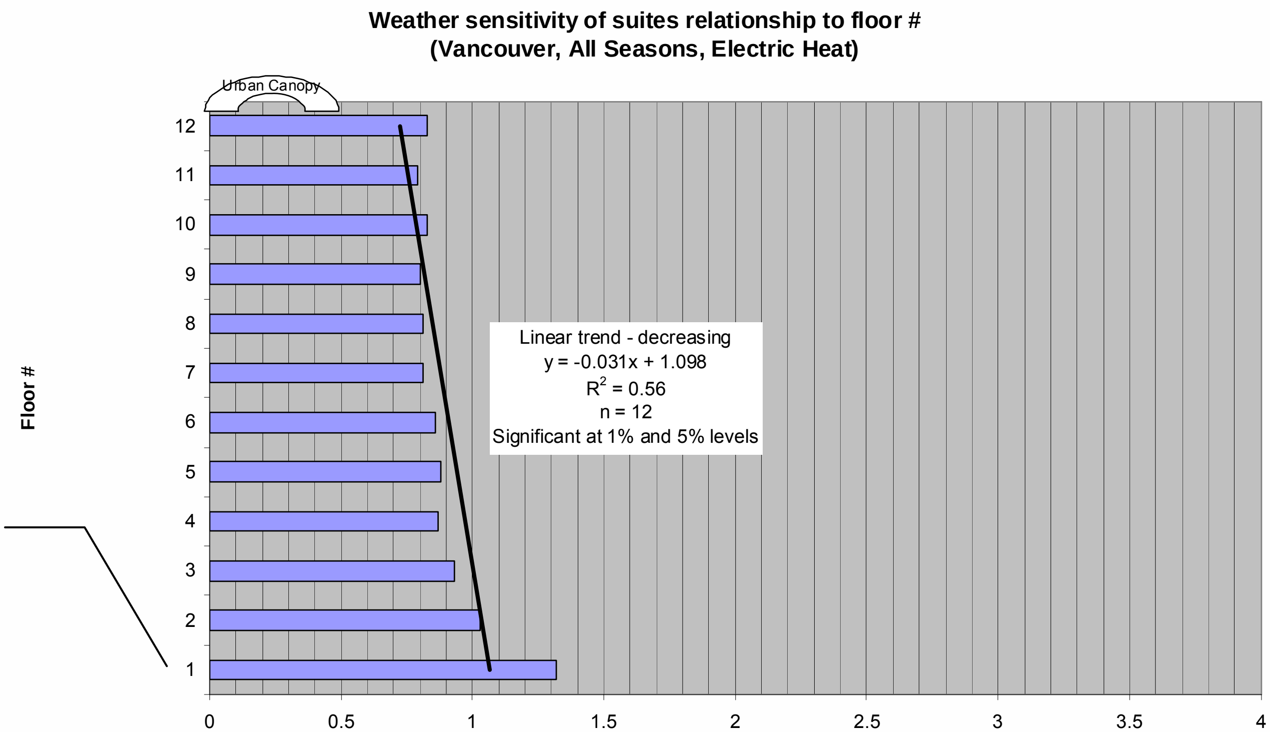
Floor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
kWh per (K x day)	1.32	1.03	0.93	0.87	0.88	0.86	0.81	0.81	0.8	0.83	0.79	0.83	0.77	0.93	0.87	0.91	0.89	0.97

Floor	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
kWh per (K x day)	0.84	1.12	0.99	1.04	1.09	1.16	1.07	1.17	1.34	1.28	1.37	1.3	1.4	0.82	1.36	1.05	1.49	2.16

Weather Sensitivity of suites [kWh/(K x day)]

Decreasing weather sensitivity of suites by floor numbers 1–12 (Vancouver, Electric Heat)

Electric Heat



Floor	1	2	3	4	5	6	7	8	9	10	11	12
kWh per (K x day)	1.32	1.03	0.93	0.87	0.88	0.86	0.81	0.81	0.8	0.83	0.79	0.83

Weather Sensitivity of suites [kWh/(K x day)]

Suites on Floor # 1 are often more weather sensitive due to unheated parking garages situated below grade

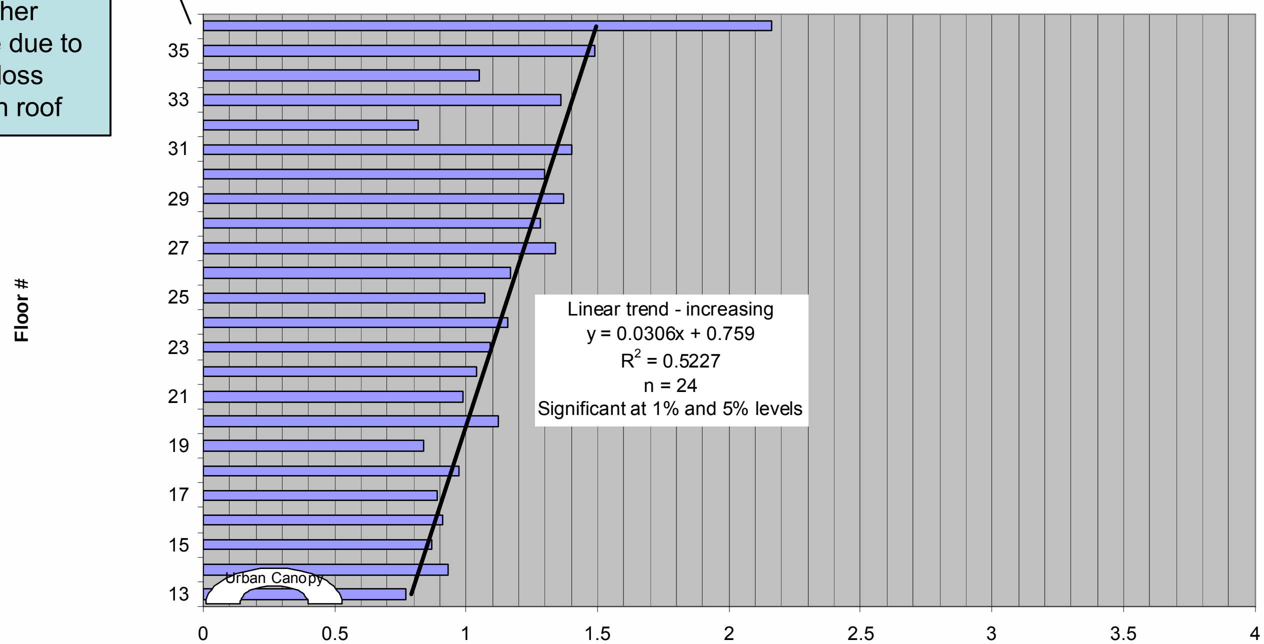
BC hydro FOR GENERATIONS

Increasing weather sensitivity of suites by floor numbers 13+ (Vancouver, Electric Heat)

Electric Heat

Top floor suites are more weather sensitive due to heat loss through roof

Weather sensitivity of suites relationship to floors 13 and above (Vancouver, All Seasons, Electric Heat)



Floor	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
kWh per (K x day)	0.77	0.93	0.87	0.91	0.89	0.97	0.84	1.12	0.99	1.04	1.09	1.16	1.07	1.17	1.34	1.28	1.37	1.3	1.4	0.82	1.36	1.05	1.49	2.16

Weather Sensitivity of suites [kWh/(K x day)]

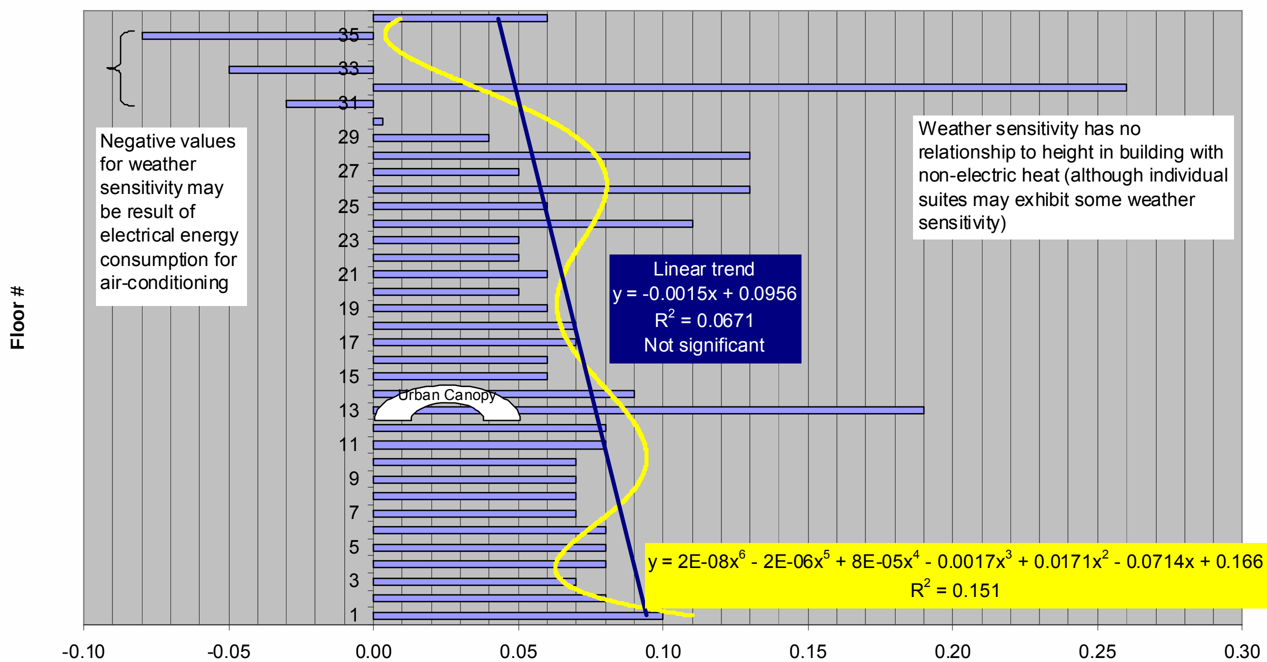
BC hydro FOR GENERATIONS

Roland Wahlgren and Harinder Bains
BC Hydro Customer Information Management—Load Analysis

Weather sensitivity of suites by floor number (Vancouver, Non-electric)

Non-electric heat

Weather sensitivity of suites relationship to floor #
(Vancouver, Non-electric heat)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Series1	0.1	0.08	0.07	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.08	0.08	0.19	0.09	0.06	0.06	0.07	0.07

	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Series1	0.06	0.05	0.06	0.05	0.05	0.11	0.06	0.13	0.05	0.13	0.04	0	-0.03	0.26	-0.05		-0.08	0.06

Weather Sensitivity of suites [kWh/(K x day)]

BC hydro FOR GENERATIONS

Electric Heat

Weather sensitivity of tall buildings in Vancouver and adjacent municipalities by building age

Does weather sensitivity depend on the age of the building? After all, architectural styles, proportion of glazing, materials used, and urban density have all changed over the course of decades.

Weather sensitivity is the ratio between suite energy consumption and heating degree-days in the linear relationship of these variables . The measure is independent of changes in patterns of energy consumption such as increasing ownership of large-screen televisions.

To test the hypothesis that weather sensitivity in Vancouver's (and its adjacent municipalities of Burnaby, Richmond, and North Vancouver) tall residential building stock does depend on building age we took a simple approach of classifying buildings by the decade in which they were built.

The Table (next slide) shows the weather sensitivity (WS) and coefficient of determination (R^2) for suites on each floor of the aggregate building stock grouped by decade. Only electrically-heated suites (from 113 buildings) were included in this analysis. Their age distribution is shown on the next slide.

Examples of typical building designs through the decades are shown in a series of five slides.

The chart plotted from the Table values shows noticeable differences in weather sensitivity between buildings of different ages. The "envelopes" (polynomials of order 6) colour-coded to buildings in each age class provide a visual guide to the differences.

An energy and monetary weather sensitivity cost comparison example is provided, in a later slide, between typical 1960's-built and 2000's built suites.

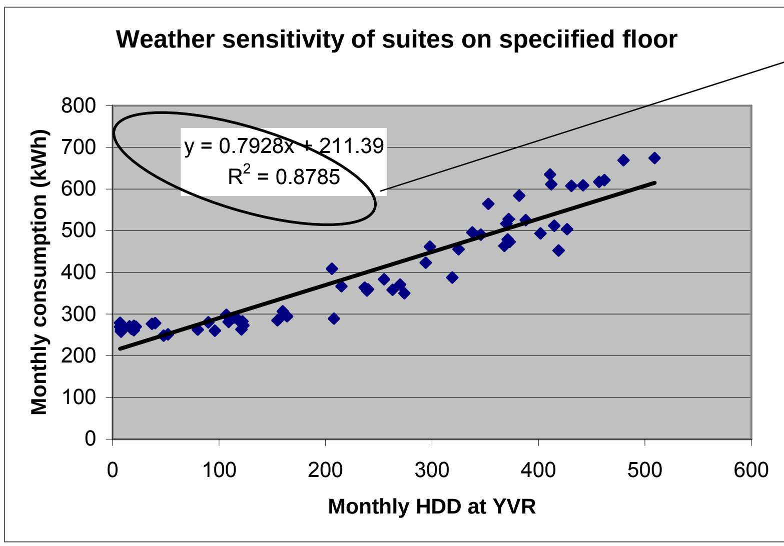
Weather sensitivity of tall buildings in Vancouver and adjacent municipalities by building age

Electric Heat

Weather sensitivity calculation used heating degree days at YVR from April 2004 to June 2009 with corresponding monthly consumption values for average suites on specified floor of aggregated buildings in sample (N = 63 comes from the 63 months in the consumption/weather database)

The building database subsets for each decade all contained at least 21 floors. R^2 values were recorded to illustrate that for the first 21 floors the weather sensitivity values were usually associated with strong statistical significance even when only 4 or 5 buildings were represented..

This example of a weather sensitivity chart is for suites on floor 10 in the 2000's-built set of buildings



	1960s-built		1970s-built		1980s-built		1990s-built		2000s-built		
Floor	WS Suites	R^2	WS Suites	R^2	WS Suites	R^2	WS Suites	R^2	WS Suites	R^2	Floor
1	1.63	0.93	2.37	0.90	2.62	0.93	1.45	0.90	1.15	0.91	1
2	0.93	0.93	1.50	0.92	1.93	0.94	1.18	0.91	0.95	0.90	2
3	0.63	0.81	1.22	0.84	1.46	0.93	1.09	0.90	0.87	0.89	3
4	0.72	0.86	1.60	0.92	1.55	0.92	0.96	0.89	0.90	0.90	4
5	0.57	0.84	1.10	0.86	1.30	0.91	1.04	0.91	0.83	0.88	5
6	0.68	0.86	1.15	0.88	1.30	0.91	0.96	0.89	0.78	0.89	6
7	0.52	0.80	1.18	0.89	1.16	0.91	0.93	0.90	0.83	0.88	7
8	0.56	0.83	1.12	0.90	1.21	0.89	0.95	0.89	0.77	0.87	8
9	0.49	0.77	0.91	0.86	1.25	0.91	0.90	0.90	0.86	0.88	9
10	0.61	0.82	1.16	0.87	1.20	0.90	0.84	0.89	0.79	0.88	10
11	0.39	0.68	1.38	0.86	1.03	0.88	0.94	0.8[illegible]	0.75	0.86	11
12	0.69	0.76	1.24	0.89	1.05	0.87	0.91	0.88	0.75	0.87	12
13	0.24	0.33	1.12	0.83	1.35	0.89	0.87	0.89	0.70	0.86	13
14	0.65	0.78	1.48	0.89	0.99	0.90	1.10	0.89	0.81	0.86	14
15	0.80	0.72	1.18	0.88	1.19	0.89	0.87	0.87	0.86	0.87	15
16	0.21	0.20	1.51	0.88	1.08	0.87	1.02	0.88	0.83	0.86	16
17	0.35	0.39	1.49	0.86	1.16	0.88	0.99	0.87	0.87	0.85	17
18	0.30	0.32	1.36	0.89	1.40	0.87	0.97	0.86	1.07	0.86	18
19	0.18	0.09	1.65	0.90	0.96	0.87	0.96	0.85	0.93	0.86	19
20	0.18	0.10	1.30	0.88	1.17	0.87	1.20	0.88	1.09	0.86	20
21	1.06	0.40	2.60	0.86	1.34	0.86	1.04	0.86	1.07	0.88	21
22					1.06	0.85	1.11	0.88	1.15	0.82	22
23					1.21	0.85	1.15	0.88	1.27	0.85	23
24					1.61	0.81	1.14	0.85	1.64	0.86	24
25					4.15	0.58	1.05	0.86	1.31	0.81	25
26					3.75	0.67	1.22	0.86	1.12	0.79	26
27							1.34	0.87	1.35	0.82	27
28							1.32	0.85	1.55	0.88	28
29							1.25	0.87	1.67	0.84	29
30							1.29	0.85	1.93	0.90	30
31							1.28	0.69	1.70	0.90	31
32							0.77	0.68	1.03	0.64	32
33							1.16	0.70	1.97	0.88	33
35							1.05	0.63	1.66	0.83	35
36							1.40	0.66	1.54	0.64	36
37							2.52	0.67	1.26	0.77	37
38									1.80	0.78	38
39									1.31	0.71	39
40									1.71	0.79	40
41									2.23	0.79	41
42									0.35	0.09	42
43									0.04	0.00	43
45									0.06	0.00	45
46									2.10	0.52	46

1960s-built: 1100 Harwood, 1516 Davie, 1875 Robson, 1933 Robson, 989 Nelson. Building sample size = 5

1970s-built: 325 Keefer, 4955 Newton St. Bby, 5652 Patterson Ave Bby, 5645 Barker Ave, Bby. Building sample size = 4

1980s-built: Various. Building sample size = 15

1990s-built: Various. Building sample size = 67

2000s-built: Various. Building sample size = 22

BC hydro FOR GENERATIONS

Weather sensitivity of tall buildings in Vancouver and adjacent municipalities by building age

Electric Heat

Age distribution of electrically-heated tall residential buildings in Vancouver, Burnaby, Richmond, and North Vancouver (Total = 113)

	1960's	1970's	1980's	1990's	2000's
Qty	5	4	15	67	22

Built year decade

Electric Heat

Visual guide to building design trends (1 of 5)

Source: http://www.6717000.com/1100harwood/

1966

1100 Harwood St.

Modern

Glass, brick, concrete

13 Floors

Electric Heat

Visual guide to building design trends (2 of 5)

Source: http://www.bing.com/maps/

1976

325 Keefer St.

Modern

Glass, concrete

13 Floors

Electric Heat

Visual guide to building design trends (3 of 5)

Source: http://www.bing.com/maps/

1989

1212 Howe St.

Postmodern

Glass, aluminum, concrete

17 Floors

Electric Heat

Visual guide to building design trends (4 of 5)

Source: http://www.bing.com/maps/

1995

5189 Gaston St.

Neomodern

Glass, concrete

20 Floors

Electric Heat

Visual guide to building design trends (5 of 5)

Source: http://www.bing.com/maps/

2003

1238 Burrard St.

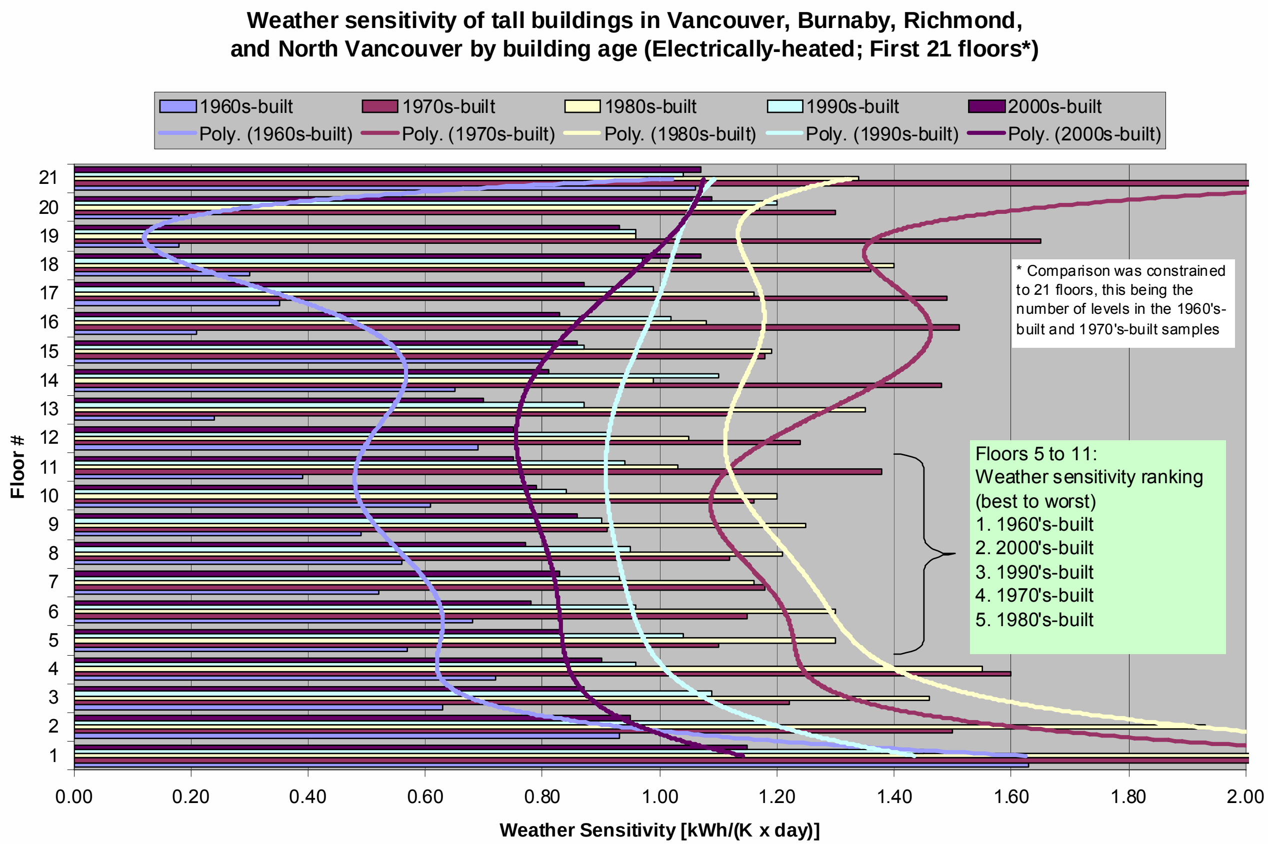
Neomodern

Glass, brick, concrete

13 Floors

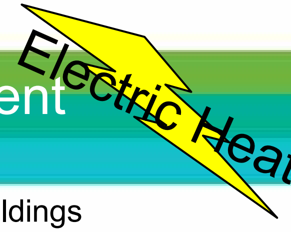
Weather sensitivity of tall buildings in Vancouver and adjacent municipalities by building age

Electric Heat



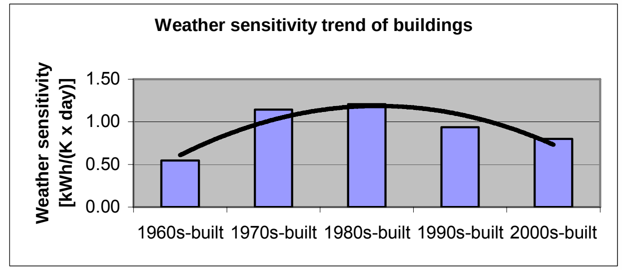
BC hydro FOR GENERATIONS

Weather sensitivity of tall buildings in Vancouver and adjacent municipalities by building age



Energy and monetary cost comparison of responding to weather in 1960's and 2000's-built buildings

Floor	1960s-built WS Suites	1970s-built WS Suites	1980s-built WS Suites	1990s-built WS Suites	2000s-built WS Suites
5	0.57	1.10	1.30	1.04	0.83
6	0.68	1.15	1.30	0.96	0.78
7	0.52	1.18	1.16	0.93	0.83
8	0.56	1.12	1.21	0.95	0.77
9	0.49	0.91	1.25	0.90	0.86
10	0.61	1.16	1.20	0.84	0.79
11	0.39	1.38	1.03	0.94	0.75
Avg WS	**0.55**	**1.14**	**1.21**	**0.94**	**0.80**



Weather Sensitivity (WS) is ratio of electrical consumption to heating degree-days.

Example: If WS = 0.5, then 0.5 kWh of consumption (increase or decrease) is needed to respond to a weather change of 1 degree-day (increase or decrease).

Comparison of weather sensitive energy costs for suite occupants (floors 6 to 9):
Typical mid-winter month: 400 HDD per month

1960's-built weather sensitivity = 0.55 kWh/HDD
Energy cost of responding to weather = **218 kWh**
Monetary cost of responding to weather (approx @ $0.0627 per kWh) **$13.69**

2000's-built weather sensitivity = 0.80 kWh/HDD
Energy cost of responding to weather = **321 kWh**
Monetary cost of responding to weather (approx @ $0.0627 per kWh) **$20.10**

Ratio: 1.5

The balance of a typical electricity bill would comprise lighting, appliances, and other loads that are not weather sensitive.

Building Age Analysis Summary

- Tall residential buildings built from the 1970's to the present are more weather sensitive than 1960's-built stock
- Possible reasons for this observation are:
  - Architectural style (elimination of roof overhangs increases wind-driven rain effect);
  - Trend to increasing proportion of glazing in building envelope;
  - Trend to using building envelope materials with higher heat loss coefficients (glass versus concrete);
  - Building sites are in previously undeveloped, therefore more weather exposed locations, in Vancouver and its adjacent municipalities
- Electrical utility perspective
  - Electrical load increases with urban growth at a rate which is faster than previous experience;
  - Capacity planners for urban residential substations need to be aware of trends;
  - Address problem by educating architects about designing to minimize weather sensitivity
- Societal perspective
  - Energy conservation considerations appear to be taking second place to style (but are improving relative to 1980's);
  - Limited energy resources are wasted by design decisions not taking sustainable society into account;
  - Unnecessary burdens of extra energy costs and physical discomfort are imposed on occupiers of highly weather sensitive suites (for example, the 1970's and 1980's-built stock)

Conclusions

- Weather sensitivity of electrically-heated suites increases with height in tall buildings (especially above the 12th storey) so weather sensitivity of Vancouver downtown grid will increase as more tall buildings are commissioned
- Weather sensitivity is higher for buildings built in the 1970's through 2000's than in earlier decades due possibly to changing trends in building designs and use of building envelope materials
- Opportunities exist for BC Hydro to work with tall-building architects and developers to incorporate design features to reduce impact of tall building weather sensitivity on grid
  - Roof overhang ratio
  - Infiltration
  - Glazing proportion
  - Building envelope materials
- Next steps: Case studies of individual buildings

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