GIS in Air Pollution Research, the Role of Building Surfaces

Stephen C. Hurlock, Jochen Stutz
Department of Atmospheric and Oceanic Sciences
University of California, Los Angeles
steveh@atmos.ucla.edu

Paper 2042
2004 ESRI International User Conference
San Diego, California
August 11, 2004

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Stephen C. Hurlock, Jochen Stutz, Department of Atmospheric and Oceanic Sciences
University of California, Los Angeles
steveh@atmos.ucla.edu

ABSTRACT

Buildings can strongly influence air quality because their surfaces chemically process gases, such as nitrogen oxides, and their volumes affect pollutant concentrations. However, actual surface areas and volumes and their vertical distributions are thus far poorly characterized, limiting our ability to model this important aspect of urban air pollution.

This paper presents the first application of GIS to quantify the distribution of surface areas and volumes for use in urban air quality models. GIS data from the city of Santa Monica was used to develop 3-D models of selected areas, representative of various urban environments. These models allow calculation of factors such as building surface area, building volume and open air volume. Inclusion of these factors into new and evolving air quality models shows striking results and should lead to higher fidelity calculations of the vertical and temporal distributions of pollutants in urban environments.

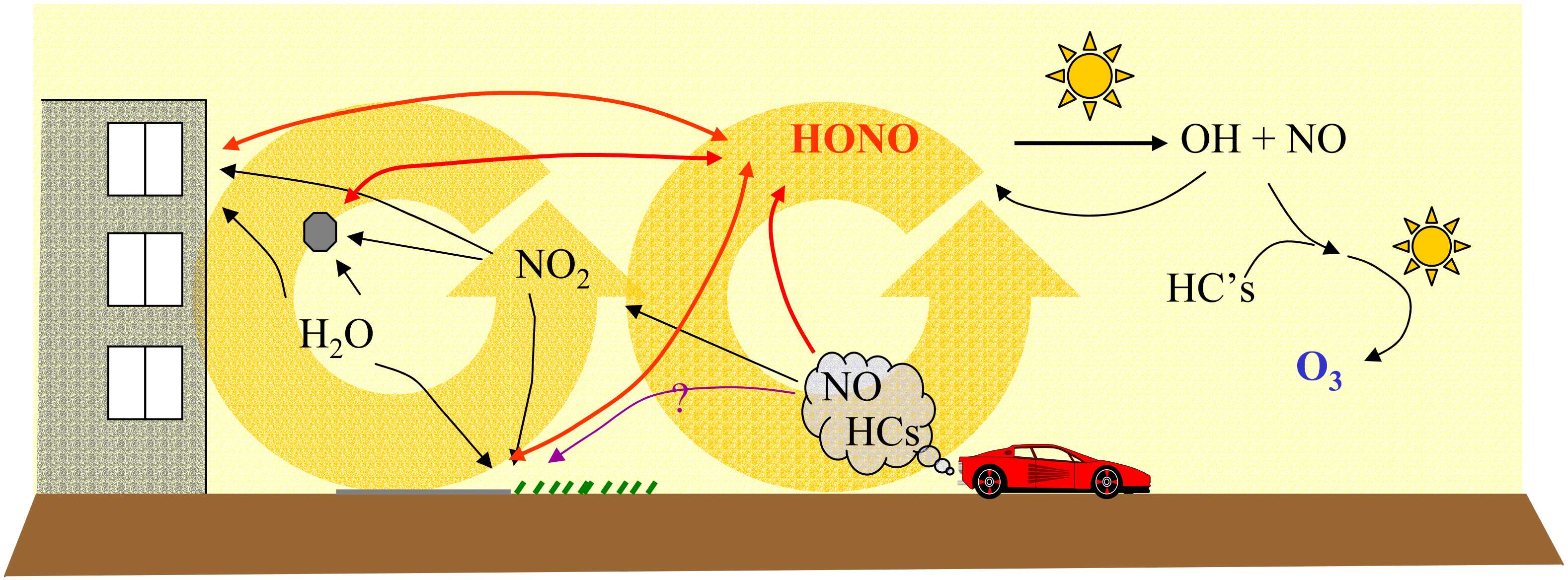
The influence of buildings on urban air quality has been recognized for a long time.

Moses Maimonides, Hebrew philosopher, scientist, and jurist, 1135-1204, wrote:

"Comparing the air of cities to the air of deserts and arid lands is like comparing waters that are befouled and turbid to waters that are fine and pure. In the city, **because of the height of its buildings, the narrowness of its streets**, and all that pours forth from its inhabitants and their superfluities…the air becomes stagnant, turbid, thick, misty, and foggy… ."

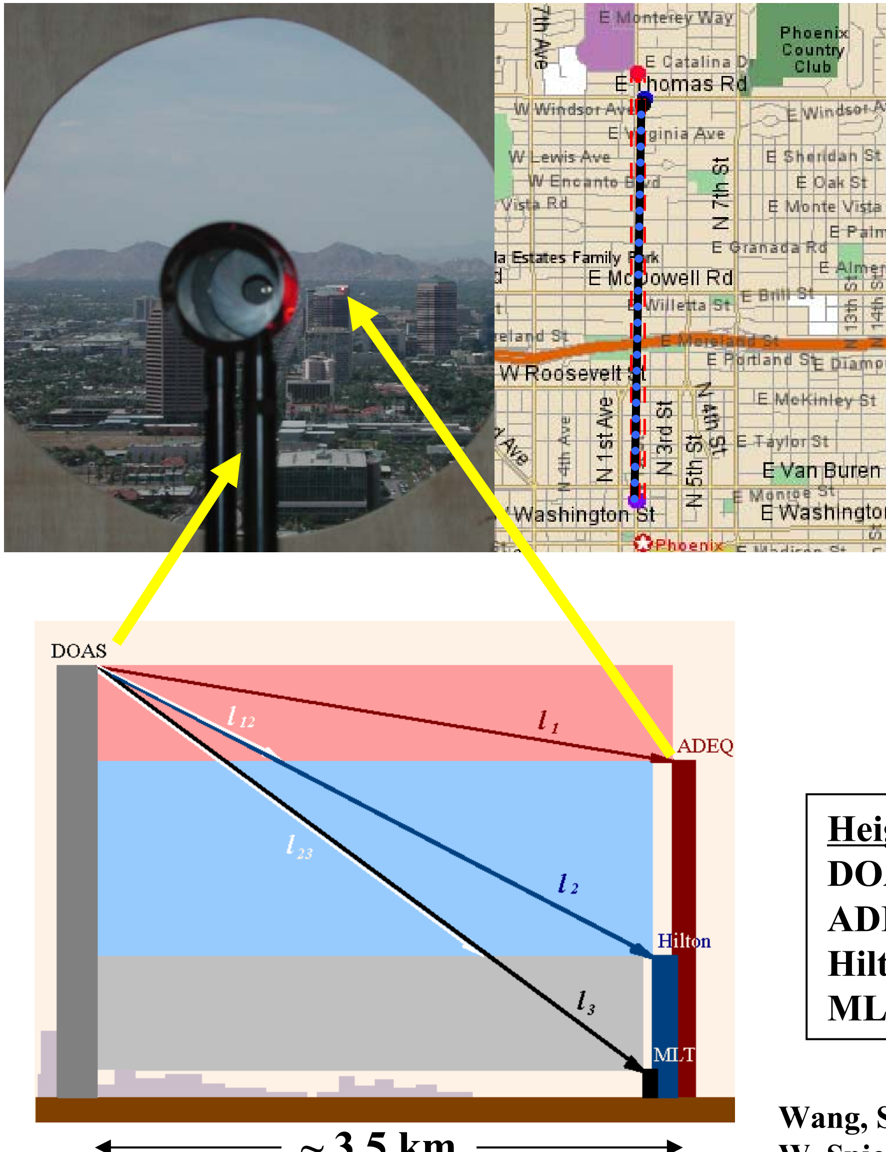
Quoted in: Barbara J. Finlayson-Pitts, James N. Pitts, Jr., "Chemistry of the Upper and Lower Atmosphere," 2000, Academic Press

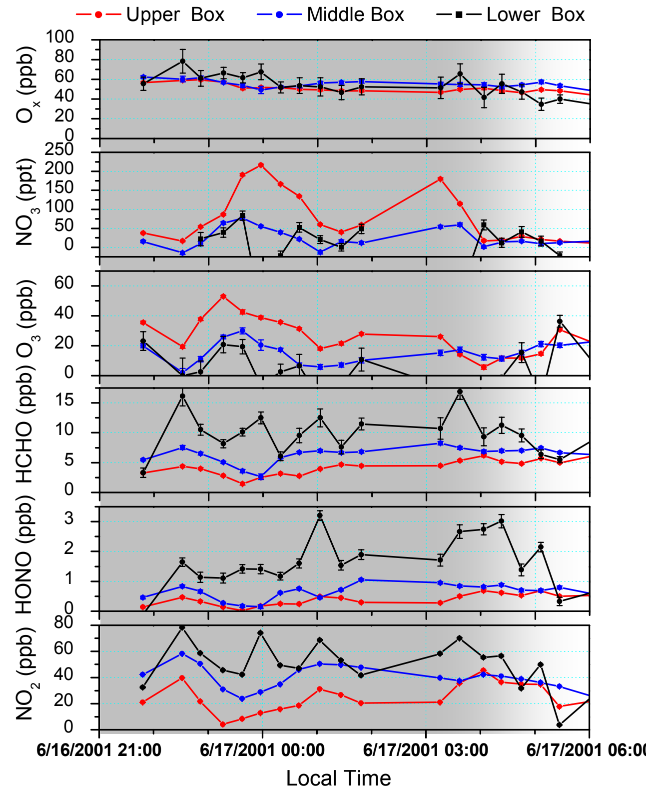
Urban air quality is determined by many interacting factors



- For example, concentration of nitrous acid (HONO) depends on:
- Emissions of NO and Hydrocarbons
- Atmospheric chemistry, including solar-induced photochemistry
- Relative humidity, smog particles, and other aerosols
- Vertical and horizontal transport of pollutants
- Absorption and chemistry on the ground and on vegetation
- **Absorption and chemical transformation on building surfaces**

Optical absorption measurements show time-dependent vertical profiles of pollutant concentrations

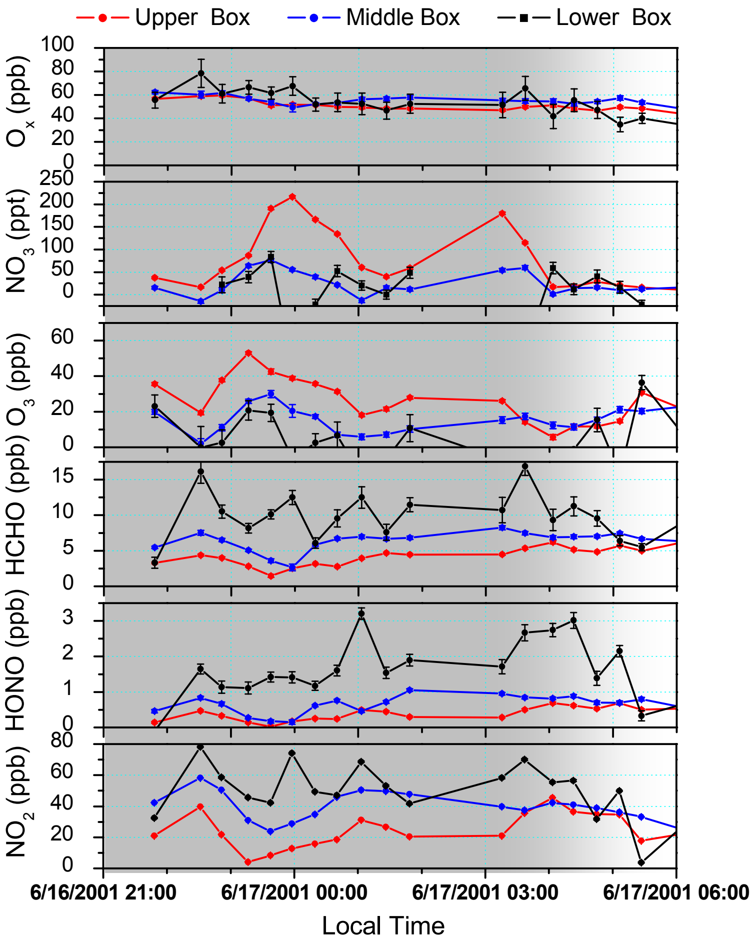




Height:		Light path:
DOAS	~140 m	
ADEQ	~110 m	Upper ~3.51 km × 2
Hilton	~ 45 m	Middle ~3.29 km × 2
MLT	~ 10 m	Lower ~3.23 km × 2

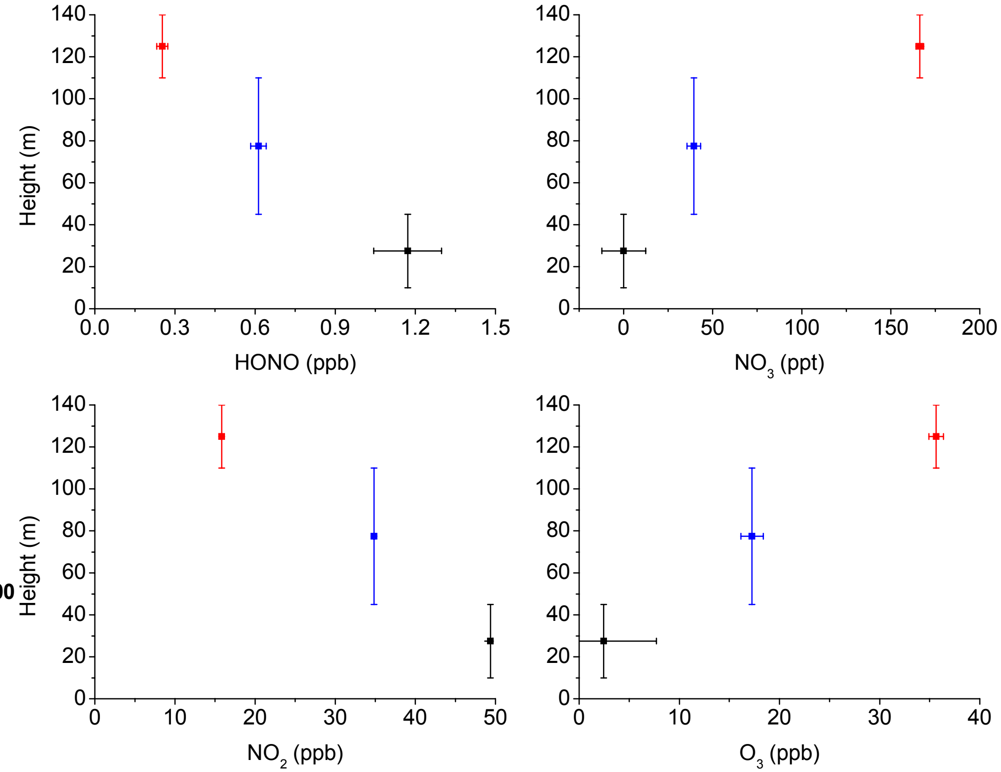
Wang, S., R. Ackermann, A. Geyer, J. C. Doran, W. J. Shaw, J. D. Fast, C. W. Spicer, and J. Stutz, Vertical Variation of Nocturnal NOx, Chemistry in the Urban Environment of Phoenix, Proc. 83rd AMS Ann., 2003

Observations can be plotted as vertical concentration profiles



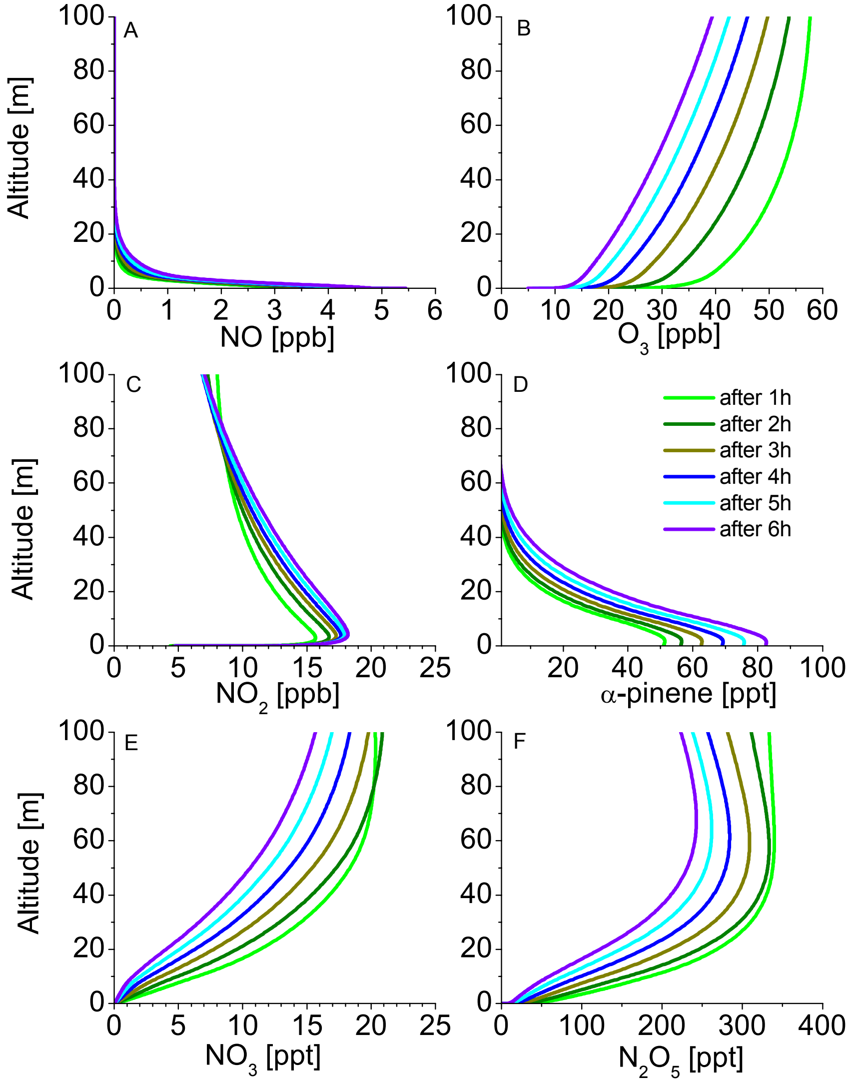
Direct measurements throughout the night, 6/16-17/2001
Phoenix

Profiles in this height vs. concentration form can be compared with model calculations



Derived profiles at 00:19am 6/17/2001
Phoenix

Chemical transport models confirm observed concentration profiles



Building volumes and surfaces have not been previously included in urban atmospheric chemistry models.

Geyer, A., and J. Stutz, Vertical Profiles of NO3, N2O5, O3, and NOx in the Nocturnal Boundary Layer: 2. Model studies on the altitude dependence of composition and chemistry, J. Geophys Res., vol. 109, doi:10.1029/2003JD004211, 2004

How do buildings influence urban air quality?

- Building surfaces process pollutant gases
    - Absorption, chemical transformation and release
    - Depends on surface area or surface/volume vs. height
    - These parameters and functions are not available and not currently included in air quality models
- Buildings occupy volume, resulting in increased pollutant concentrations
    - e.g., traffic emissions in an urban canyon
    - Building volumes vs. height are not available and not currently included in air quality models
- Buildings also influence wind profiles, vertical and horizontal transport of pollutants
    - This complex aerodynamic phenomenology has received some attention
- GIS provides ideal tools for generating statistics needed for analyzing the influence of the surface and volume factors

Building effects can be incorporated into models to calculate pollutant vertical profiles

$$\frac{dc_i(z,t)}{dt} = -\frac{\partial j_i(z,t)}{\partial z} + P_i(z,t) - L_i(z,t) + E_i(z,t)$$

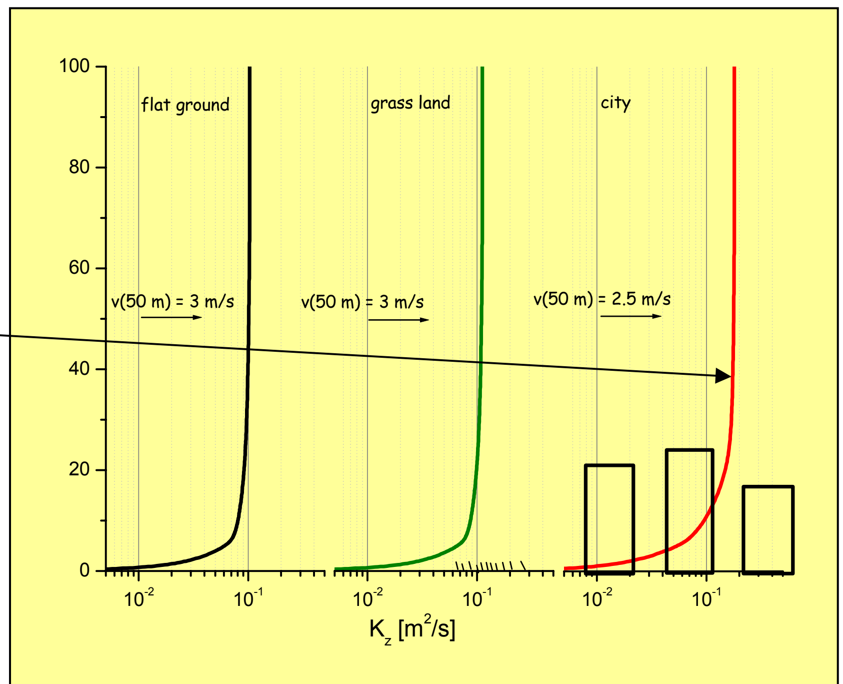
Rate of change of vertical distribution of pollutants depends on:

Vertical flux profile, $\mathbf{j_i}$ depends on the altitude and time dependent eddy diffusivity, K(z,t)

Production and **L**oss of pollutants can occur via reactions with building surfaces

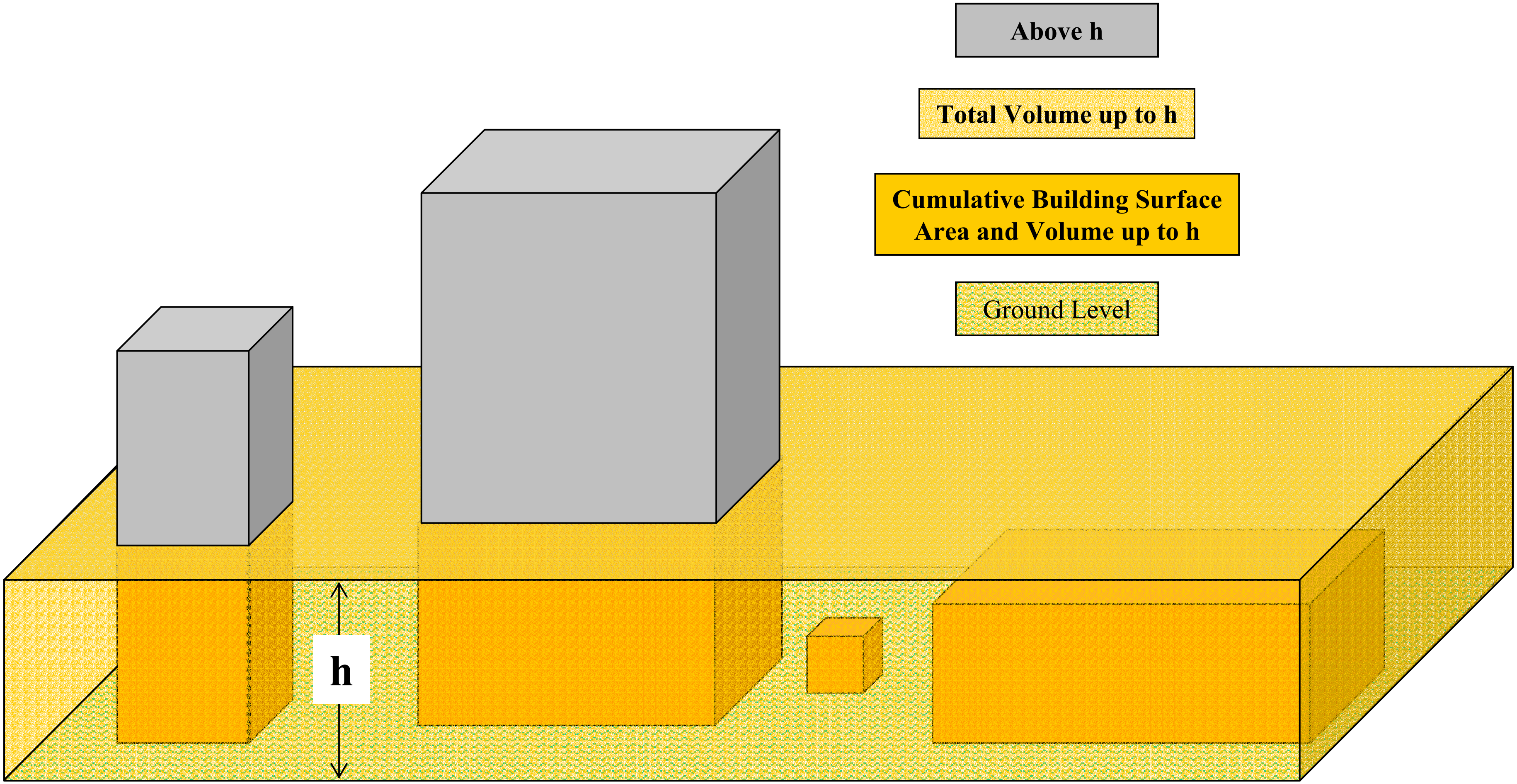
Emission of pollutants by building surfaces is not considered important

K(z,t), and therefore $\mathbf{j_i}$, is strongly influenced by the presence of buildings.



Term which is influenced by building surfaces and volumes

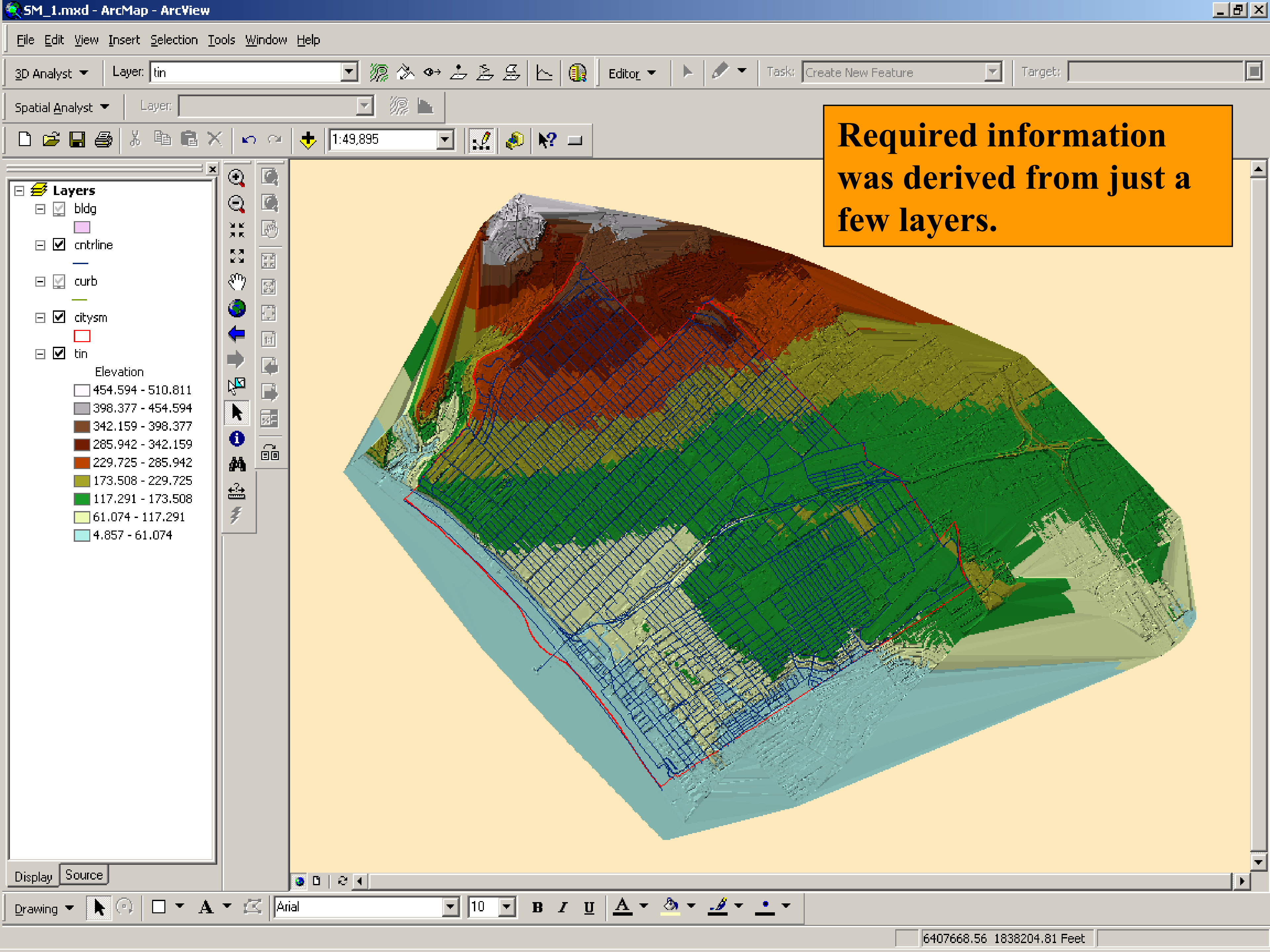
What information does the model need that GIS can provide?



The model needs the building surface area, the building volume and the total volume as a function of height above the ground.

Approach to developing the required data

- Data sources
  - Selected point, line, polygon and TIN layers provided to UCLA by Santa Monica Geographic Information System
  - Digital images generated from large paper maps owned by UCLA Research Library
- Software
  - ESRI ArcGIS 8.3
  - Microsoft EXCEL
  - Microsoft Visual Basic for Applications (VBA)


SM_1.mxd - ArcMap - ArcView
File Edit View Insert Selection Tools Window Help
3D Analyst
Layer: tin
Editor
Task: Create New Feature
Target:
Spatial Analyst
Layer:
1:49,895
Required information was derived from just a few layers.
Layers
bldg
cntrline
curb
citysm
tin
Elevation
454.594 - 510.811
398.377 - 454.594
342.159 - 398.377
285.942 - 342.159
229.725 - 285.942
173.508 - 229.725
117.291 - 173.508
61.074 - 117.291
4.857 - 61.074
Display
Source
Drawing
Arial
10
6407668.56 1838204.81 Feet

Buildings attributes table contains information needed to calculate required surface area statistics

AREA	PERIMETER	BLDG_	BLDG_ID	IGDS_LAYER	IGDS_ZVALU	IGDS_OFFSE
6504.23786	405.33888	2	1	COVERED	498.660	17280
2803.63107	257.58096	3	2	COVERED	506.040	17111
4581.77471	404.09659	4	3	COVERED	516.818	17420
2967.75960	262.79383	5	4	COVERED	516.818	17589
697.74917	107.36266	6	5	COVERED	492.333	17371
164.50222	382.77763	7	6	COVERED	501.354	16851
431.94225	299.85222	8	7	COVERED	514.124	17710
357.34222	117.52012	9	8	COVERED	489.053	17032
3874.00575	319.71113	10	9	COVERED	491.279	18989
2722.30615	244.83871	11	10	COVERED	499.011	17795
3562.89480	272.62604	12	11	COVERED	479.564	19110
6890.58346	412.28703	13	12	COVERED	486.944	18904
6724.63604	480.66601	14	13	COVERED	487.882	16694
781.46941	130.44820	15	14	COVERED	483.313	16621
6031.84061	476.17933	16	15	COVERED	498.660	17892
4755.30148	348.49126	17	16	COVERED	491.748	22944
5668.30349	381.25057	18	17	COVERED	478.509	18771
5650.92722	351.72333	19	18	COVERED	477.689	16524
7282.16568	581.03932	20	19	COVERED	482.727	19171
5394.03374	390.54857	21	20	COVERED	492.216	18062
622.87556	100.75927	22	21	COVERED	483.313	18013
4054.35954	265.80429	23	22	COVERED	484.133	23065
5442.95694	427.71691	24	23	COVERED	475.580	18674
4301.77141	335.98993	25	24	COVERED	467.497	19733
3486.73293	363.63056	26	25	COVERED	472.535	16318
4270.43177	298.56656	27	26	COVERED	472.066	16439
4389.313	[illegible]	28	27	COVERED	460.372	257980

Footprint area = roof area

Perimeter

Roof elevation is above sea level.
Calculation requires above ground level.
This presented a challenge.

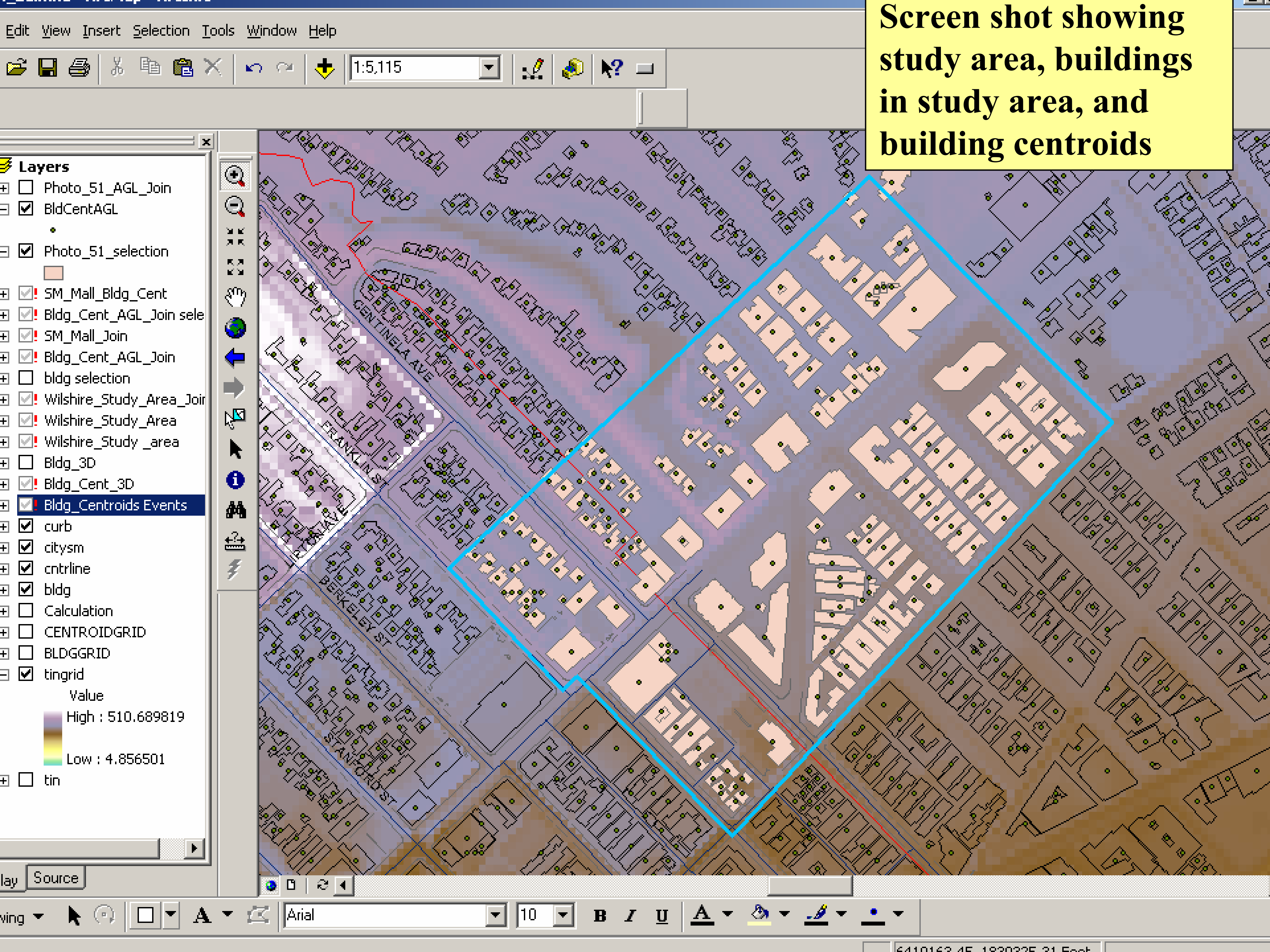
Methodology

- Calculate x and y centroid positions of building polygons using VBA
- Create event layer from building polygons table including x and y centroids, roof heights and building IDs
- Convert event layer to raster with 25’ elements
- Convert ground elevation TIN to Raster with 25’ elements
- Subtract tingrid from bldggrid to get difference grid
- Convert difference grid to point layer, containing roof height above ground level
- Join point layer to building polygon layer
- Attributes table of resulting join contains all information to calculate statistics
- Export to Excel for processing with VBA

Aerial Photography and knowledge of Santa Monica used to select study area

For the analysis here, a study area representing a typical downtown area, with a mix of high rise and lower buildings along the main thoroughfare (Wilshire Boulevard in this case) with lower buildings behind, was selected.

Screen shot showing study area, buildings in study area, and building centroids



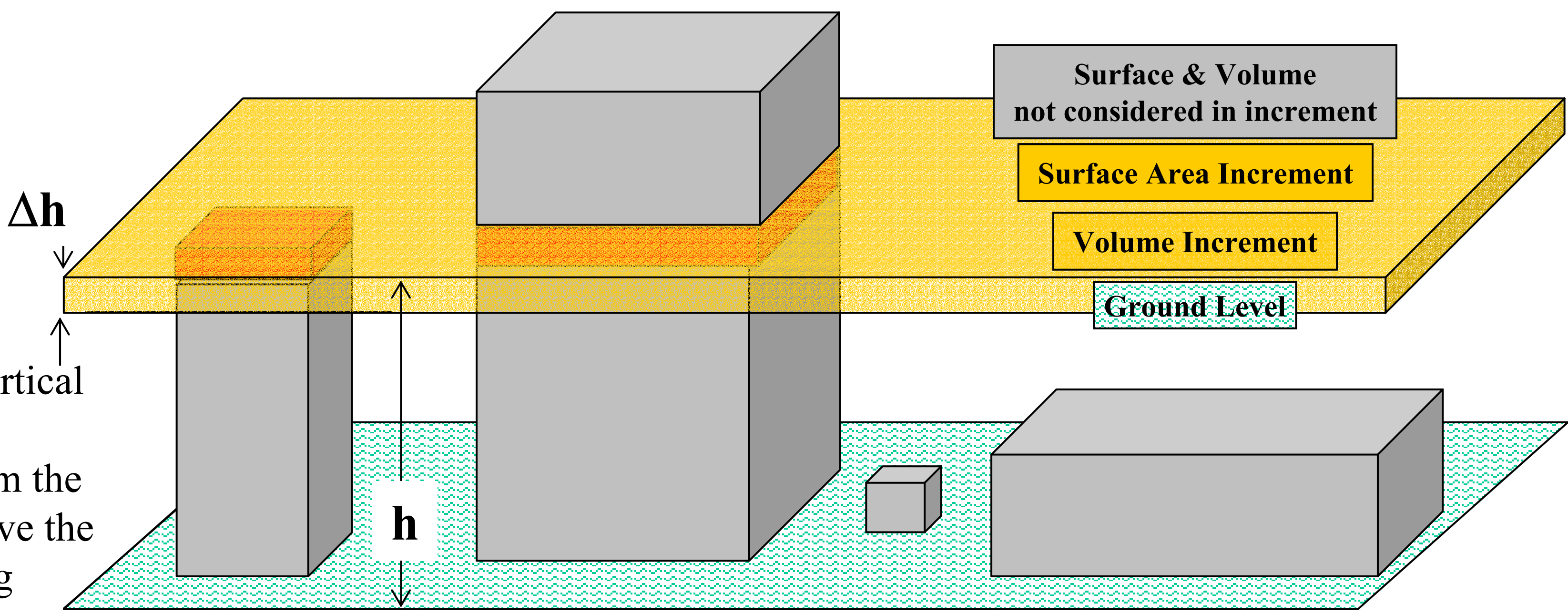
Wilshire_Study_Area_Join.xls [Read-Only]

	H	I	J	K	L	M	N
1	GRID_CODE	Distance	FID_12	AREA	PERIMETER	BLDG_	BLDG_ID_1
282	26.0	5.89520541	5163	11825.77294	490.39624	5165	5165
283	26.0	12.39899135	7156	4848.52339	357.45177	7158	7158
284	27.0	9.92172294	7360	4167.71796	315.45126	7362	7362
285	28.0	6.56952607	4227	1363.19787	154.70091	4229	4229
286	28.0	3.27973279	5776	6318.18621	365.12601	5778	5778
287	28.0	16.04769268	6749	40380.57528	843.06377	6751	6751
288	28.0	12.47463214	7461	3947.13113	303.89490	7463	7463
289	28.0	13.80705517	7483	10331.29302	728.89925	7485	7485
290	28.0	8.73908582	7586	13020.02181	508.75323	7588	7588
291	28.0	12.12912112	7880	161.59923	51.53338	7882	7882
292	28.0	10.63024362	7748	7279.10965	467.45791	7750	7750
293	28.0	6.41078184	7993	156.67743	51.06186	7995	7995
294	29.0	7.12864424	5967	3801.97931	326.10740	5969	5969
295	29.0	6.78375564	6328	11069.35761	469.34469	6330	6330
296	29.0	7.24326220	8465	2070.82379	193.63427	8467	8467
297	29.0	10.86317399	8598	421.91228	82.23343	8600	8600
298	30.0	8.21005798	6095	4631.89943	285.37758	6097	6097
299	31.0	9.57983963	6611	1450.29765	167.10068	6613	6613
300	33.0	11.08986633	8033	150.99687	49.76468	8035	8035
301	33.0	7.72337432	8140	151.00239	50.11825	8142	8142

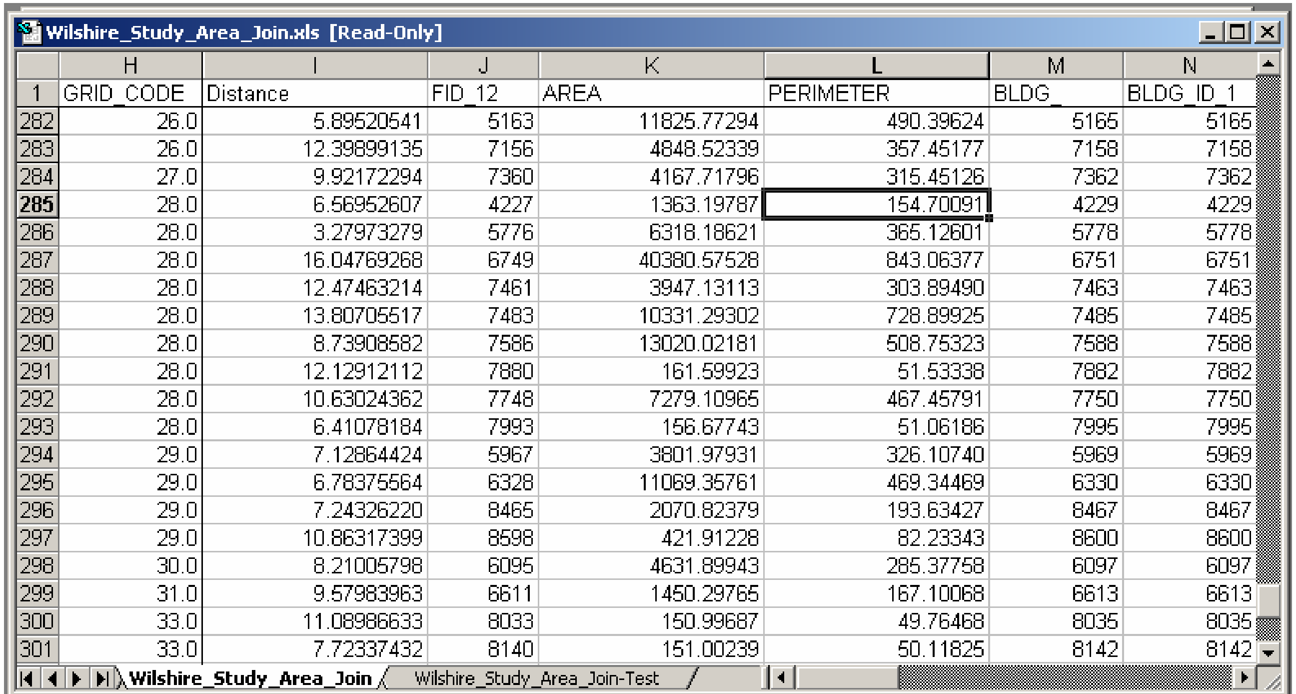
Wilshire_Study_Area_Join / Wilshire_Study_Area_Join-Test

Processed building polygon attributes table allows calculation of required building statistics

- **Height for cell containing building centroid above local ground (roof height above ground)**
- **Distance of actual building centroid from cell center is small**
- **Roof/footprint area allows volume increment calculation**
- **Perimeter allows external surface area increment calculation**
- **Each building has a unique ID**



Statistics are developed by marching a vertical interrogation increment from the ground to above the tallest building



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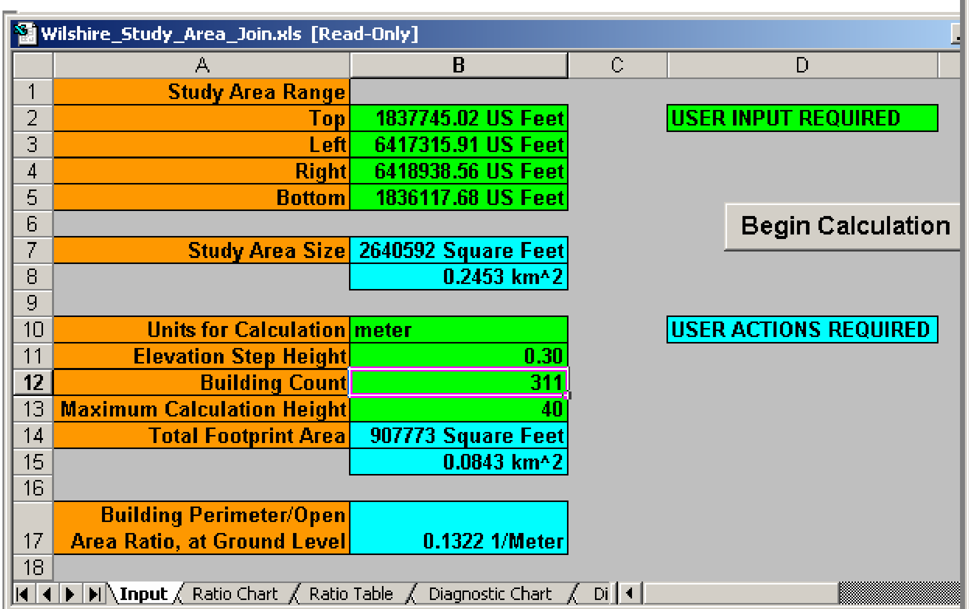
300	33.0	11.08986633	8033	150.99687	49.76468	8035	8035
301	33.0	7.72337432	8140	151.00239	50.11825	8142	8142

Wilshire_Study_Area_Join / Wilshire_Study_Area_Join-Test

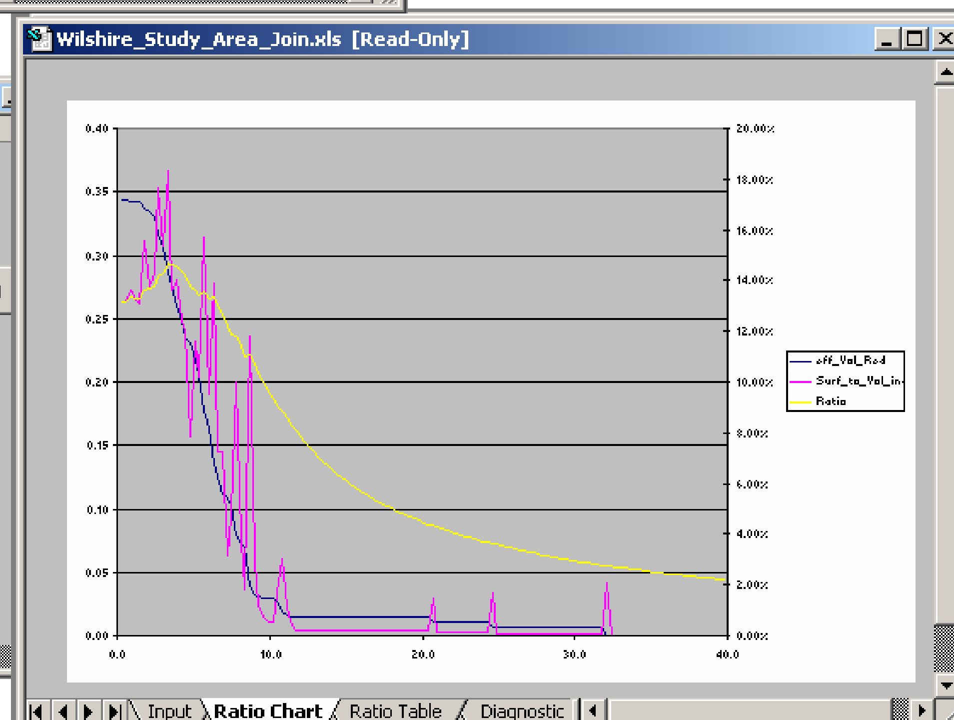
Attribute table imported into MS Excel can be processed using VBA to yield the required building surface and volume statistics



Wilshire_Study_Area_Join.xls [Read-Only]

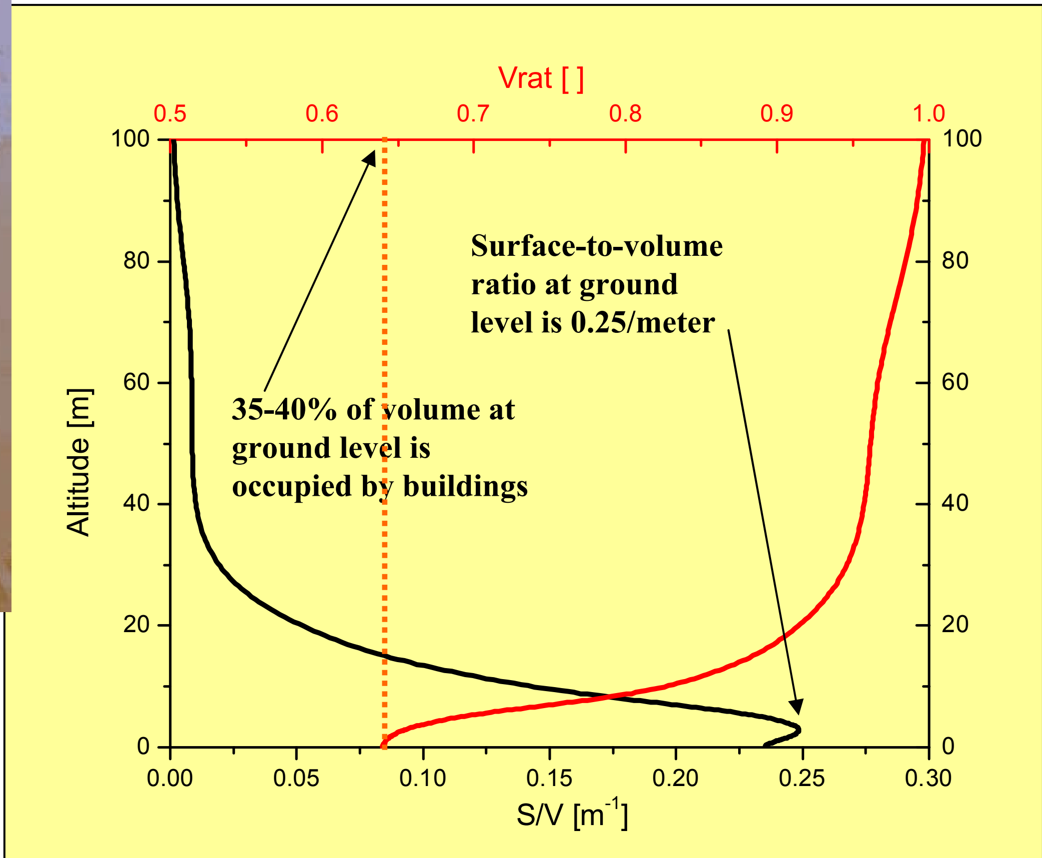
	A	B	C	D
1	Study Area Range			
2	Top	1837745.02 US Feet		USER INPUT REQUIRED
3	Left	6417315.91 US Feet		
4	Right	6418938.56 US Feet		
5	Bottom	1836117.68 US Feet		Begin Calculation
6				
7	Study Area Size	2640592 Square Feet		
8		0.2453 km^2		
9				
10	Units for Calculation	meter		USER ACTIONS REQUIRED
11	Elevation Step Height	0.30		
12	Building Count	311		
13	Maximum Calculation Height	40		
14	Total Footprint Area	907773 Square Feet		
15		0.0843 km^2		
16				
17	Building Perimeter/Open Area Ratio, at Ground Level	0.1322 1/Meter		
18				

Input / Ratio Chart / Ratio Table / Diagnostic Chart / Di



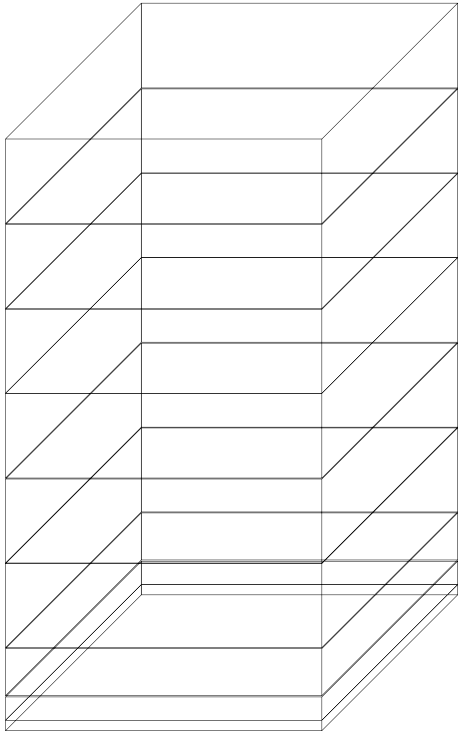
Even for this "modest" downtown area, building spatial statistics parameters are quite impressive

3-Dimensional view of the urban canopy of the Wilshire district of Santa Monica, CA, used in this study is developed by extruding polygons to roof height above ground with 3-D Analyst

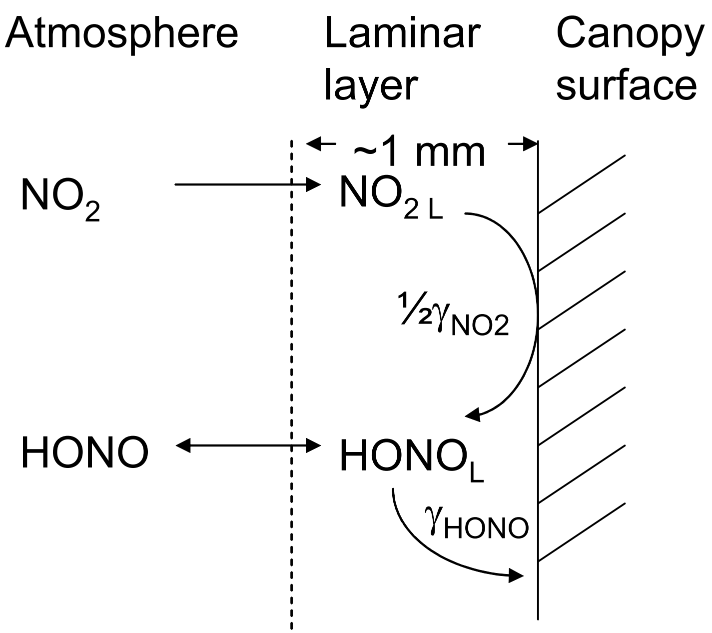


Vertical variation of the surface-to-volume ratio, S/V, and the volume reduction factor, Vrat, for this area are developed by smoothing VBA output.

Nocturnal Chemistry and Transport Model
NCAT



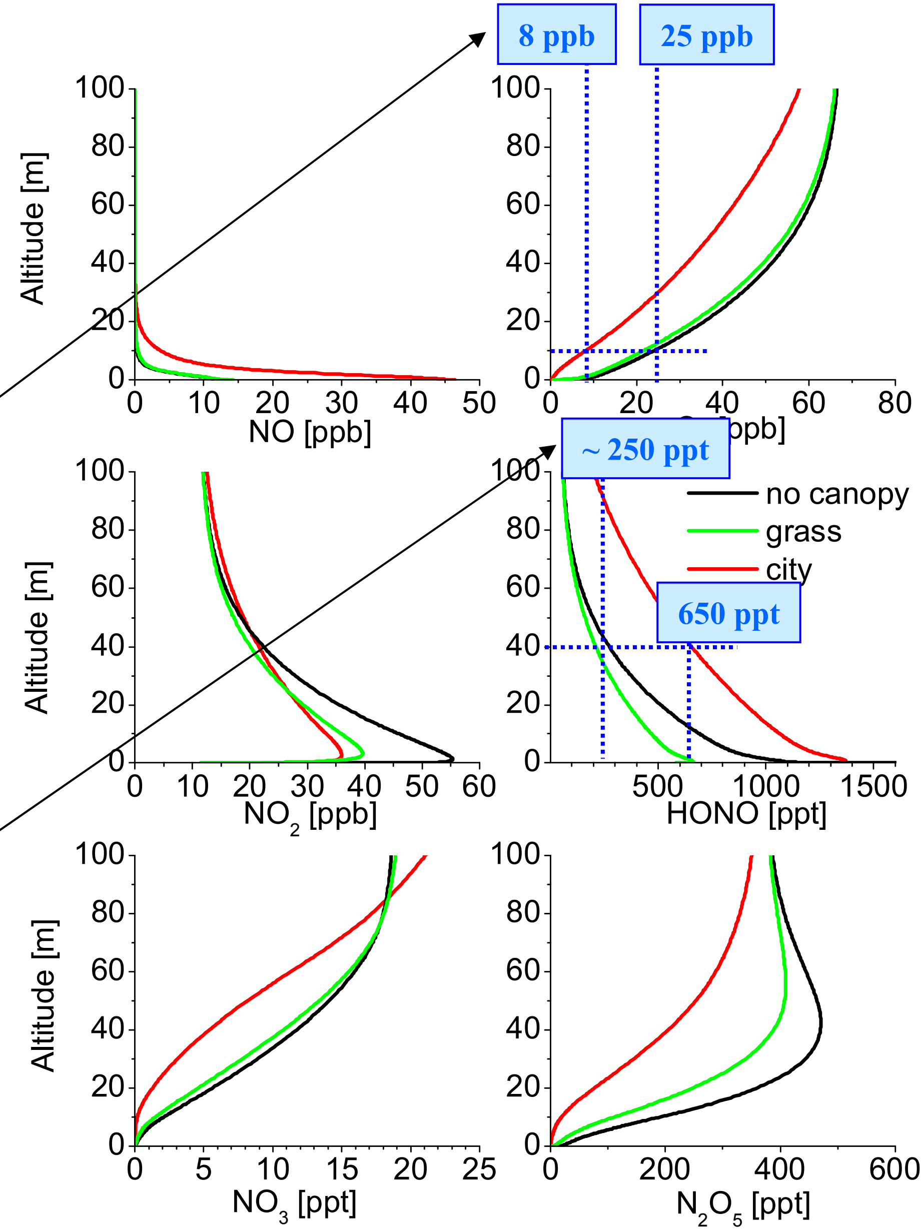
- One-dimensional chemical transport model
- RACM chemical mechanisms
- log/linear spaced layers in the lowest 100m
- vertical mixing of scalars and reactive species
- emissions of VOC and NO near the ground
- chemistry at ground
- explicit treatment of chemistry on building surfaces



Model calculations of concentration profiles of NO, O_3, NO_2, HONO, NO_3, and N_2O_5 in the lowest 100 m of the NBL above different canopies (three hours after nightfall).
Significant differences seen for some pollutants when buildings are included.

Example; O_3 (ozone) concentrations of 8 ppb vs. 25 ppb at 10 m altitude is a very large effect.

Example; HONO (nitrous acid) concentrations of ~250 ppt vs. 650 ppt at 40 m altitude is a very large effect.



Conclusions

- **Influence of buildings on urban air pollution has been qualitatively understood for a long time**
- **Influence of buildings has not previously been quantitatively included in urban atmospheric chemistry models**
- **Evolving model development has identified building statistics needed as input**
- **GIS data and tools have been used to provide the statistical information, which was not otherwise available**
- **Building spatial statistics parameters are significant, even for modest building density and size**
  - **Buildings can occupy 35% and more of volume at ground level, decreasing with altitude**
  - **Building surface area to air volume can be 0.25/meter and more at ground level, also decreasing with altitude**
- **Inclusion of these statistics into new model shows significant influence compared with flat ground or vegetation, with some pollutant concentration profiles increasing or decreasing by as much as 200-300% in certain altitude regimes**

Acknowledgements

- GIS data provided by City of Santa Monica Geographic Information System
- U S Department of Energy
- Shuhui Wang, UCLA Department of Atmospheric and Oceanic Sciences
- Andreas Geyer, formerly of UCLA Department of Atmospheric and Oceanic Sciences
- Expert advice from GIS professionals
    - Mike Price, Entrada/San Juan, Inc.
    - Rob Michaels, Orange County, CA Sanitation District
    - Yafang Su, UCLA Academic Technology Services