DEVELOPMENT AND VALIDATION OF A MODEL TO CALCULATE WIND SPEEDS IN URBAN CANYONS

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Abstract

Studies on air circulation became of great importance in recent years, since are crucial for the energy consumption of buildings, for the pollutant dispersion within cities and for the good comfort conditions for the pedestrians and the habitants. The semi-empirical model developed in this study aims to accurate wind speed computation inside street canyons.

In the framework of the Urbvent European Research project, an extended experimental campaign took place in five different urban street canyons in the centre of Athens during the summer of 2001. Wind speed and direction measurements took place, every 30 seconds at several heights within the canyon, as well as and above on the rooftop of the buildings. Wind speed measured near the building facades using the same time interval. The experimental campaign lasted three days per canyon.

The experimental data were grouped into different categories based on the measurements of the wind speed above the rooftop of the buildings and the incidence angle on the canyon axis. For all of the derived categories existing algorithms were gathered and grouped into a semi-empirical model.

By the use of the above mentioned model wind speed calculated inside the canyons at exactly the same spots where wind speed was measured during the measuring campaign. After comparing between measured and computed wind speed values, derived from the semi-empirical model, we resulted into agreement.

KEYWORDS

Wind speed and direction calculated values; wind speed and direction measured inside and outside canyon; urban canyon; semi-empirical algorithm.

INTRODUCTION

Wind characteristics around buildings and inside the urban canyons of a city, in different heights from the ground, it is of great importance for the safety and the comfort of its inhabitants. Increased wind speeds and turbulence can create a hostile environment for the inhabitants of the city and its structures. A model able to esteem

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wind speed inside a city would be important for the calculation of maximum wind loads expected close to the buildings and for the dispersion of atmospheric pollutants in a specific region. The already knowledge for wind is based either in numerical studies (Hunter et al., 1990/1991) or either in wind tunnel studies (Wedding et al., 1977; Hoydysh and Dabbert, 1988; Kastner-Klein, 1999). Studies based on measured wind speed values are limited (De Paul and Sheih, 1986; Nakamura and Oke, 1988; Santamouris et al., 1999).

In the framework of URBVENT, a European Research project, wind flow characteristics were measured through an extended experimental campaign. The measuring procedure included wind speed and direction measurement of wind outside and inside the canyons. The measurements took place inside the canyons at four different height levels from the ground and also close the canyons facades. The model calculates wind speed inside an urban canyon, based on the already known algorithms, for the cases of ambient flow higher than the threshold value of 4 m/sec. For very low ambient wind flow the model uses the experimental data in order to calculate wind speed in the center of the canyon and close to its facades.

Analysis for all wind's incidence angles and speeds higher or lower than 4 m/sec, proved that the proposed model operates within sufficiently accuracy. However limitations were posed due to model's assumptions and simplifications.

1. FIELD EXPERIMENTS

Table 1 presents the geometrical characteristics of the five canyons. Also it presents in which specific spots per canyon were wind flow inside and outside the canyons was measured. Analytical the set up was the following:

1. In the centre of each canyon the meteorological station of the University of Athens was placed, for three days and for twelve hours per day. The mobile meteorological station was installed on a vehicle equipped with a telescopic PT8 Combined Collar Mast Assembly with extended height of 15.3 meters. On the telescopic mast the following anemometers were attached at four different heights (3.5 – 7.5 – 11.5 – 15.5 meters) in order to record and storage every 30 seconds wind speed and direction in the middle of the canyon.

- Wind speed in the middle of the canyon was measured withA100K Pulse output anemometers
- Wind direction in the middle of the canyon was measured with W200 Porton Windwane ($\pm 300^0$ range) anemometers.

2. Simultaneously wind speed was measured near the facades of the canyon on three orthogonal axes, as well as wind speed and direction outside the canyon, with the following anemometers:

- A three-axis anemometer was used to measure the three components of wind speed inside the canyon adjacent to the facades. The anemometer was mounted on the exterior façade of a building facing into the canyon at a distance of 3 m from the wall.
- A cup anemometer was placed at a distance of 6 m above the top of the canyon to measure the wind speed and direction out of the canyon.

2. DESCRIPTION OF THE DEVELOPED SEMI-EMPIRICAL MODEL

When the predominant direction of the airflow was approximately normal (say ± 20 degrees) to the long axis of the street canyon, three types of airflow regimes were observed as a function of the building (L/H) and canyon (H/W) geometry, (Oke,

1988). When the buildings are well apart, (H/W>0.05), their flow fields do not interact. At closer spacing the wakes are disturbed. When the height and spacing of the array combine to disturb the bolster and cavity eddies, characterized by secondary flows in the canyon space where the downward flow of the cavity eddy is reinforced by deflection down the windward face of the next building downstream. At even greater H/W and density, a stable circulatory vortex is established in the canyon because of the transfer of momentum across a shear layer of roof height and a flow regime occurs where the bulk of the flow does not enter the canyon.
If the wind speed out of the canyon is below some threshold value the coupling between the upper and secondary flow is lost, (Nakamura and Oke, 1988), and the relation between wind speeds above the roof and within the roof is characterized by a considerable scatter. End effects or finite –length canyon effects, play an important role in the airflow distribution inside canyons. For canyons with L/W $\approx$ 20 (Yamartino and Wiegand, 1986) was reported that, finite-length canyon effects begin to dominate over the vortex. Similar phenomena reported by Santamouris et al, (1999). Thus, prediction of the airflow in high aspect ratio canyons may concentrate on cases where end effect does not dominate the flow.
The orientation of the canyon, the geometrical characteristics (width, height and length of the canyon without intersections) and a file with ambient flow data (wind speed and direction outside canyon) are the inputs used by the model. By defining the coordinates (x, y) of a point the model predicts a wind speed value at the specific spot.

The flow chart of the proposed model is presented in Figure 1.

I. The model calculates based on the input data, if the aspect ratio of the canyon (H/W) is greater than 0.7 so it is a canyon situation or otherwise the space between the buildings is not a street canyon.

II. The next calculation is if the ratio of the building length between main intersections and the width between buildings (L/W) is greater than 20. If the ratio L/W is less than 20 then, the end effects dominate inside the canyon and extended experimental analysis indicated that a wind speed value of 0.5 m/s could be considered as mean (Results of the European Projects URBVENT Part 1, 2004). If it is greater than 20, it means that there is a wind circulation in the canyon and the calculations of the model continue.

III. Consequently, if the wind speed outside the canyon is less than 4 m/s and its direction is perpendicular or oblique to the canyon, the values from Table 2 (Empirical Values) can be used.

IV. <u>If the wind's incidence angle was parallel to the main axis of the canyon (with wind speed greater or less than 4 m/sec) the following algorithms were used:</u>

In the obstructed sublayer $0 \le z \le h_b$ the following exponential law describes the variation of wind with height below rooftops:

$$u_p = U_0 \cdot \exp(\frac{y}{z_2}) \quad (1)$$

and

$$z_2 = 0.1 \cdot h_b^2 / z_0 \quad (2)$$

Where U_0 was a constant reference speed, z_2 was the roughness length for the obstructed sub-layer, h_b the mean buildings height, y was the height from ground in which wind speed could be calculated and z_0 the aerodynamic roughness length of the area.

The aerodynamic roughness length z_0 is defined as the height where the wind speed becomes zero. Although the roughness length is not equal to the height of the individual roughness elements on the ground, there is one to one correspondence between those roughness elements and the aerodynamic roughness length. Once the aerodynamic roughness length is determined for a particular surface, it does not change with wind speed, stability and stress.

Typical values of the aerodynamic roughness length are presented by Stull (1997) based on plenty of studies. As expected higher roughness elements are associated with larger aerodynamic roughness lengths. For the centres of large towns and cities the proposed vale is z_0=1, while for the Rocky Mountains the proposed value is z_0=100. For the centres of cities with very tall buildings the proposed value is z_0=2-3. For the centre of the city of Athens where the mean buildings height is close to 30 meters, we considered for z_0 the value 3.

<u>If the wind's incidence angle was perpendicular/oblique to the main axis (and its speed greater than 4 m/sec) of the canyon the following algorithms were used:</u>

The following part of the model is based on the study of Hotchkiss and Harlow, (1973). Use of the proposed algorithms permits the calculation of the cross and vertical wind speed component (u, v). The algorithms consider incompressible flow, absence of sources or sinks of vorticity within the canyon, and appropriate boundary conditions for the simple two-dimensional rectangular notch of depth H and width W. The proposed algorithms are the following:

$$u = \frac{\mathrm{A}}{k} \cdot \left[e^{ky}(1+ky) - \beta \cdot e^{-ky}(1-ky)\right] \cdot \sin(kx) \qquad (3)$$

And

$$v = -\mathrm{A} \cdot y \cdot \left(e^{ky} - \beta \cdot e^{-ky}\right)\cos(kx) \qquad (4)$$

Where

$$k = \pi / W \qquad (5)$$

$$\beta = \exp(-2kH) \qquad (6)$$

$$\mathrm{A} = ku_0 / (1-\beta) \qquad (7)$$

$$y = z - H \qquad (8)$$

And u_0 is the wind speed above the canyon and at the point x=W/2, z=H.

The above-mentioned algorithms were tested and approved by Yamartino and Wiegard (1986). The same authors have proposed the following expression to calculate the along canyon component, $w(z)$:

$$w(z) = w_r \cdot \log[(z+z_0)/z_0] / \log[(z_r+z_0)/z_0] \qquad (9)$$

Where w_r was the wind speed values measured outside the canyon at z_r meters above the ground and z_0 was the surface roughness.

The horizontal wind speed inside the canyon was:

$$v_h = (u^2 + v^2)^{0.5} \qquad (10)$$

So, the total wind speed inside canyon at any point (x, y) was:

$$v_t = ({v_h}^2 + w^2)^{0.5} \qquad (11)$$

The results of the experimental procedure are given in the form of box-plots. A box-plot was used as a graphic representation of the data distribution, which shows the locations of percentiles. The line in the middle of the box is the median, or the 50th percentile of the sample. The lower and upper lines of the box are the 25th and the 75th percentiles, representing the lower and upper quartile, respectively. The length of the box represents the interquartile range. The lower and upper "whiskers" show the range of data, if there are no outliers. Data are considered outliers if they are located 1.5 times the interquartile range away from the top or bottom of the box. In each box plot two red lines are plotted in order to present the calculated values derived from the model. For the goodness of fit between the experimental measurements of wind speed inside a canyon and the ones raised from the application of the theoretical model, the t-test of the differences of mean values was applied, taking into account the variation of the samples (Georgakis, 2004). The comparison for the two set of values led to the conclusion that the model's prediction could be characterized as satisfactory.

3. DISCUSSION OVER THE EXPERIMENTAL AND THE COMPUTED WIND SPEED VALUES

3.1 Wind speed outside the canyon less than 4 m/sec

The box plot analysis, present in Diagrams 1-5, 11-15 and 20-24 regards the cases when the ambient flow was less than 4 m/sec and parallel, perpendicular and oblique to the main axis of the canyons. For the case of parallel flow together with the box plot for the wind speed outside the canyon, six box plots present the experimental and the computed values at the four level heights from the ground and also close the canyon facades. For the cases of perpendicular flow the first box plot depicts the ambient wind speed and the four following box plots depict the experimental vertical values close to the canyon facades (uplifts depicted with negative values and down lifts depicted with positive values) for the two perpendicular flows ($\pm 90^0$ and $\pm 270^0$ to the main axis of the canyon). Also, the last four box plots in these diagrams regard only the experimental values in the centre of the canyon, at the four level heights from the ground, in order to integrate the total flow inside the canyon. For the cases of oblique flow the diagrams are similar to the ones which regard to the perpendicular flow, except of the fact that now there are four different flows close to the canyons facades, so the total amount of box plots are thirteen.
For Voukourestiou canyon lack of experimental wind speed values, due to technical problems during the experimental procedure, obstruct a representative box plot analysis close both the canyon facades. Also, for this canyon there was no box plot analysis for the case of perpendicular flow with ambient wind flow less than 4 m/sec, since there were no experimental values for the specific case.

For the case of parallel flow outside the canyon, the computed average values for the four height levels of 3.5-7.5-11.5-15.5 meters and for the different heights near to each canyons facades, are close to the average measured values for the respectively heights. Some overestimation or underestimation for the computed values of the specific flow are due to thermal effects and intermitted vortices that dominate close to canyon corners. For the case of perpendicular and oblique flow to the main axis of the canyon, experimental and computed values depicted the flow close to canyon facades. The agreement between experimental and computed mean values was satisfactory.

For Ermou canyon technical difficulties during the experimental procedure derived to not very representative plots about the specific canyon.

3.2 Wind speed outside the canyon greater than 4 m/sec

The box plot analysis, present in Diagrams 6-10, 16-19 and 25-29, regard the cases when the ambient flow was greater than 4 m/sec and parallel, perpendicular and oblique to the main axis of the canyons. Each of the above mentioned diagrams include seven box plots. The first one depicts the ambient wind flow and the four following the experimental and computed values inside the canyon at the four different height levels. The last two-box plots regard wind flow close the canyon's facades.

The computed average values for the four height levels and close to the canyons facades are very close to the average measured values for the respectively spots, for the cases of deep canyons (Dervenion and Voukourestiou). This analysis indicated a very good agreement between experimental and model values. For Ermou canyon lack of experimental wind speed values, due to technical problems during the experimental procedure, obstruct a representative box plot analysis. For Miltiadou and Kaniggos canyons their aspect ratio L/W were less than 10 (Table 1). One of the first criteria in the semi-empirical model, was that only if the aspect ratio L/W was greater than 20, the calculations of the model could take place, otherwise end effects dominate and the mean wind speed inside canyon at any height level is close to 0.5 m/sec. In order to prove to verity of the above-mentioned criterion of the model, calculation took place for both Miltiadou and Kaniggos canyon. The computed values overestimated wind speed values inside both canyons. So, the substance of the model was proved.

4. CONCLUSIONS

- Average wind speed values measured inside canyons and the computed ones indicated stratification proportionally to wind speed values measured outside canyon.
- After extended analysis for the case of ambient flow parallel to the main axis of the canyon below the threshold value of 4 m/sec, it was proved that the computed values derived from the model are in good agreement with the experimental ones (Georgakis, 2005). So, there is no need for empirical values for this case, contrarily with the case of perpendicular or oblique flow to the main axis of the canyon.
- When the aspect ratio L/W was greater than 10, the calculations of the model could take place, otherwise end effects dominate and the mean wind speed inside canyon at any height level is close to 0.5 m/sec.
- Model tends to overestimate inside canyon velocities compared to experimental ones for the cases of parallel flow and ambient flow greater than 4 m/sec. For ambient wind less than 4 m/sec and wind incidence angle parallel to the main axis of the canyon the model tends to underestimate wind speed velocities inside canyons.
- In deep the canyons such as Dervenion and Voukourestiou, there was a very good agreement between experimental and computed values for perpendicular/oblique type of flow, and for ambient wind speed greater than 4 m/sec. This model is a good practical tool for deep canyon cases.

Acknowledgements

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Street Canyon		**Ermou**	**Miltiadou**	**Voukourestiou**	**Kaniggos**	**Dervenion**
Orientation from the North	Degrees	92	45	45	12	327
Canyon width	Meters	10	6	10	8	7
Canyon length	Meters	200	50	100	70	200
Buildings height	Meters	20	12	30	28	23
Canyon aspect ratio	*H/W*	2	2	3	3.5	3.3
Wind speed and direction inside the canyon	Meters from ground	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5
Height of the	Meters	7.5-	8.0-8.0	5.0-8.0	5.0-10.0	20.0-10

two Three-axis anemometer	from ground	10.5				
Wind speed and direction anemometer, outside the canyon	Meters from ground	26	18	36	34	29

Table 1 Description of the experimental sites, definition of the measurement points, the experimental period of every canyon

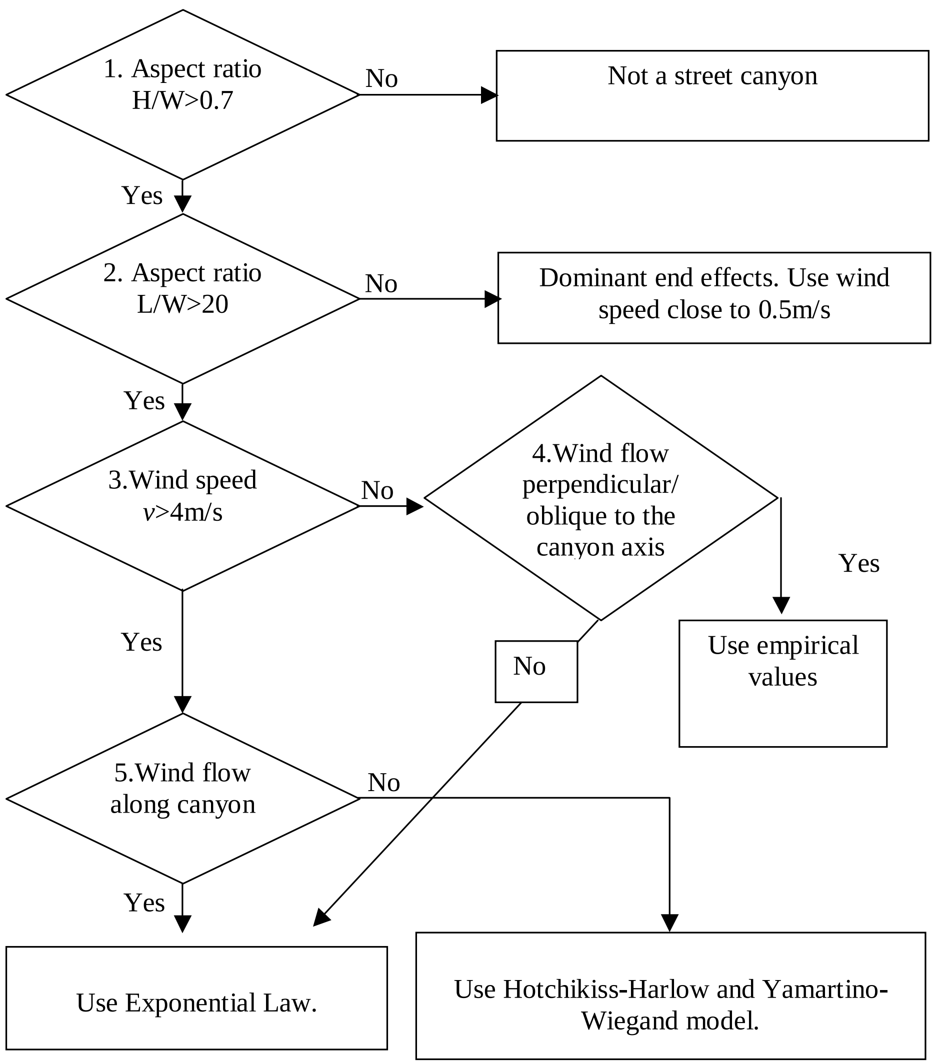
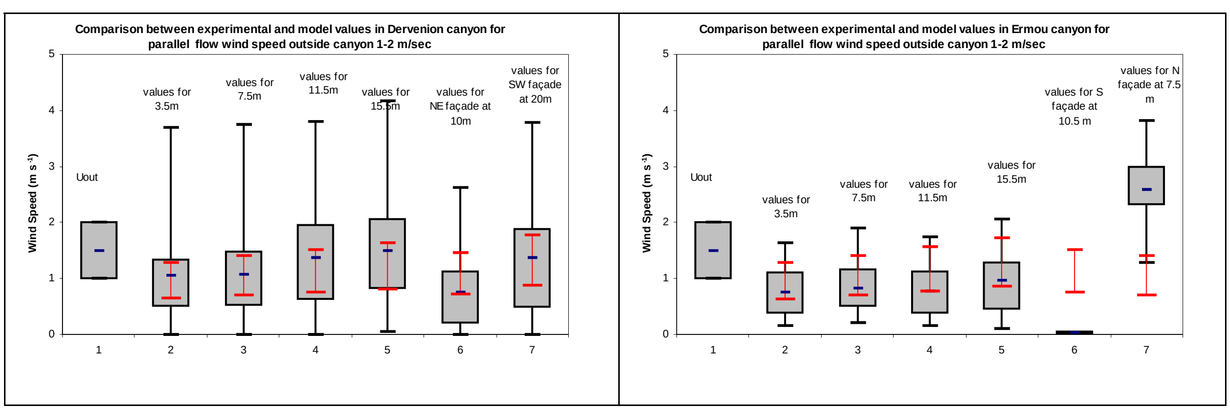
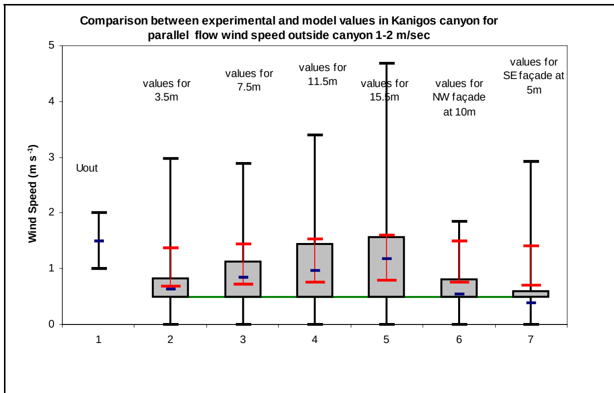


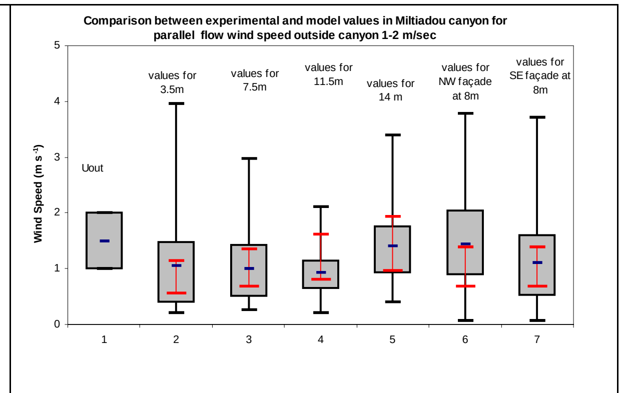
Figure 1 Flow-chart of the algorithms and the empirical values used by the model for computing wind speed inside street canyons

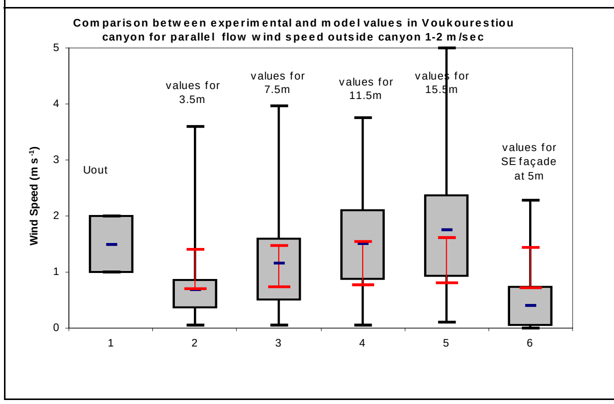
Wind speed outside the canyon (U)	**Wind speed inside the canyon**		
	Near the windward facade of the canyon		**Near the leeward facade**
	Lowest part	Highest part	
U=0	0 m/s	0 m/s	0 m/s
0<U<1	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade
1<=U<2	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade
2<=U<3	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade
3<=U<4	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade

Table 2 Empirical Values for perpendicular/oblique canyon wind speed inside the canyon

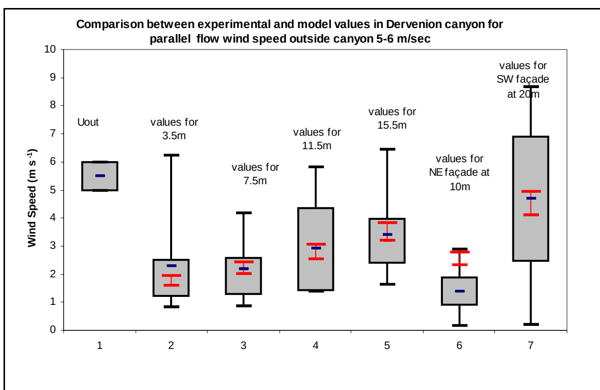


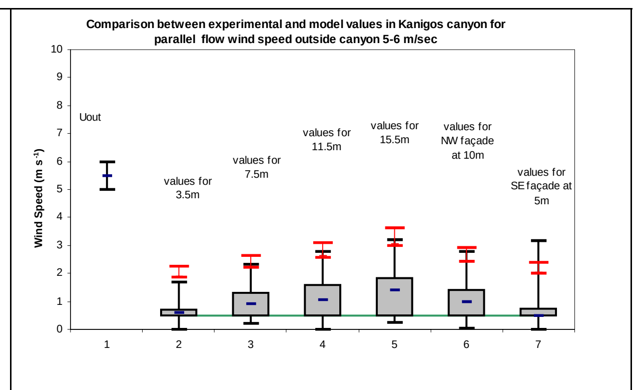


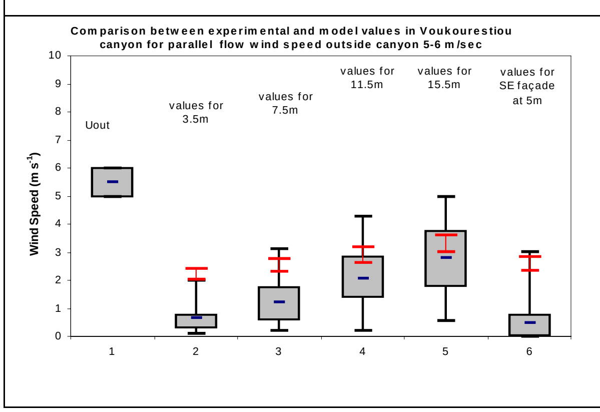


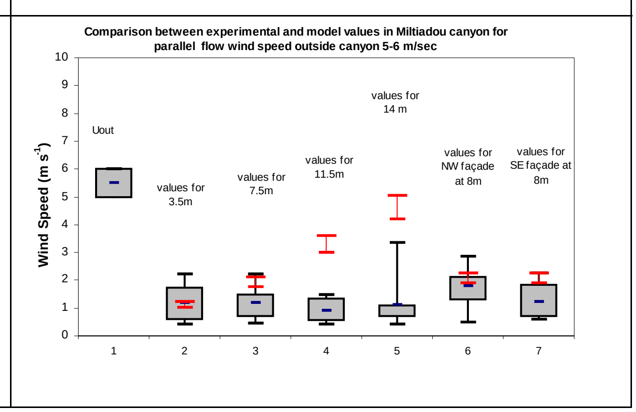


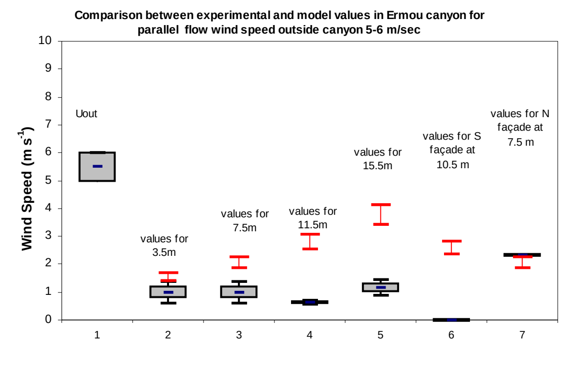
Diagrams 1-5: Experimental and computed vales of wind speed in the centre of the canyons and near the canyons facades, for incidence angle parallel to the main axis of the canyon, and wind speed outside canyon less than 4 m/sec



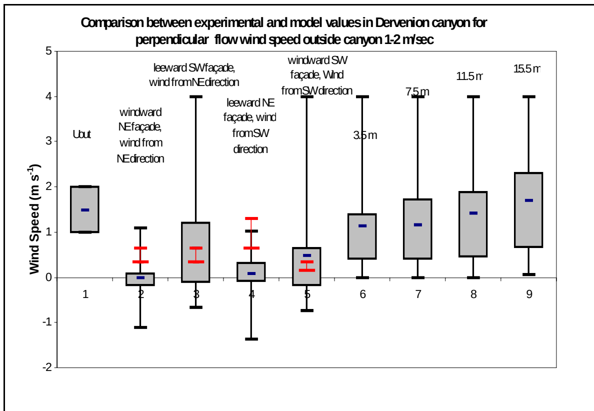


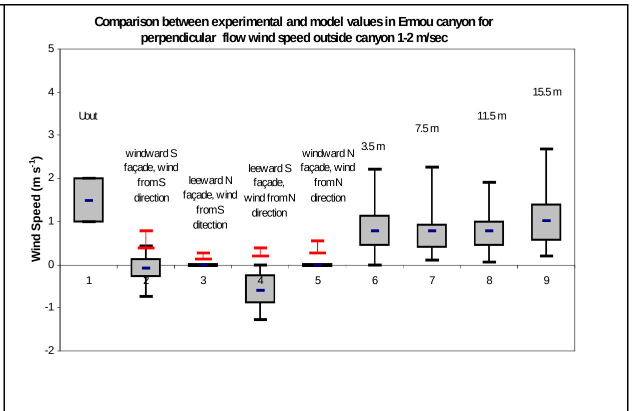


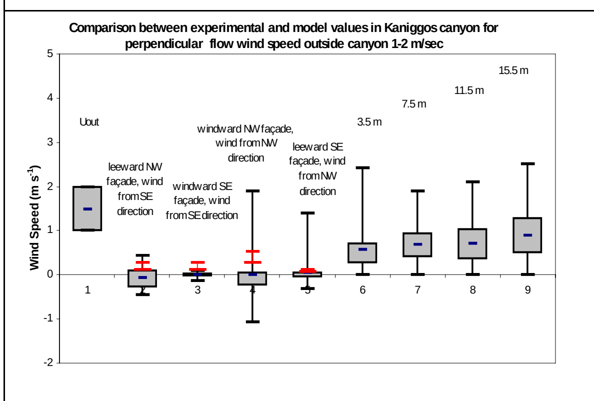


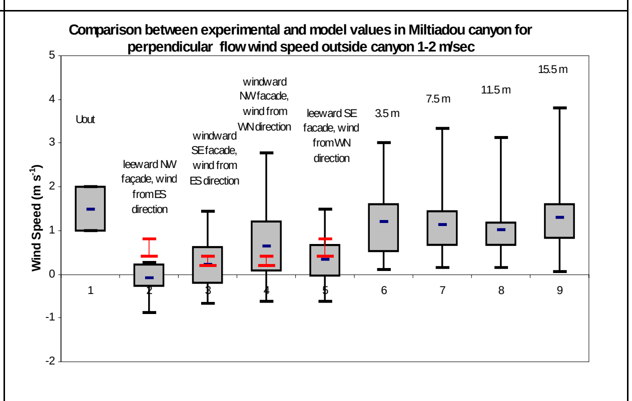


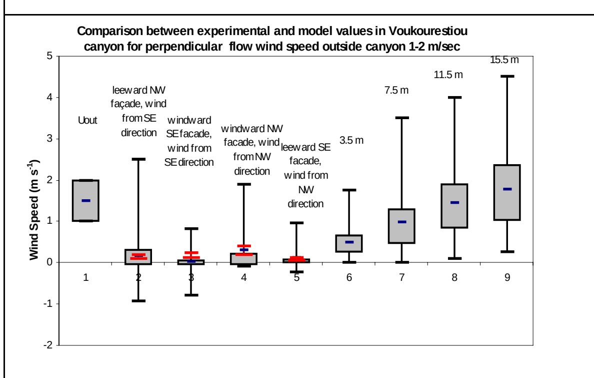
Diagrams 6-10: Experimental and computed vales of wind speed in the centre of the canyons and near the canyons facades, for incidence angle parallel to the main axis of the canyon, and wind speed outside canyon greater than 4 m/sec



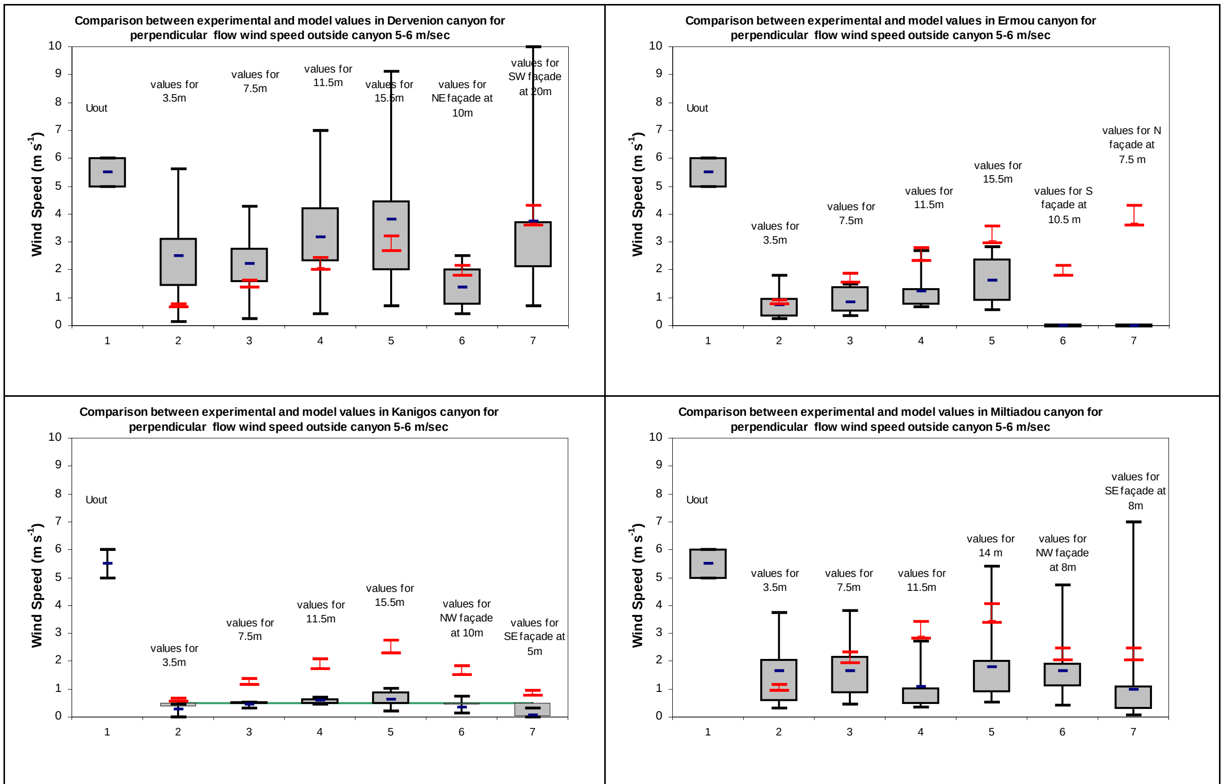




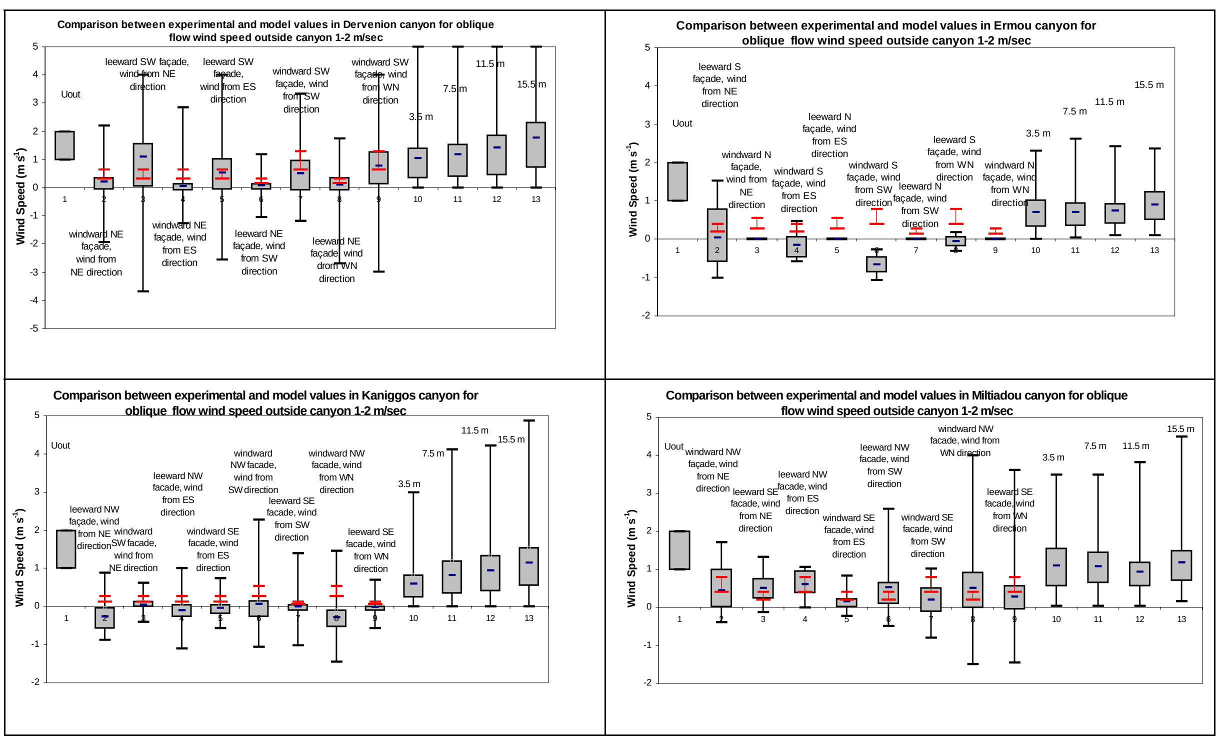


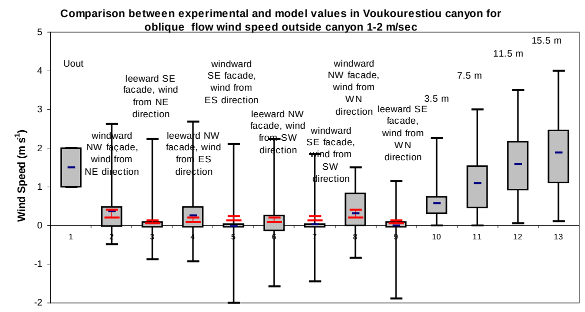


Diagrams 11-15: Experimental and computed wind speed values near the canyons facades for perpendicular incidence angle to the main axis of the canyon, and wind speed outside canyon less than 4 m/sec

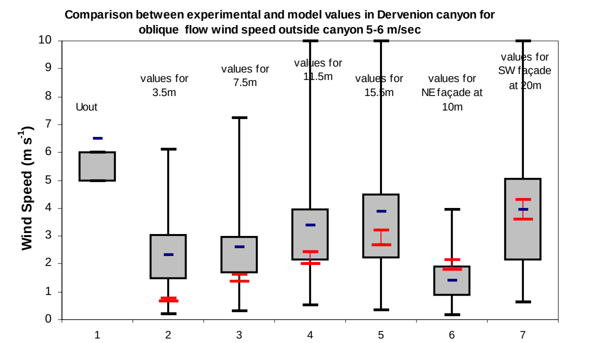


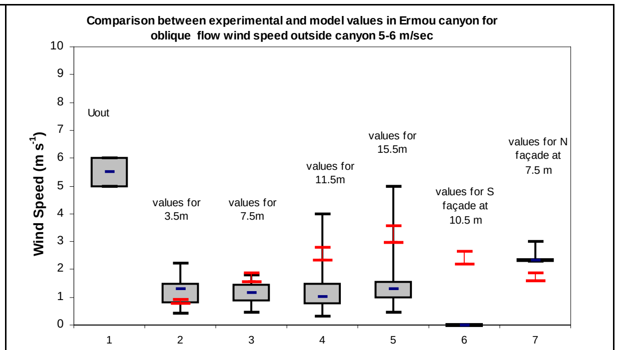
Diagrams 16-19: Experimental and computed wind speed values near the canyons facades for perpendicular incidence angle to the main axis of the canyon, and wind speed outside canyon greater than 4 m/sec

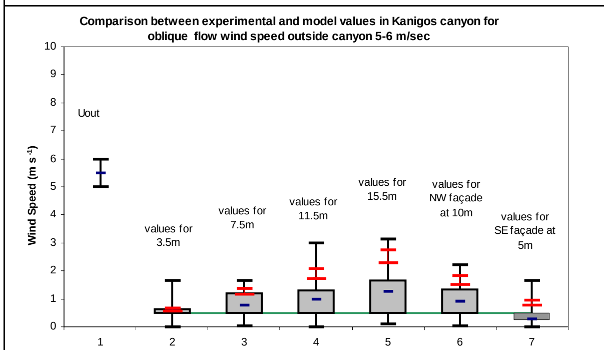


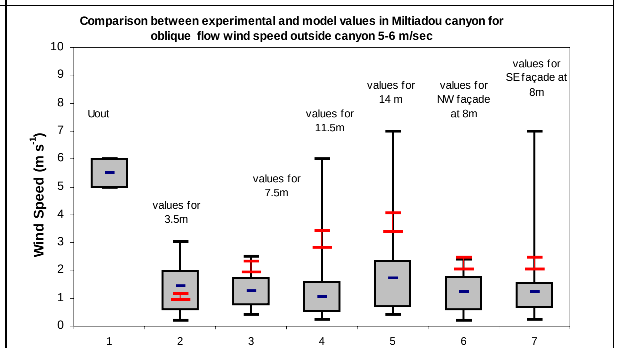


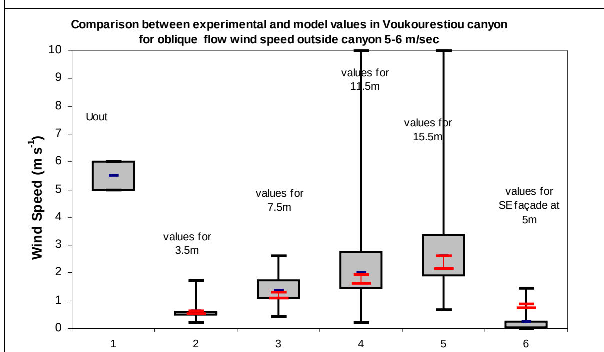
Diagrams 20-24: Experimental and computed wind speed values in the centre of the canyons and near the canyons facades for oblique incidence angle to the main axis of the canyon, and wind speed outside canyon less than 4 m/sec











Diagrams 25-29: Experimental and computed wind speed values in the centre of the canyons and near the canyons facades for oblique incidence angle to the main axis of the canyon, and wind speed outside canyon greater than 4 m/sec