Dispersion et réinjection des contaminants

by

Concordia University

Dr. Ted Stathopoulos
Dr. Bodhisatta Hajra
Mr. Mauricio Chavez

IRSST

Dr. Ali Bahloul

Outline

- **Introduction**
- **How to assess pollutant concentration**
  - Empirical Models
  - Wind Tunnel Modelling
  - Field Experiments
  - Computational Fluid Dynamics (CFD)
- **Design guidelines**
  - Existing Codes and Standards
  - ASHRAE
  - Additional Guidelines (from current study)
- **Conclusions**
- **Future research**
- **Publications**

Introduction

Air pollution is a **major environmental problem today**

- Sources of pollutants:
  - Combustion devices
  - Motor vehicles
  - Industrial and laboratory facilities
  - Office buildings
- Common pollutants:
  - Particulate matter (PM)
  - Carbon monoxide and dioxide (CO, CO_2)
  - Oxides of nitrogen and sulphur (NO_x, SO_x)
  - Formaldehyde (H_2CO)
  - Ozone (O_3)
  - Polycyclic aromatic hydrocarbons (PAH)

- Consequences:

  - Broad spectrum of acute and **chronic health effects** (*Brunekreef and Holgate 2002, Cohen et al. 2005, Peters 2005, Xia and Tong 2006, Chen et al. 2007, Lewtas 2007, Samet and Krewski 2007).*

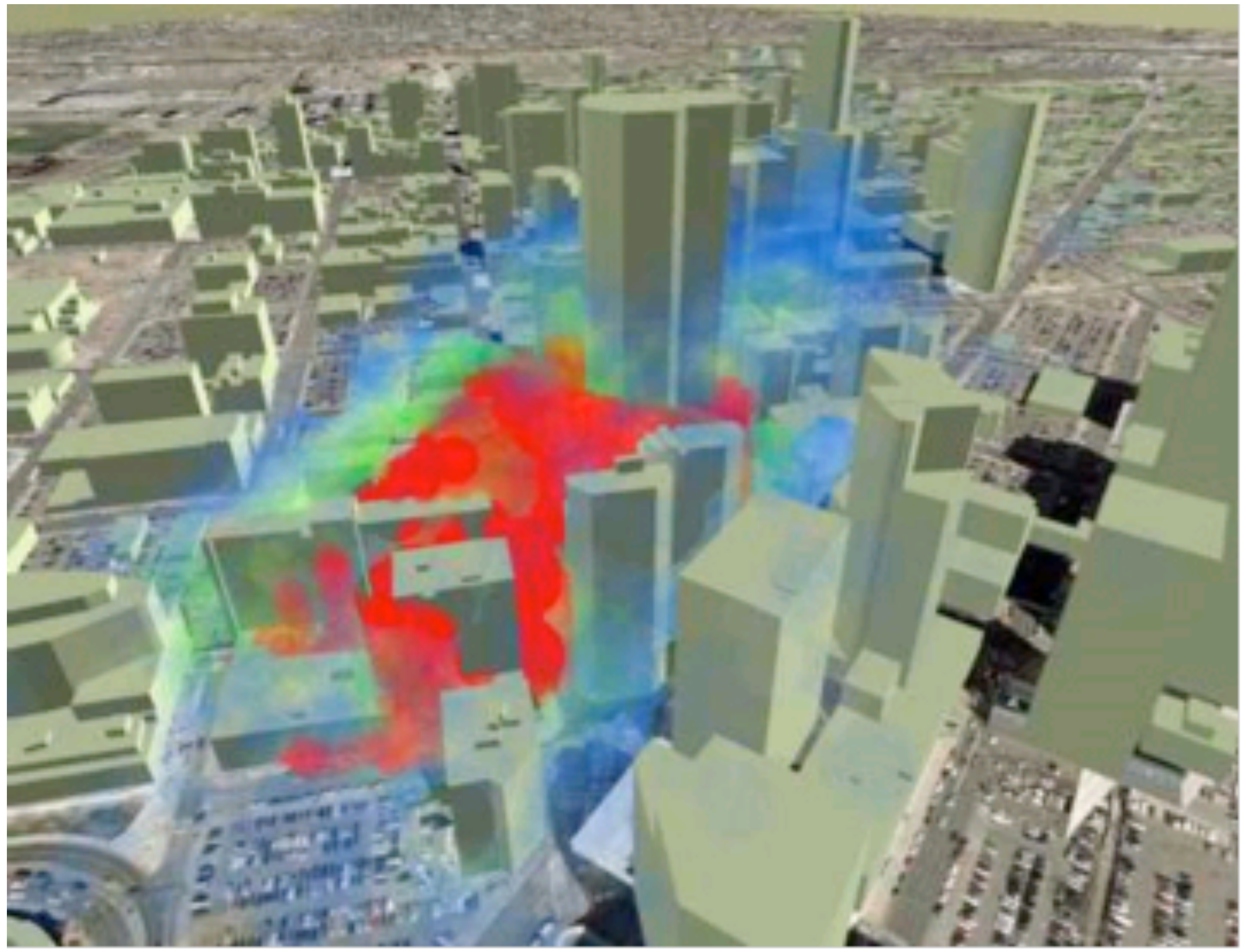
    - Respiratory disease
    - Cardiovascular disease
    - Mortality

Air pollution in urban areas:

Some examples …

Routine release of pollutants

Accidental (or non-accidental) release of hazardous materials in urban areas.

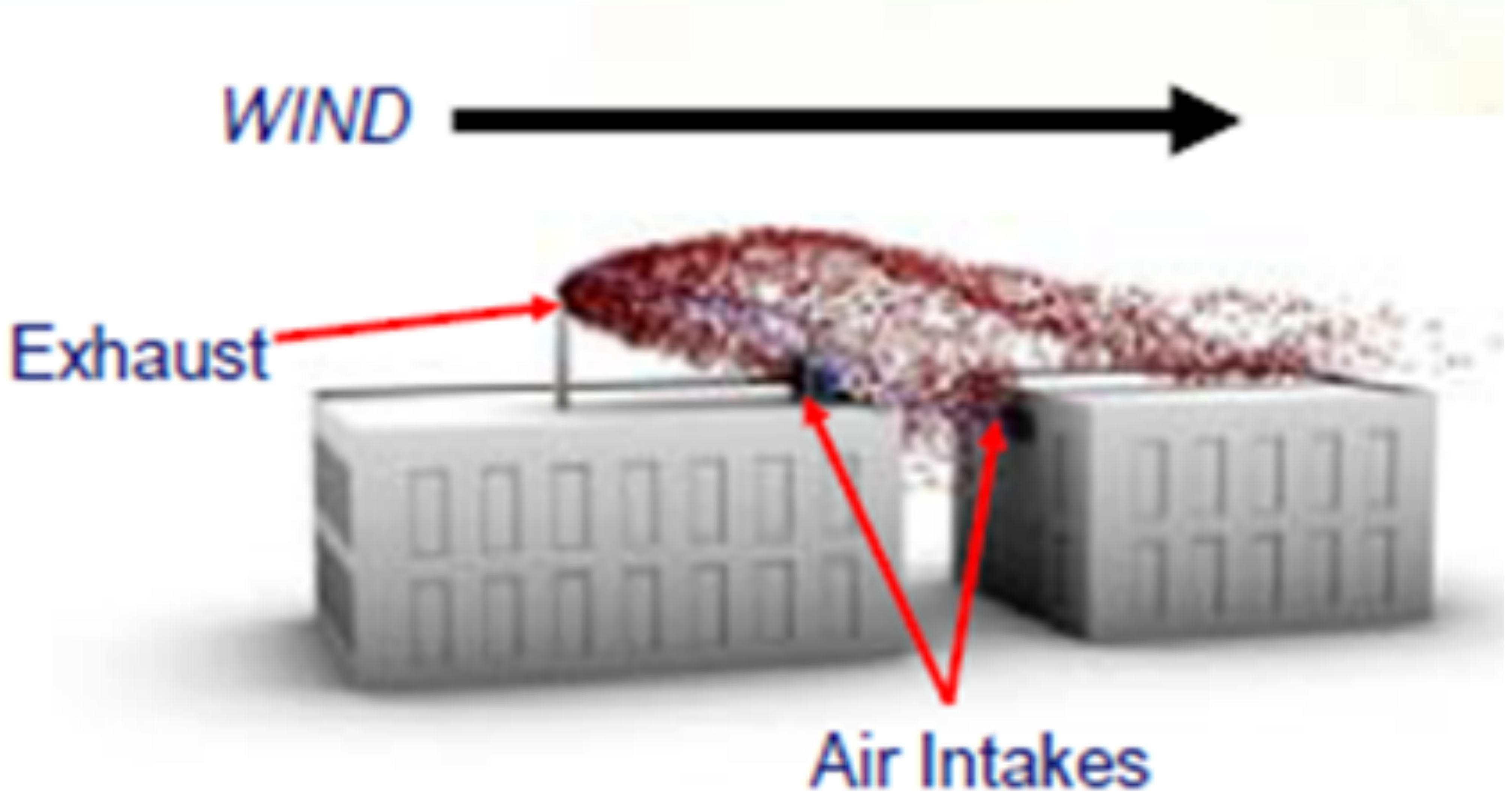


A simulated plume of hazardous material hypothetically released into the atmosphere in Denver.
(http://www.ral.ucar.edu/strategic_plan/2009/goal_nsap.php)

A fire event in Toronto
(http://www.toronto.ca/planning/pdf/higher_wkshp_c_irwin_19oct.pdf)

Episodic pollution: Re-ingestion of pollutants or ingestion on the adjacent building

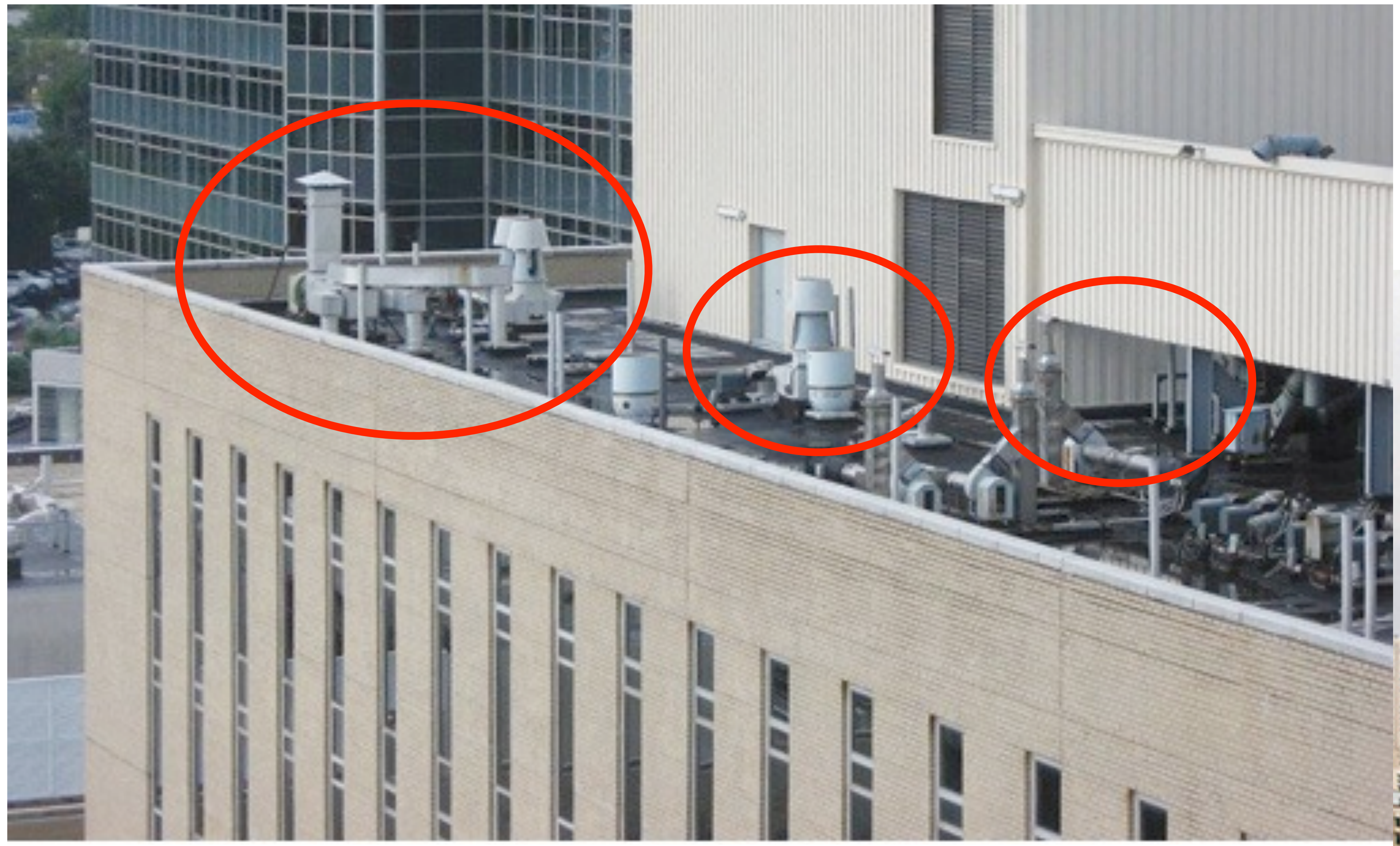
- Drivas et al. (1972) mentioned that in one case 20 % of the exhausted fumes re-entered the ventilation system of the building.
- Moon et al. (1997) reported ventilation intake pollution episodes in a day-care facility that were serious enough to cause building evacuation.



(source: www.oaa.on.ca/oaamedia/documents/Exhaust%20Re-entrainment%20and%20its%20Effect%20on%20Building%20Design.pdf)

Plenty of situations for **Re-ingestion**:

Cooling towers, laboratories, fume hoods, boilers stacks, etc.



Downtown Montreal

Concordia University, Montreal

McGill University, Montreal

Why is the adjacent building important in dispersion?

Why is the adjacent building important in dispersion?

How to assess pollutant concentration?

How to assess pollutant concentration?

- Empirical models (e.g. ASHRAE, EPA)
- Wind Tunnel Modelling
- Field Experiments
- Computational Fluid Dynamics (CFD)

Empirical models:

ASHRAE dispersion model

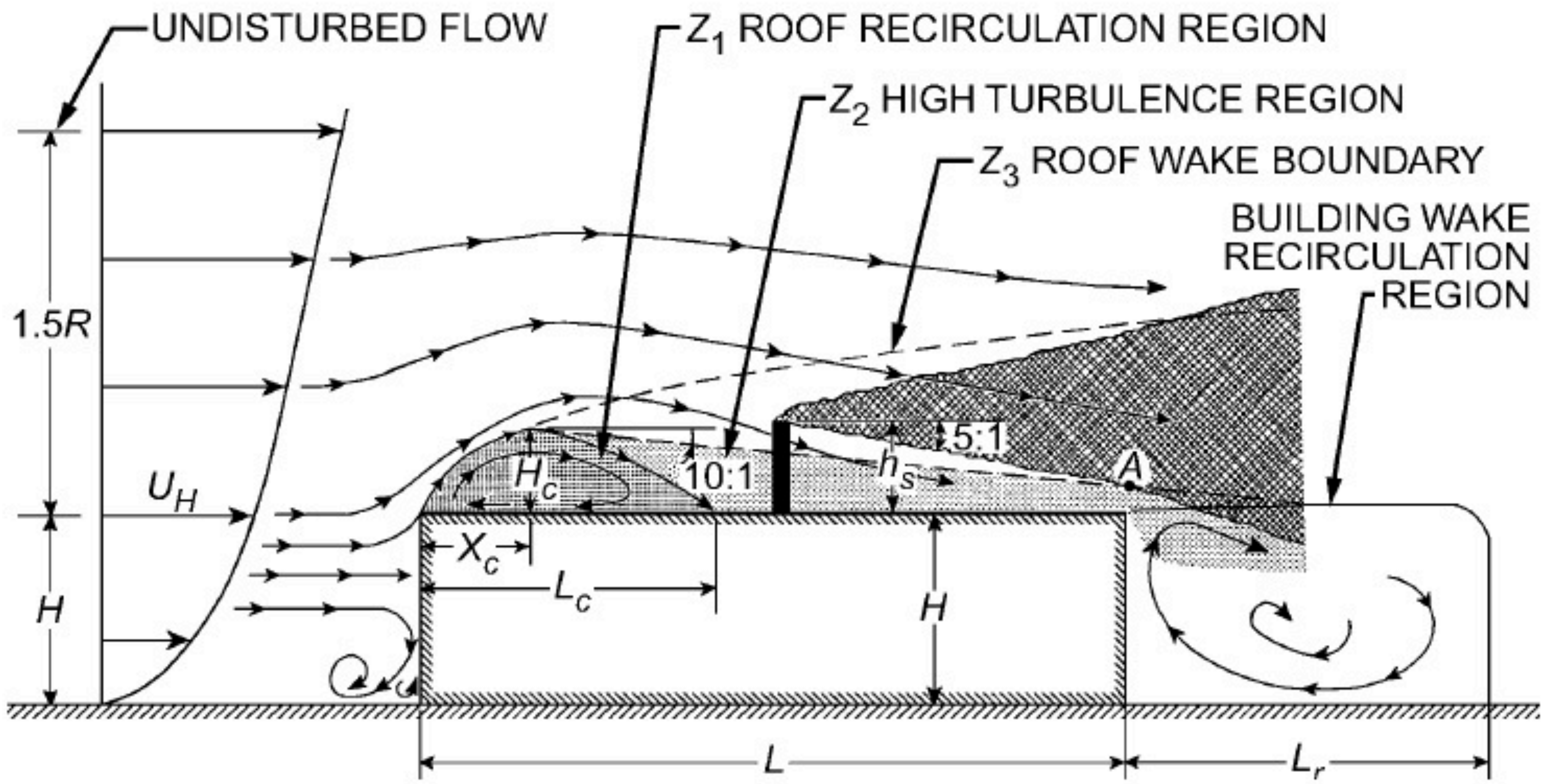
ASHRAE Dispersion Model

- **Geometric** Design Method

- Gaussian plume equations for **roof-level dilutions**

ASHRAE Dispersion Model

- Geometric Design Method



Design procedure for required stack height to avoid contamination [from Wilson (1979)]

ASHRAE Dispersion Model

- **Geometric** Design Method

The effective height of the plume above the roof or rooftop structure is

$$\mathbf{h = h_s + h_r - h_d}$$

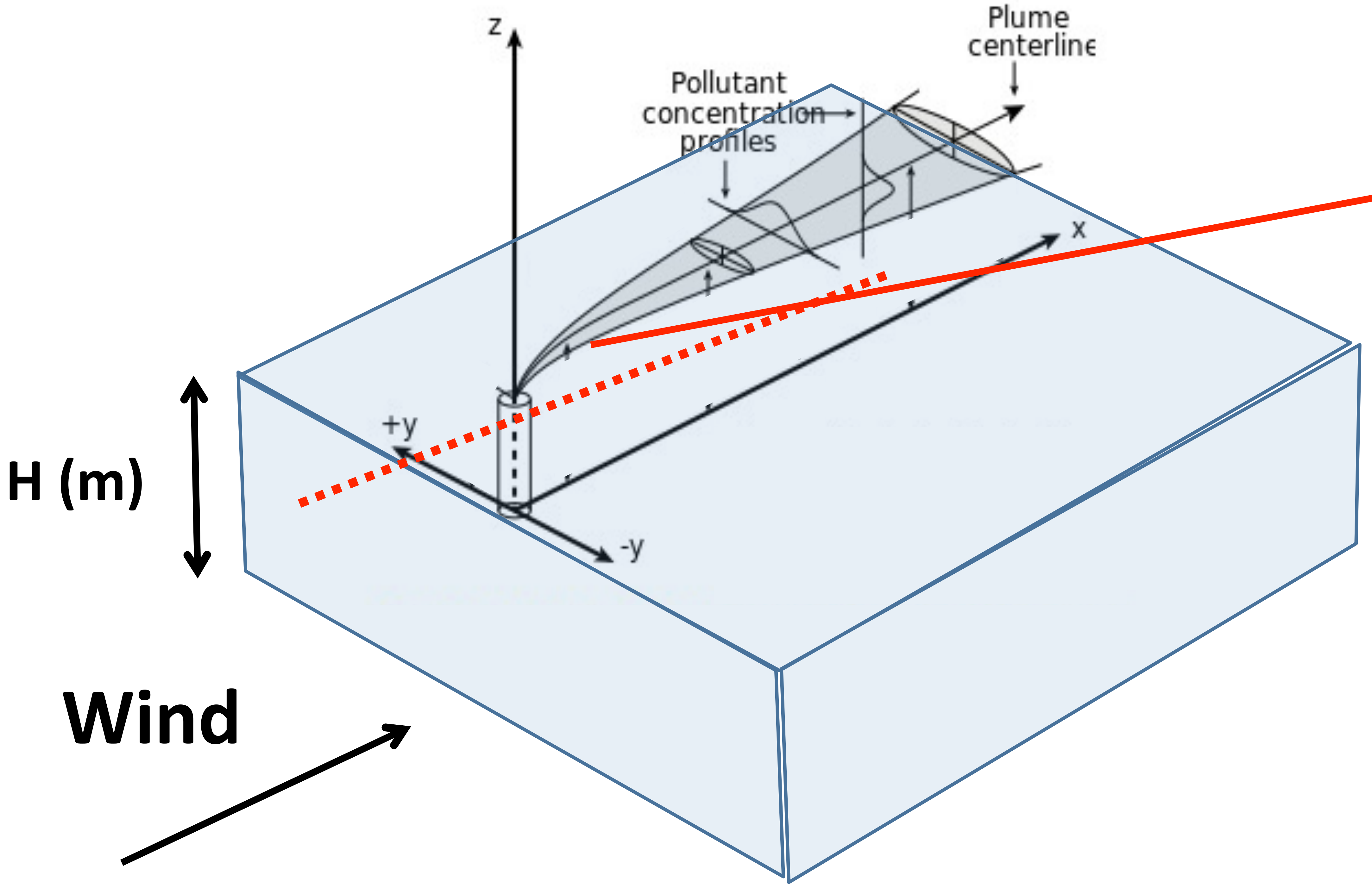
were h_s is stack height,

h_r is plume rise = $3\beta d_e(V_e/U_H)$ - Briggs (1984),

h_d is the reduction in plume height due to entrainment into the stack wake during periods of strong winds

ASHRAE Dispersion Model

- Gaussian plume equations for **roof-level dilutions**



ASHRAE-2011

$$D_r = 4\frac{U_H}{V_e} \times \frac{\sigma_y}{d_e} \times \frac{\sigma_z}{d_e} \exp\left(\frac{\xi^2}{2\sigma_z^2}\right)$$

$D_r = \frac{C_e}{C_r}$: **dilution** at roof level

ξ : vertical separation (h_{plume}-h_{top})

σ_y : cross-wind plume spread

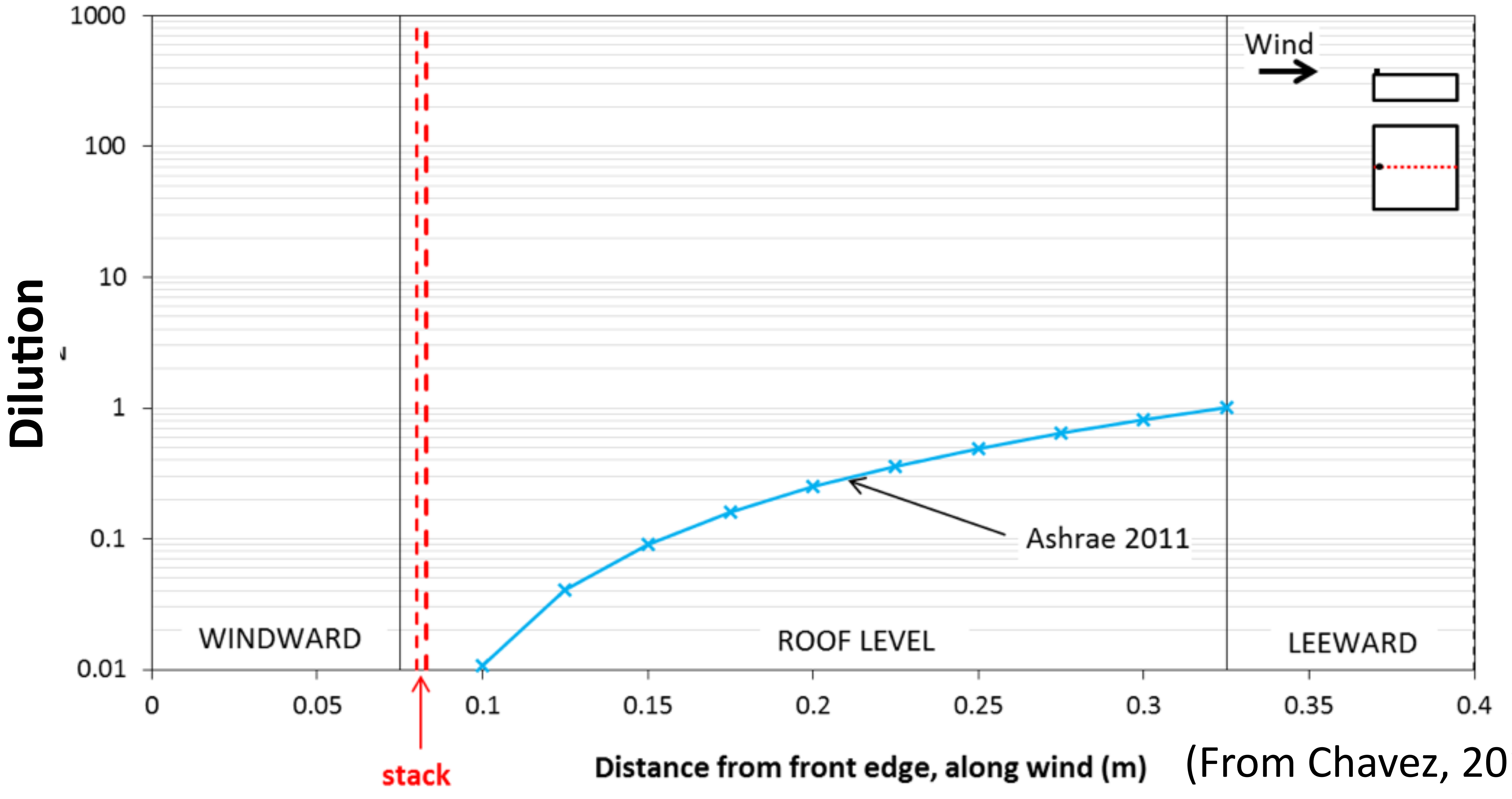
σ_z : vertical plume spread

d_e : stack diameter, m

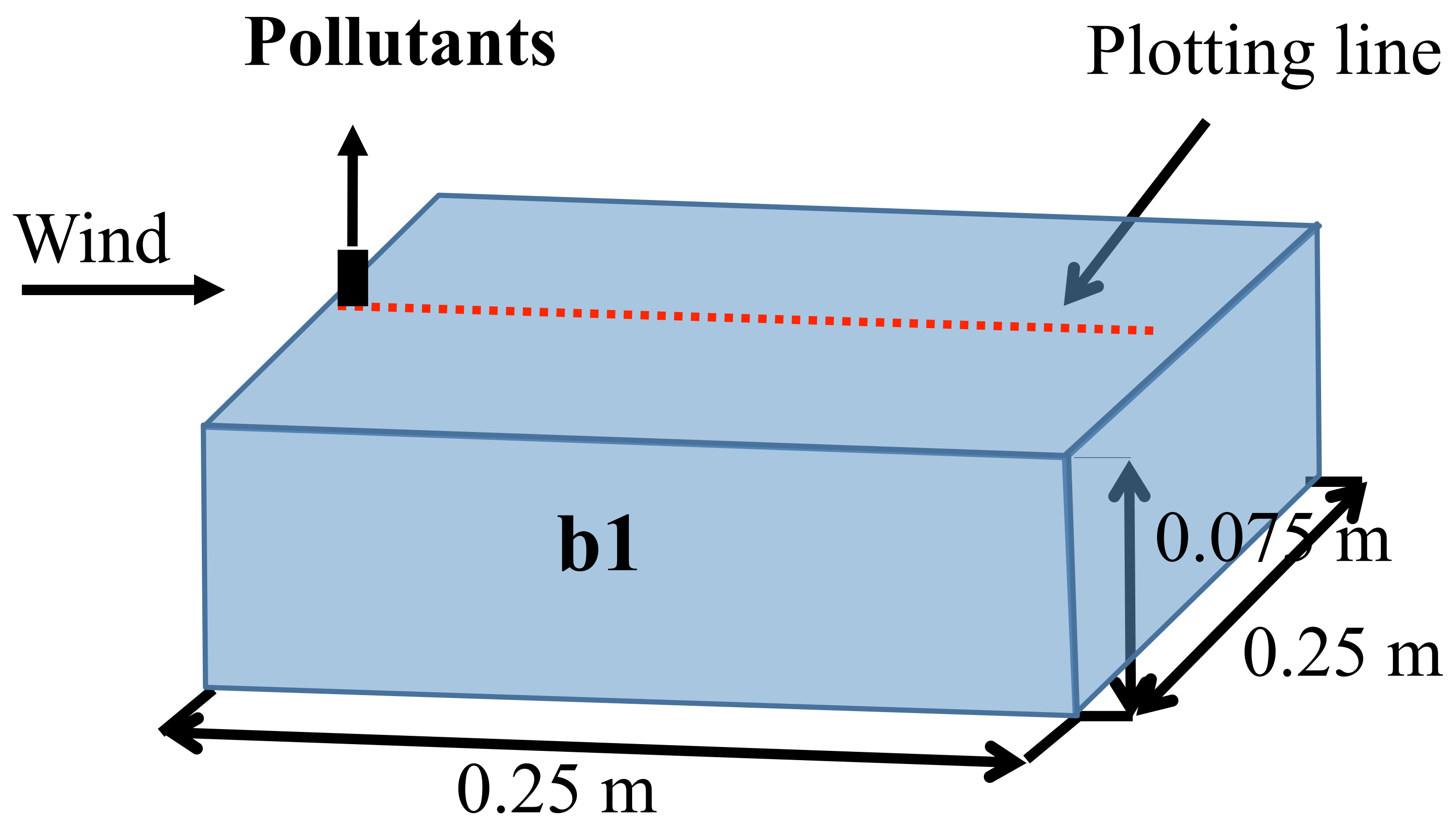
v_e : exhaust velocity, m/s

U_H: wind speed at building height, m/s

ASHRAE Dispersion Model



(From Chavez, 2014)



ASHRAE Dispersion Model

Merits	Demerits
- **Easy** to use for near-field dispersion problems of isolated buildings	- Does **not** consider effects of building geometry, **surroundings**, and wind direction - In general, **very conservative** for dilution prediction

Empirical models:

EPA approved dispersion models

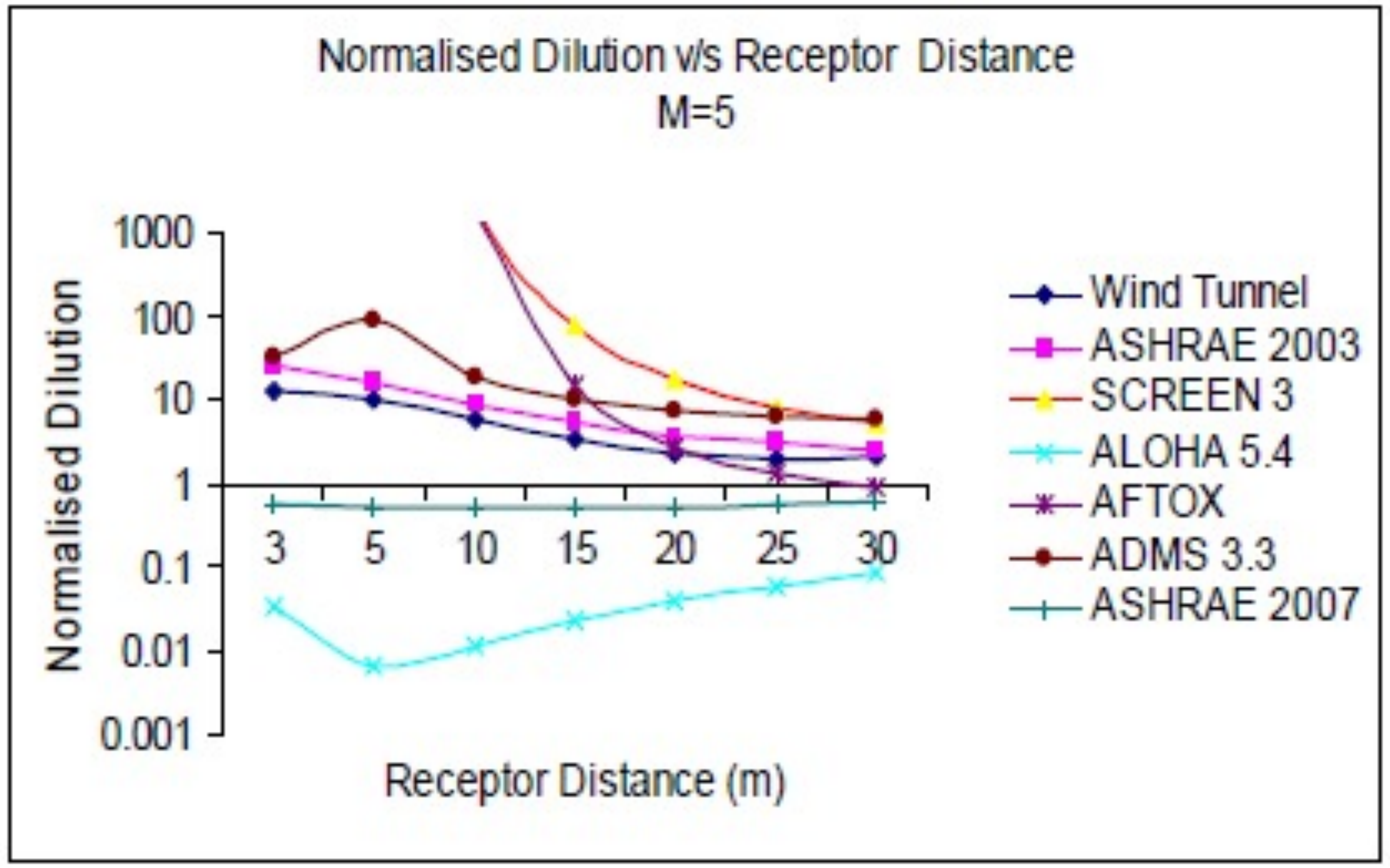
Environmental Protection Agency (EPA) models

- Atmospheric Dispersion Modelling Systems (ADMS-3)
- Air Force Toxics Model (AFTOX)
- SCREEN
- ALOHA
- CALPUFF
- Assessment System for population Exposure Nationwide (ASPEN)
- Air Force Dispersion Model (ADAM)
- DEGADIS
- HGSYSTEM
- HYROAD
- etc...

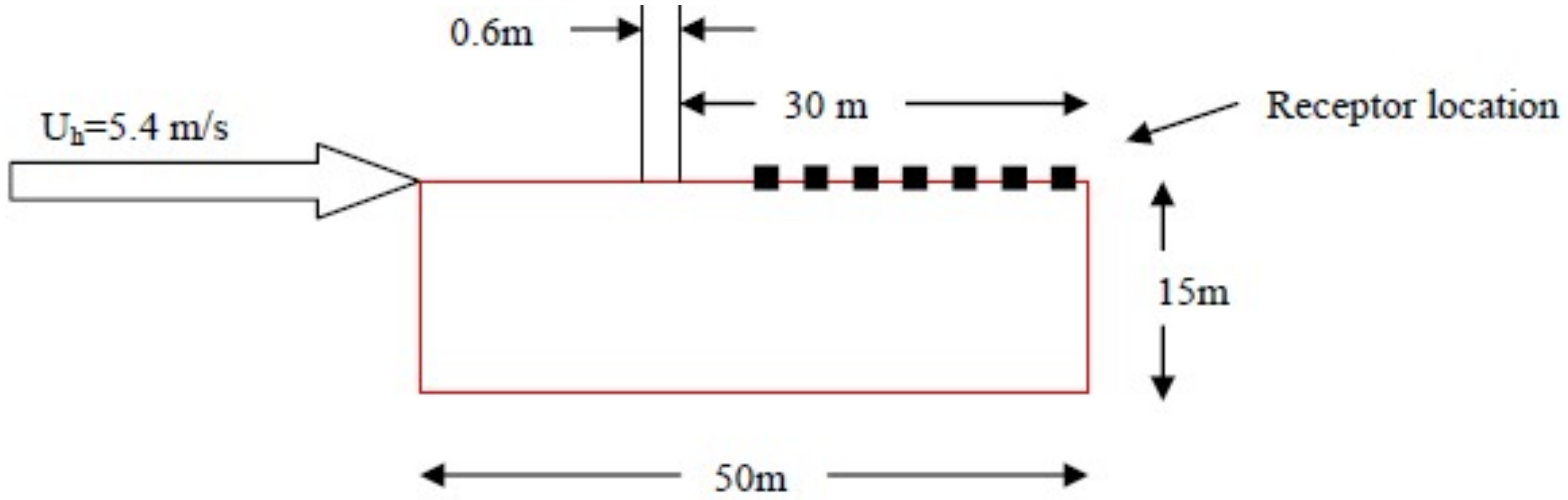
All models are based on **Gaussian** distribution

Environmental Protection Agency (EPA) models

Dilution



(From Hajra, 2012)



ADMS, AFTOX, SCREEN, ALOHA

ASHRAE and wind tunnel comparison

Environmental Protection Agency (EPA) models

Merits	**Demerits**
- Fast and **easy** to use - Suitable for **isolated** stacks - Some of these models such as ADMS and CALPUFF can model building and stack **downwash** effects	- Most models predict very **high** concentrations within the first 10 m from stack; hence **unsuitable** for near-field dispersion problems - The effect of complex **adjacent** building layout cannot be modelled

Wind tunnel modelling

Wind tunnel modelling

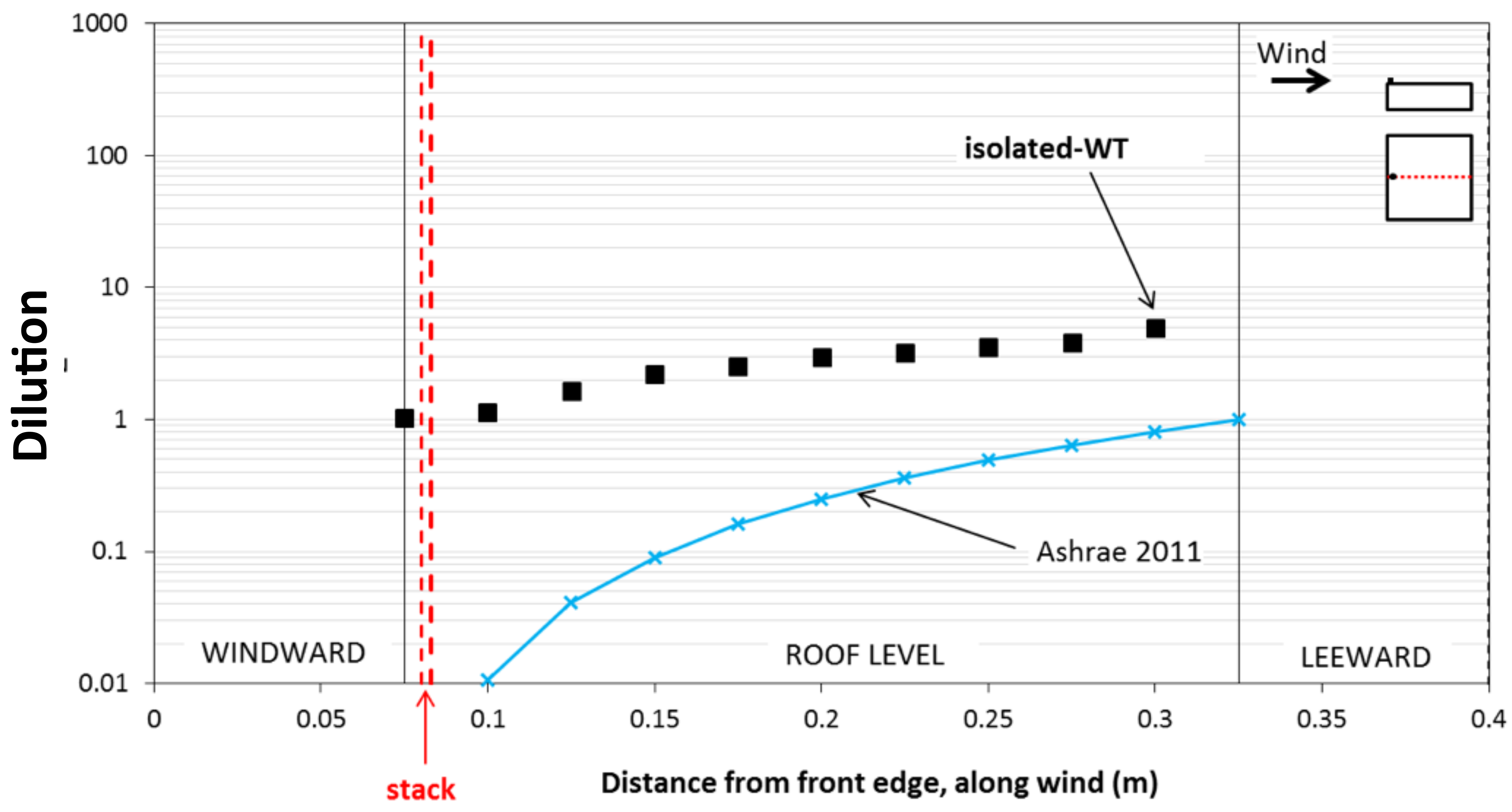
Boundary layer wind tunnel at Concordia University

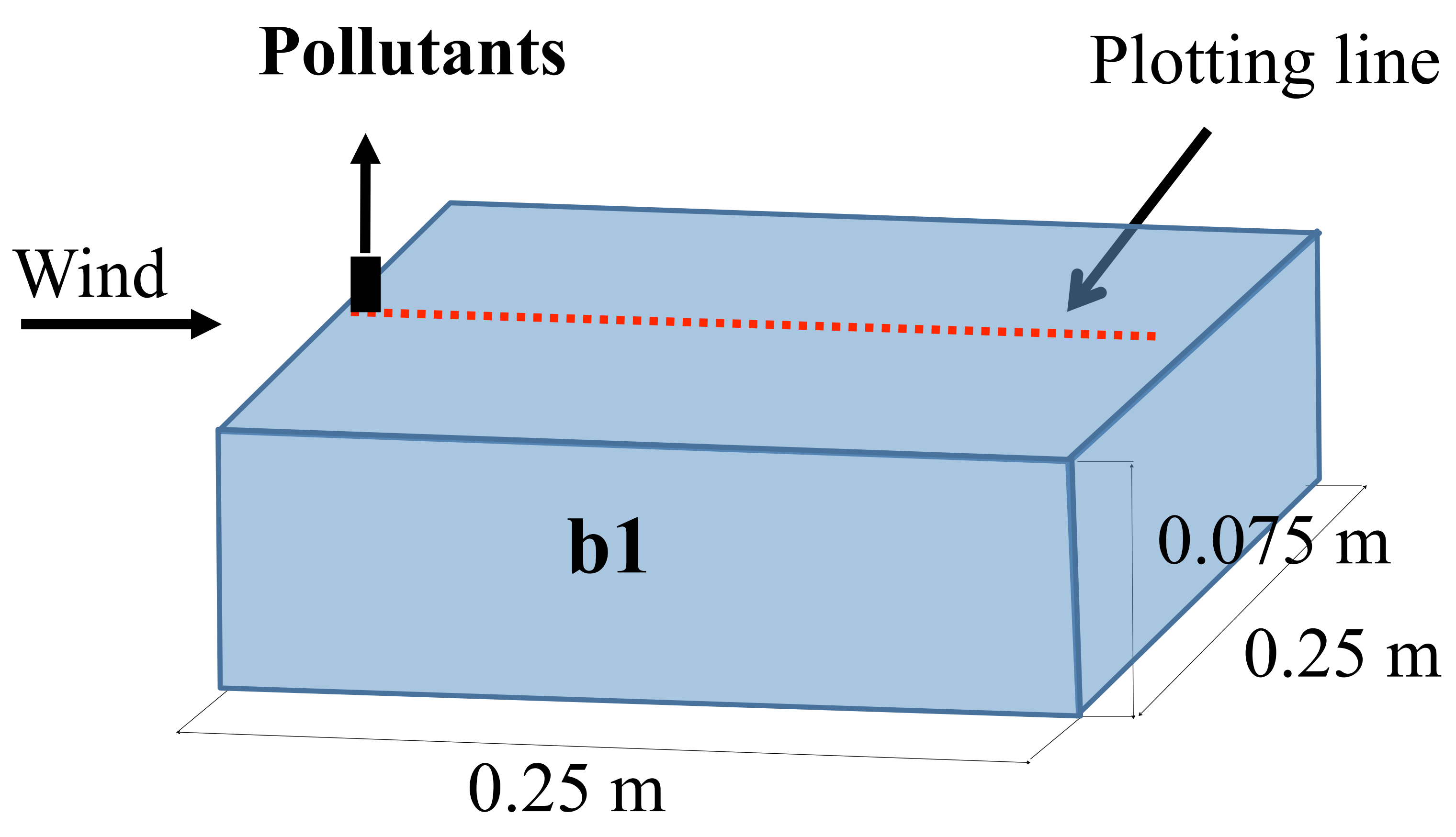
- Simulates wind flow **around building** models

- Requires a particular **geometric scale** for modelling the building and its surroundings

- For studying **wind-building/structure** interaction problems (load, pedestrian comfort, dispersion, etc.)

Wind tunnel modelling





Wind tunnel modelling

Merits	Demerits
- Effects of **surroundings**, local topography and different upstream conditions are included **- Most accurate** method of predicting dispersion of pollutants	- Building models of large sizes (scales) can **block air flow**, resulting in inaccurate modelling of actual flow conditions - Buildings with **curved** surfaces are difficult to be modelled (Reynolds similarity restrictions) - Architectural details (e.g. rooftop structures, balconies) may be difficult to model on a smaller scale

Field Experiments

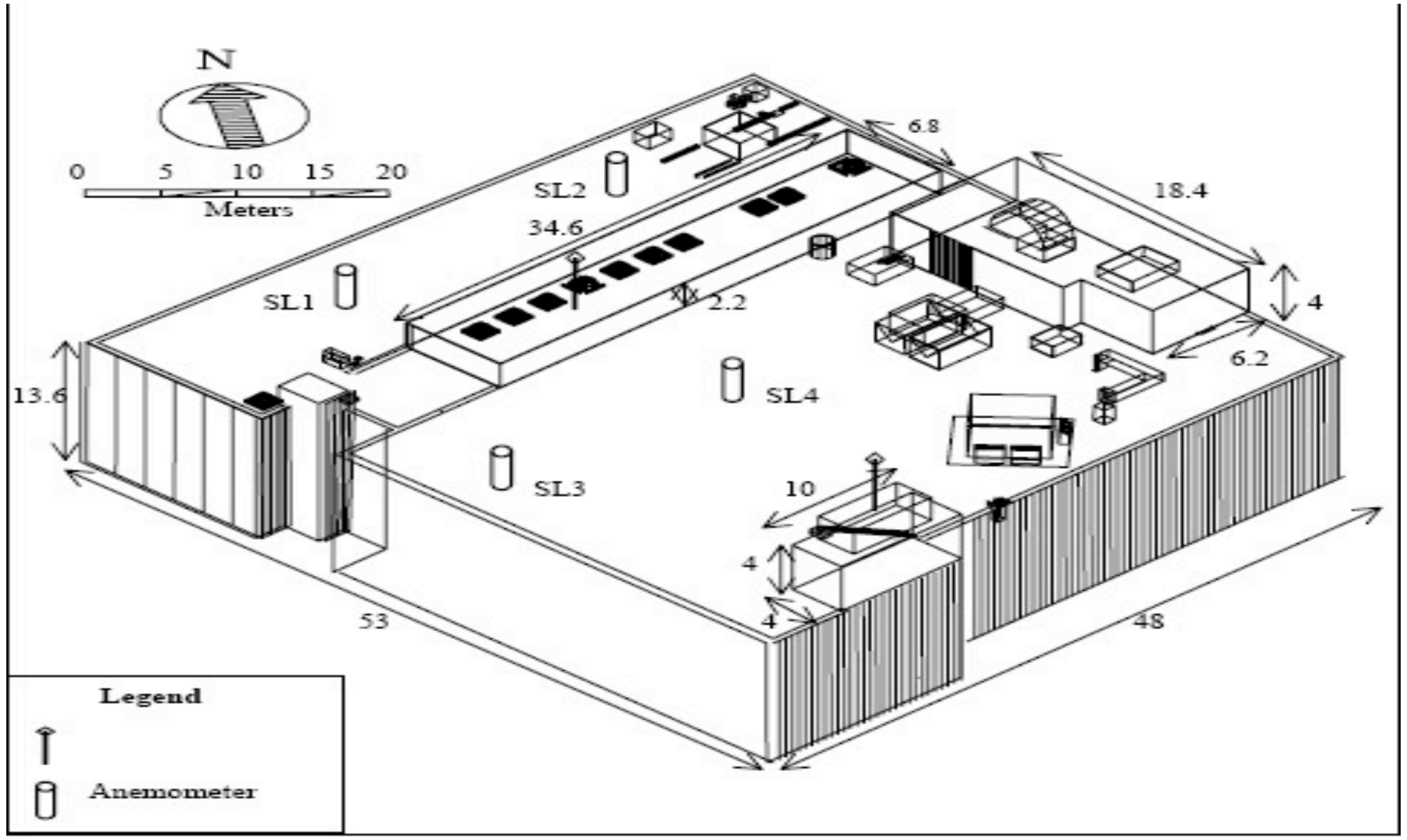
Field Experiments

- In Field Experiments the tests are done on **existing buildings**, data are real, but come too late to be used for design!
- Field Experiments are valuable to **validate the experimental** data and help improve simulation conditions and methodologies
- An **Anemometer** is used to estimate wind velocities and directions
- Tracer gas is released from a stack and **air samples are collected** at various receptors; concentrations are determined later by using suitable instrumentation

Field Experiments

BE building, Concordia University, Montreal

Field Experiments



Detailed view of the BE building showing stack locations (SL), anemometers and various rooftop structures (dimensions in m)

Field Experiments

Photograph of the test stack used on the BE building (low stack with h_s=1m)

Field Experiments

Photograph showing upwind terrain for the various field tests

Field Experiments

Merits	Demerits
- **Reliable** results since measurements are carried out in actual conditions - Absolutely necessary for **validation** purposes	- **Expensive** and dependent on proper weather conditions - **Difficult** to carry out; instrumentation and equipment problems - Being weather dependent, field tests are **time consuming**

Computational Fluid Dynamics (CFD) simulations

CFD simulations

- Numerical techniques are used to solve the basic equations in Fluid Mechanics (**Navier-Stokes Equations**)

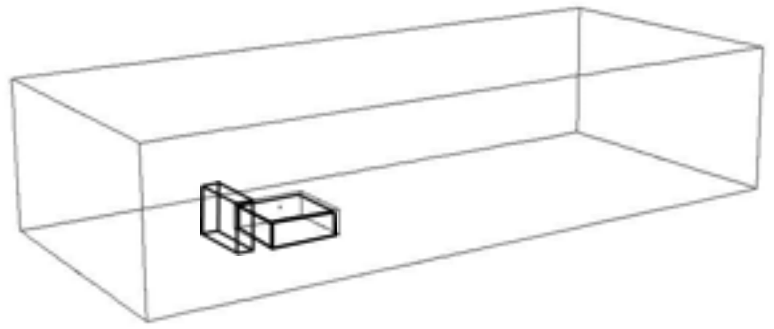
- This can be done by special computer programs or by using commercially available CFD software (such as **FLUENT**)

- Flow properties are obtained at **every point** simultaneously

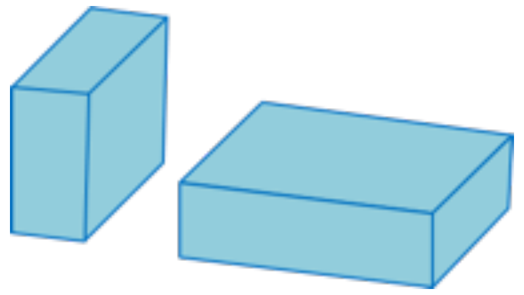
- Application of CFD is **complex** and far from being successful in several cases

CFD simulations

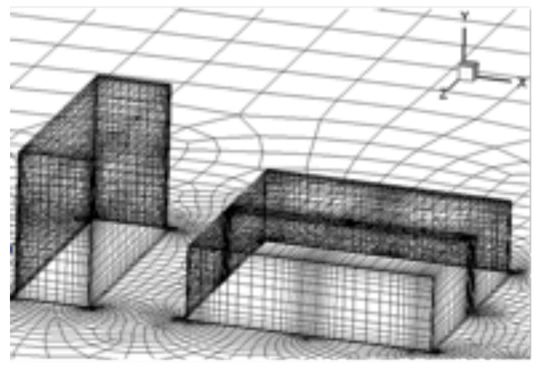
1. Domain



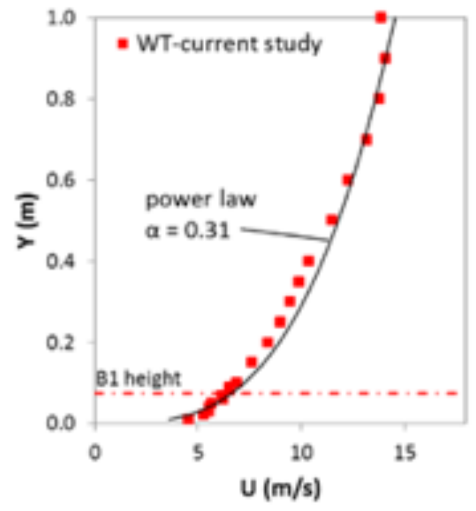
2. Model



3. Grid



4. Equations for flow and dispersion



5. Boundary condition

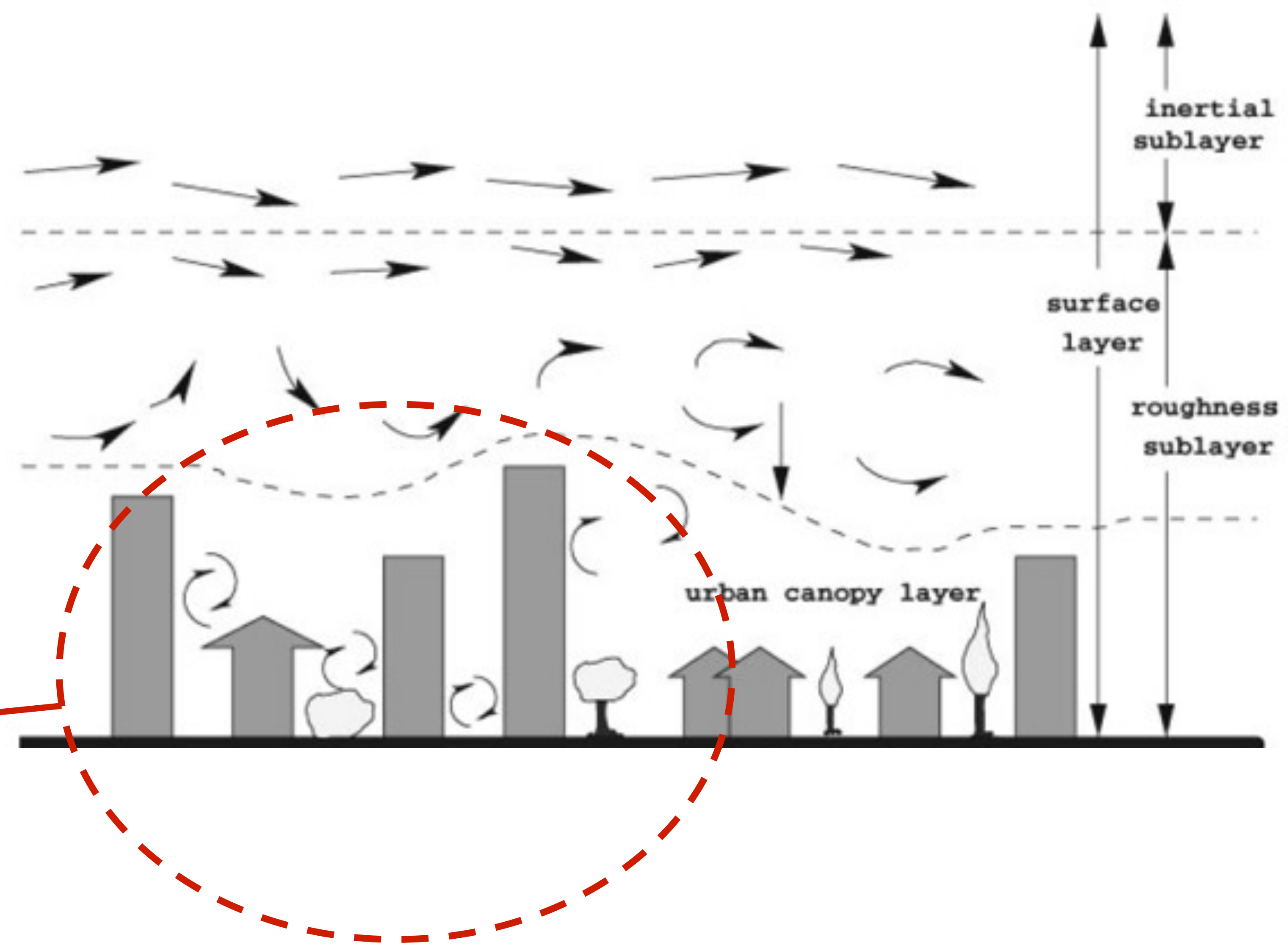
6. Convergence criterion

1) Domain

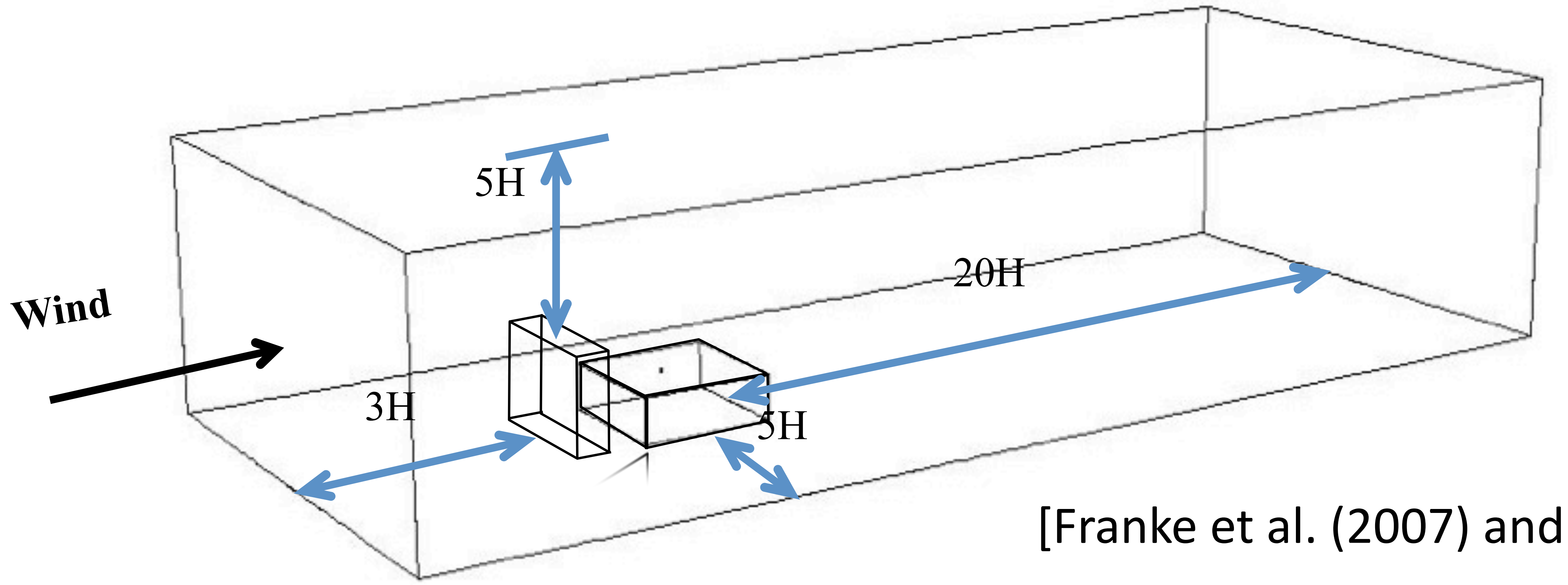
Four length scales :

(Britter & Hanna, 2003)

- ➢regional (up to 100 or 200 km)
- ➢city (up to 10 or 20 km)
- ➢neighbourhood (up to 1 or 2 km)
- ➢street (less than 100 to 200 m)



flow and dispersion within **one block**



[Franke et al. (2007) and Blocken et al. (2008)]

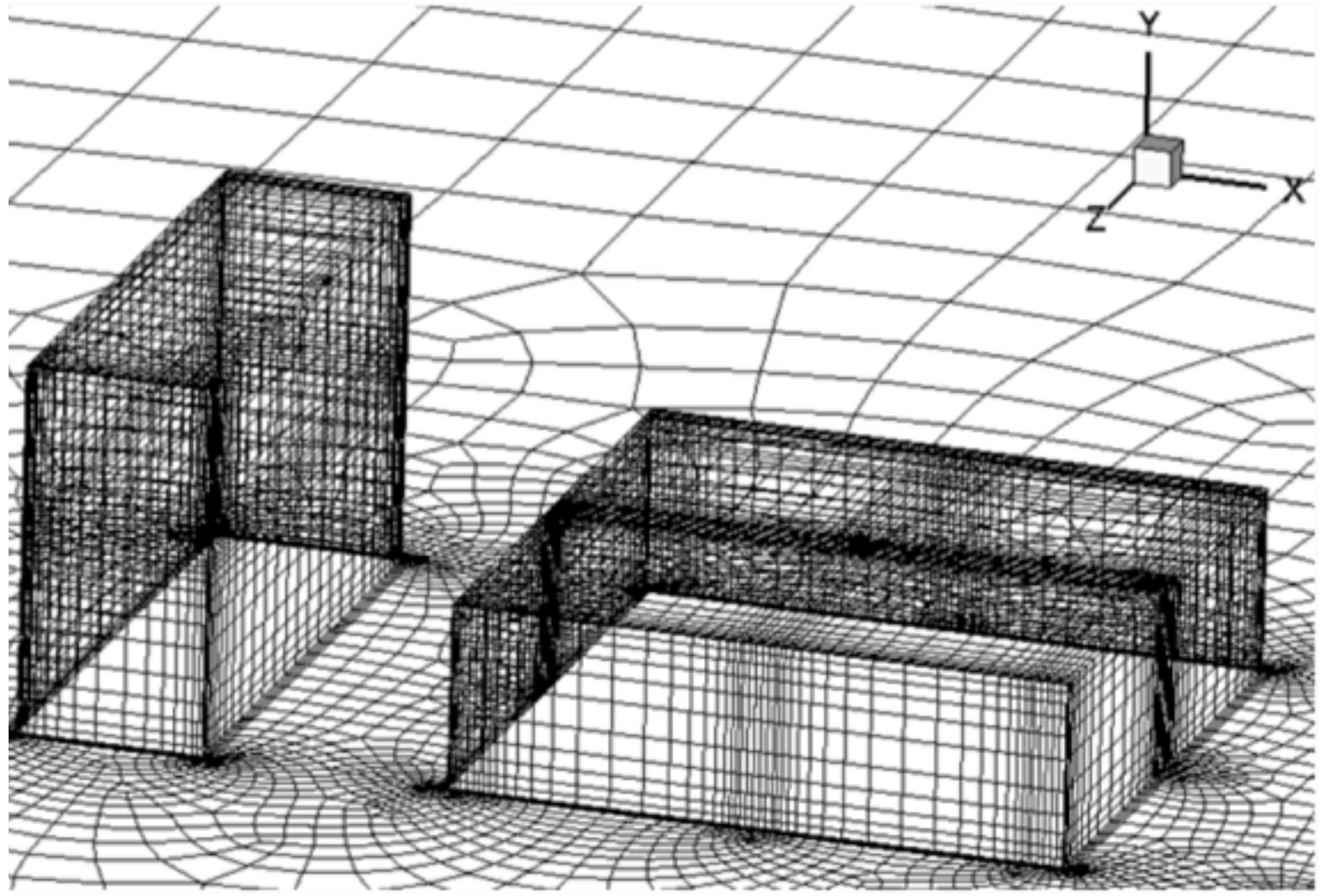
2) Physical model

To understand airflow within a cluster of buildings, we have first to understand how **simple structures** affect the incoming wind

Two-building configuration

- Scale 1:200, SF_6 concentration = 10 ppm, h_{stack} = 0.005 m (1 m)

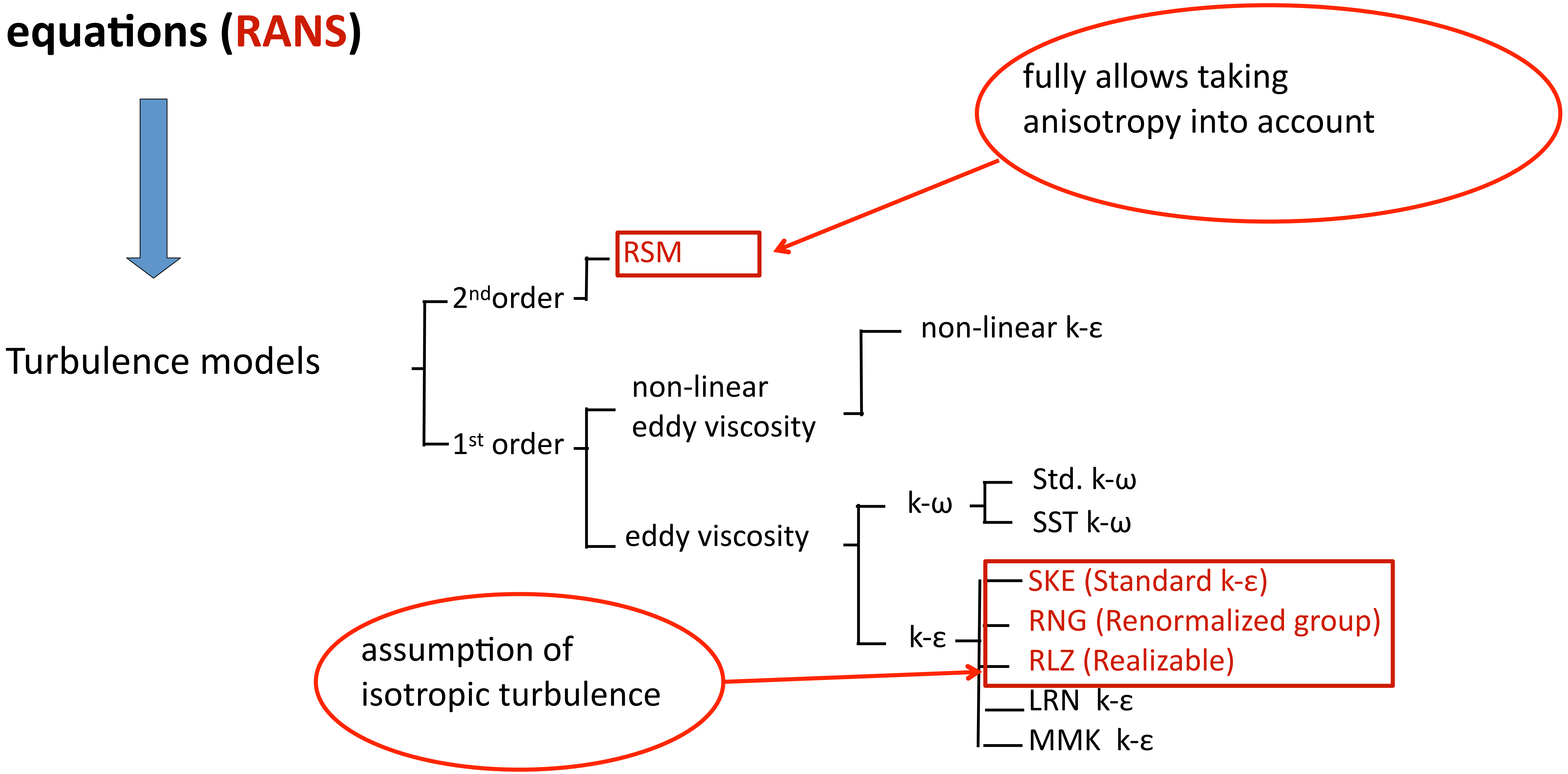
3) Grid



- The grid defines the **spatial resolution** of numerical solution
- It should be small in regions of high gradients
- The expansion ratio between two cells should be below 1.3 (Franke et al. 2007)
- A **grid sensitivity study** is recommended (Anderson, 1995)

4) Equations: **Steady** CFD simulations

Reynolds-Averaged Navier–Stokes equations (RANS)



4) Equations cont'd : Unsteady CFD simulations

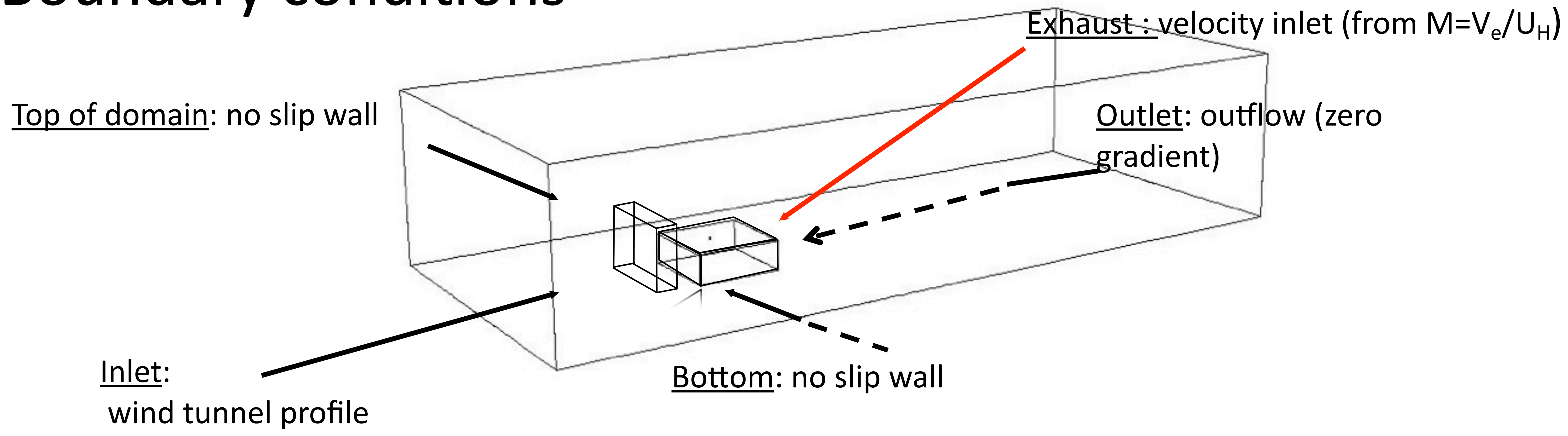
Direct Numerical Simulation (DNS) – Navier-Stokes equations are numerically solved without any turbulence model

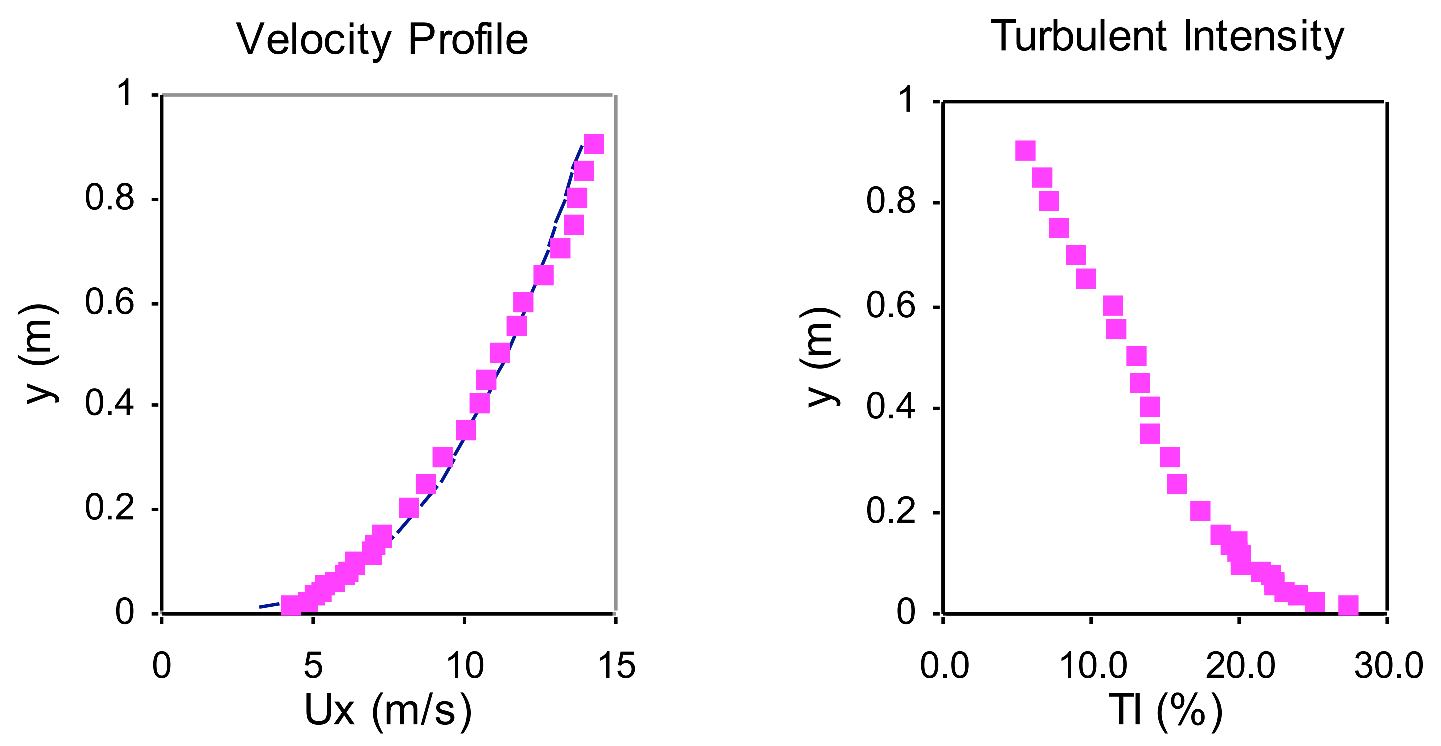
Large Eddy Simulation (LES) – Large turbulent structures are solved directly, small eddies are modelled

Detached Eddy Simulation (DES) – Hybrid URANS/LES URANS models are employed in the near-wall regions. LES is used away from the near-wall

Unsteady RANS (URANS) – ensemble averaging Navier-Stokes equations, suitable when unsteadiness is pronounced.

5) Boundary conditions





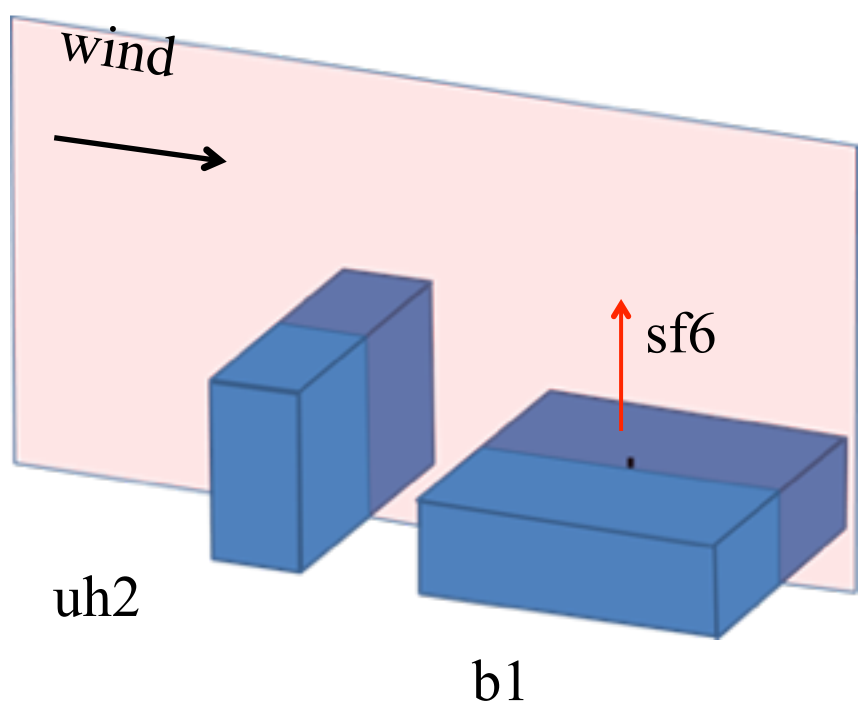
6) Convergence criterion

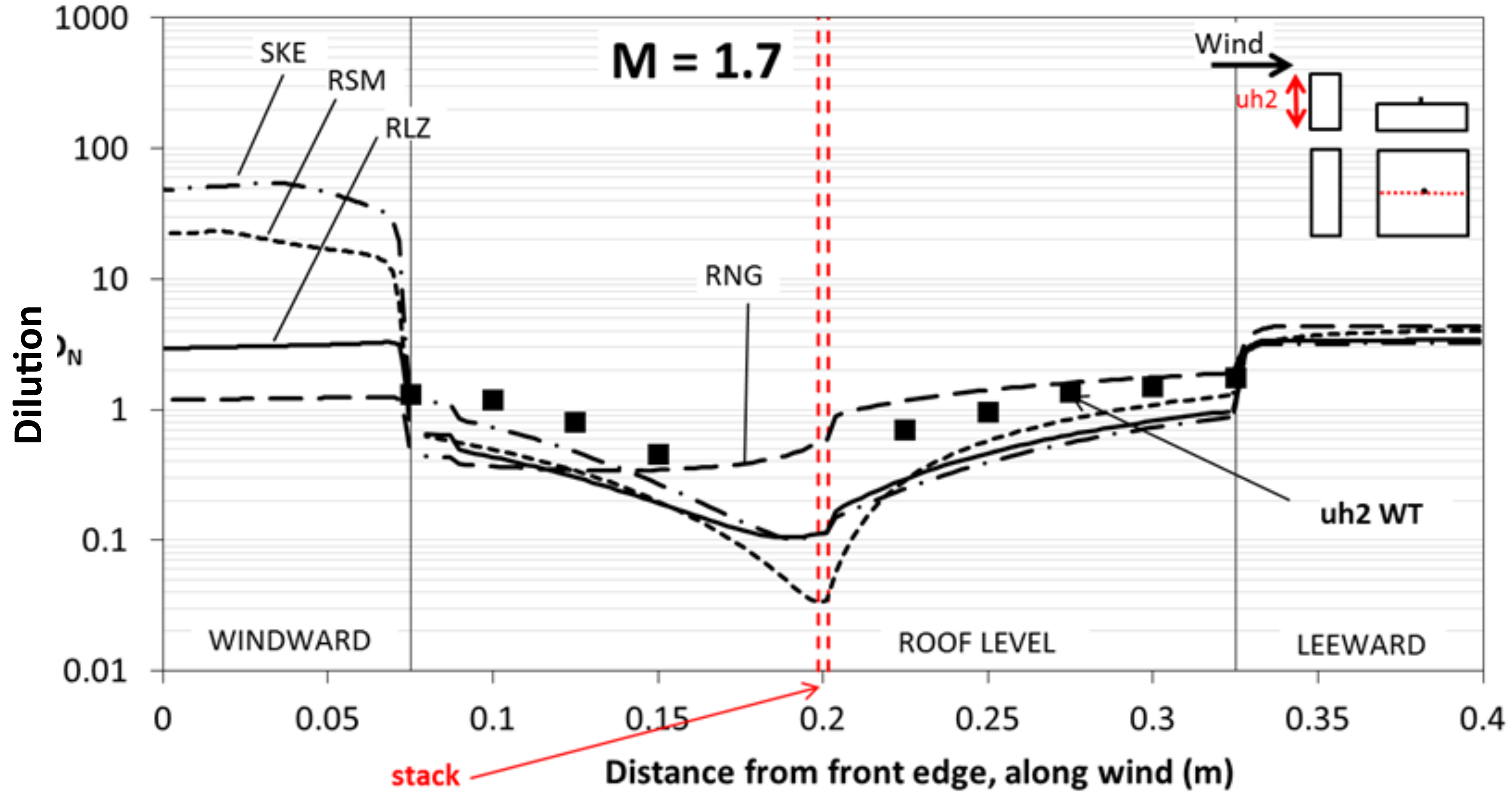
Convergence criterion based on the **residuals** of equations, designates how far the current solution is from the exact solution

For urban studies $\mathbf{10^{-5}}$ is commonly used (Franke et al. 2007); however, some cases need less

CFD results

Steady approach: Effect of turbulence models



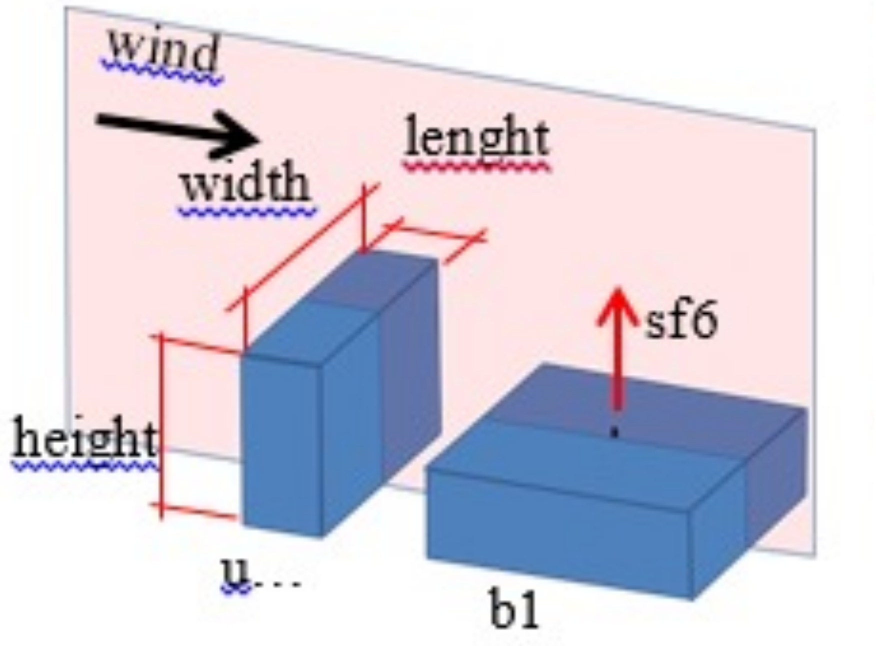


- At roof level SKE, RSM, and RLZ underestimate D_N ; RNG shows different behaviour
- Large differences on D_N on the windward wall of the emitting building is observed

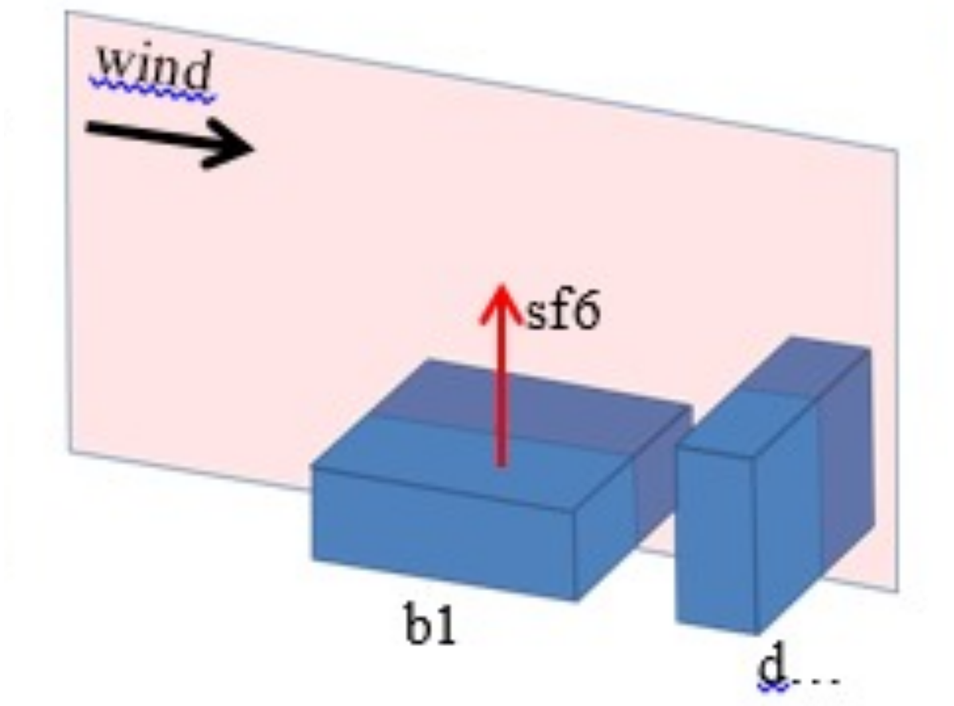
CFD results: parametric study

CFD results: parametric study

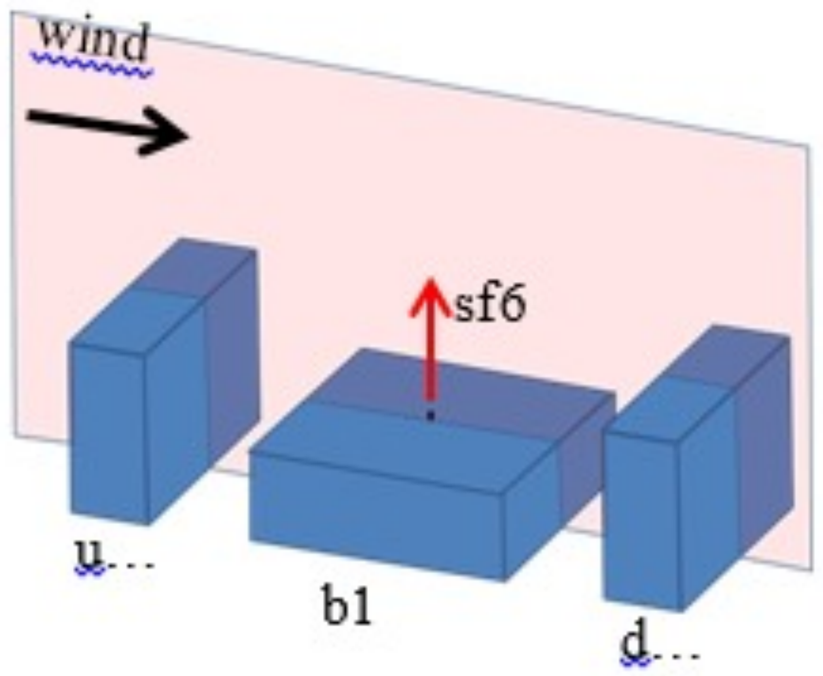
Effect of an upstream building



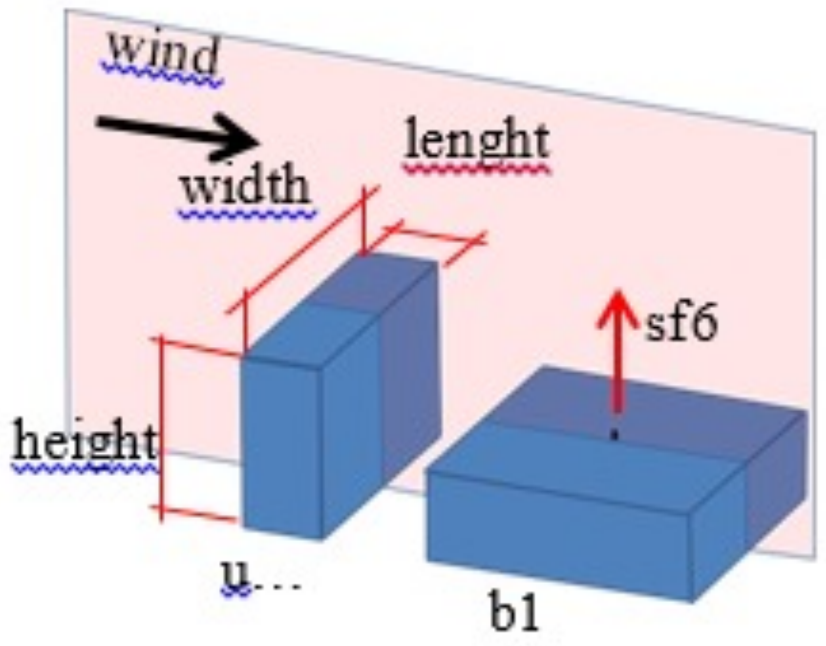
Effect of a downstream building



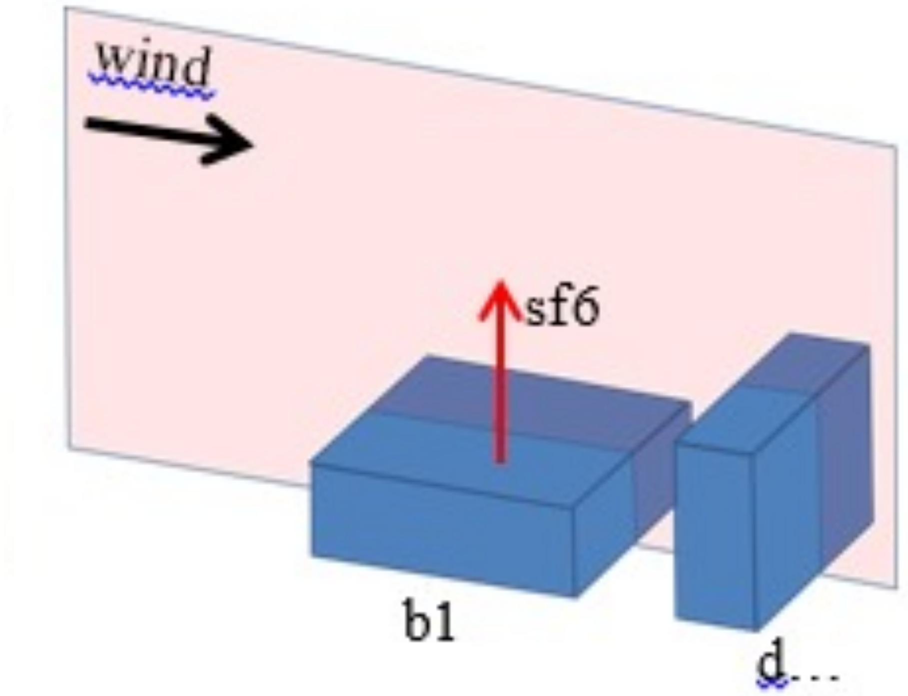
An emitting building between two buildings



Height (h)
Width (w)
Length (l)
Spacing (s)



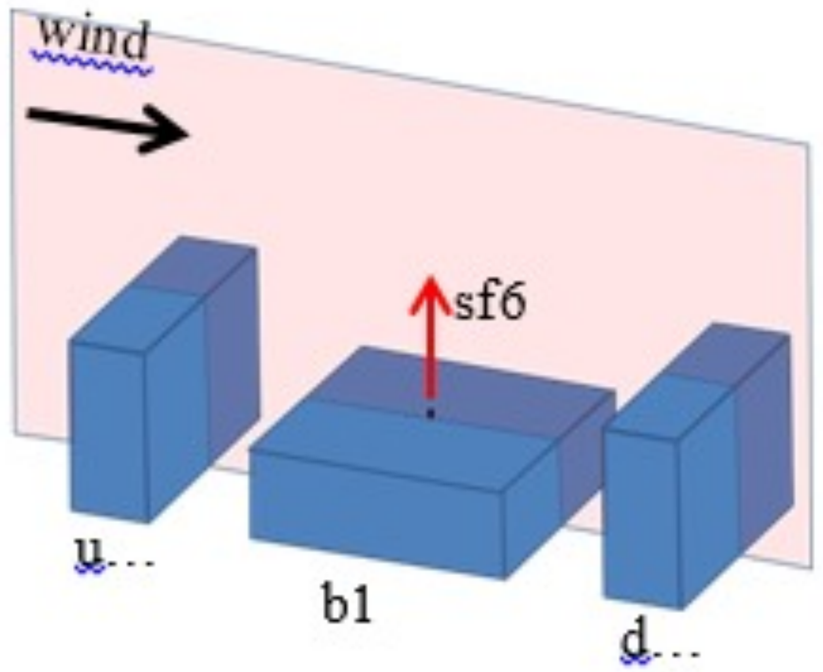
Effect of an upstream building



Effect of a downstream building

case	Height (m)	Length (m)	Width (m)
uh1	0.075	0.075	0.25
uh2	0.15	0.075	0.25
uh3	0.225	0.075	0.25
uh4	0.3	0.075	0.25
ul1	0.15	0.075	0.25
ul2	0.15	0.15	0.25
ul3	0.15	0.225	0.25
uw1	0.15	0.075	0.125
uw2	0.15	0.075	0.25
uw3	0.15	0.075	0.375
uw4	0.15	0.075	0.5

case	Height (m)	Length (m)	Width (m)
dh1	0.075	0.075	0.25
dh2	0.15	0.075	0.25
dh3	0.225	0.075	0.25
dh4	0.3	0.075	0.25
dl1	0.15	0.075	0.25
dl2	0.15	0.15	0.25
dl3	0.15	0.225	0.25
dw1	0.15	0.075	0.125
dw2	0.15	0.075	0.25
dw3	0.15	0.075	0.375
Dw4	0.15	0.075	0.5



An emitting building between two buildings

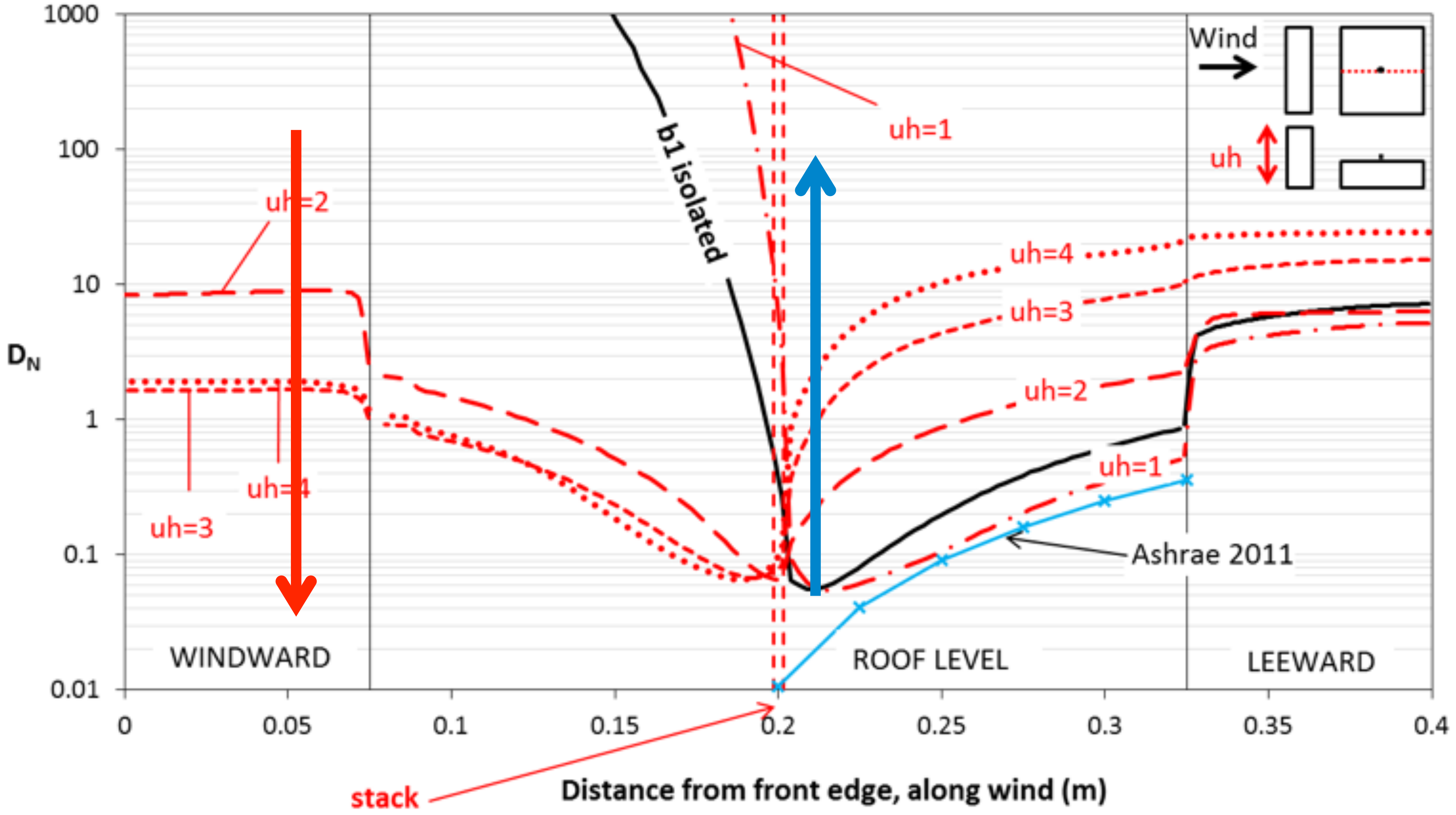
case	Height (m) of the upstream building (m)	Height (m) of the downstream building (m)	Length (m)	Width (m)
uh1dh4	uh1=0.075	dh4 = 0.3	0.075	0.25
uh2dh4	uh2=0.15	dh4 = 0.3	0.075	0.25
uh3dh4	uh3=0.225	dh4 = 0.3	0.075	0.25
uh4dh4	uh4=0.3	dh4 = 0.3	0.075	0.25
uh4dh1	uh4=0.3	dh4 = 0.075	0.075	0.25
uh4dh2	uh4=0.3	dh4 = 0.15	0.075	0.25
uh4dh3	uh4=0.3	dh4 = 0.225	0.075	0.25

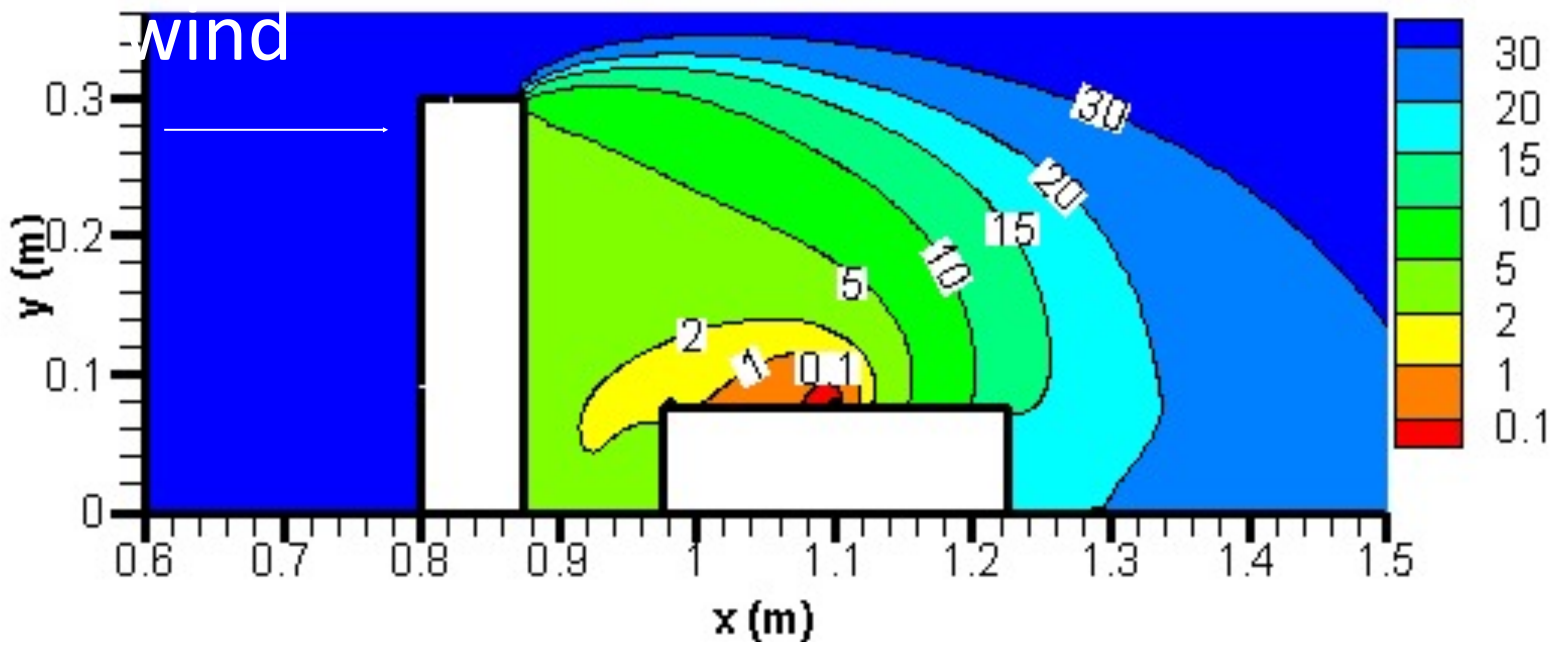
In total 29 cases were simulated

CFD simulations

Effect of <u>upstream</u> building height

Dilution

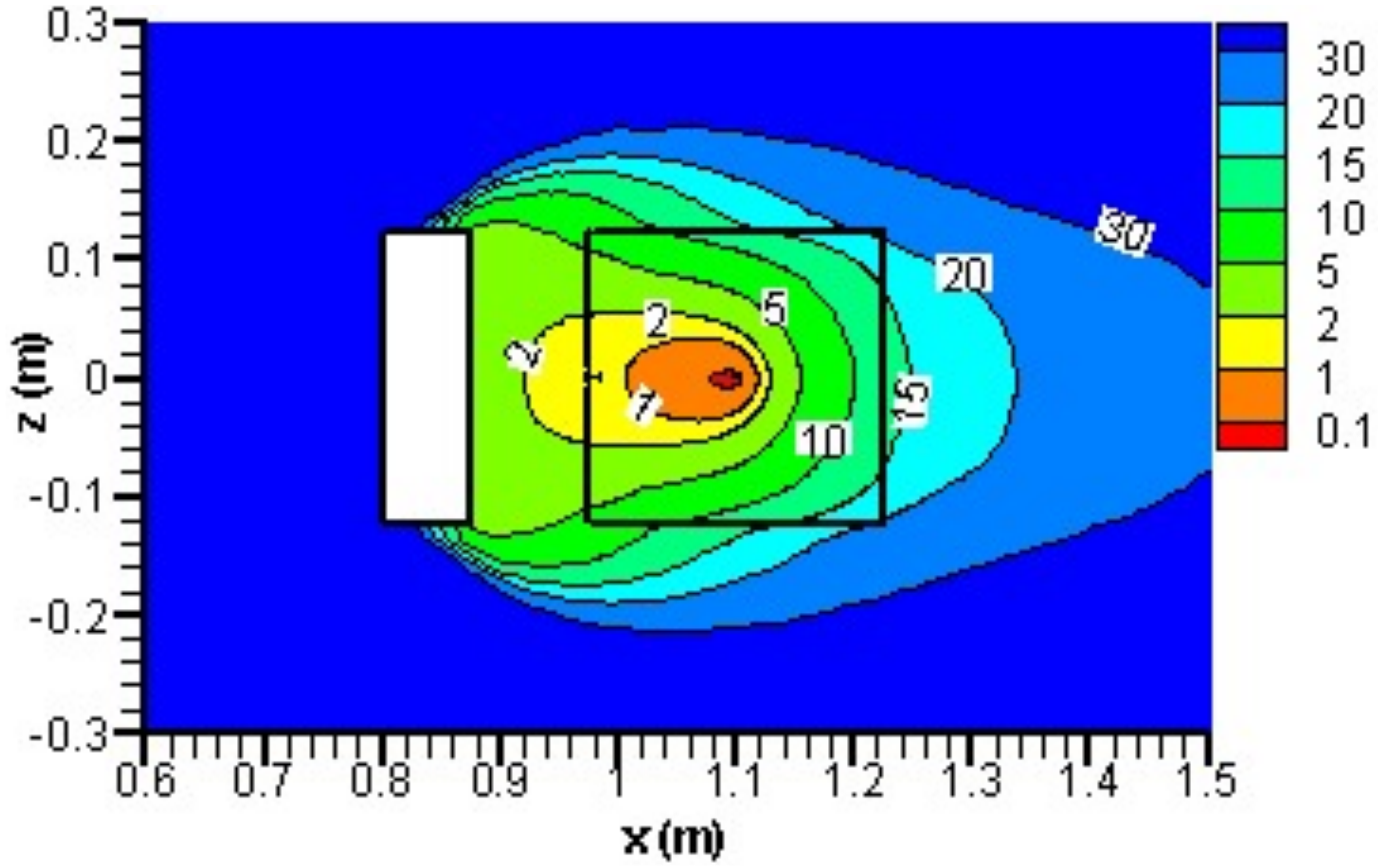




Elevation, uh4

D_N

Dilution



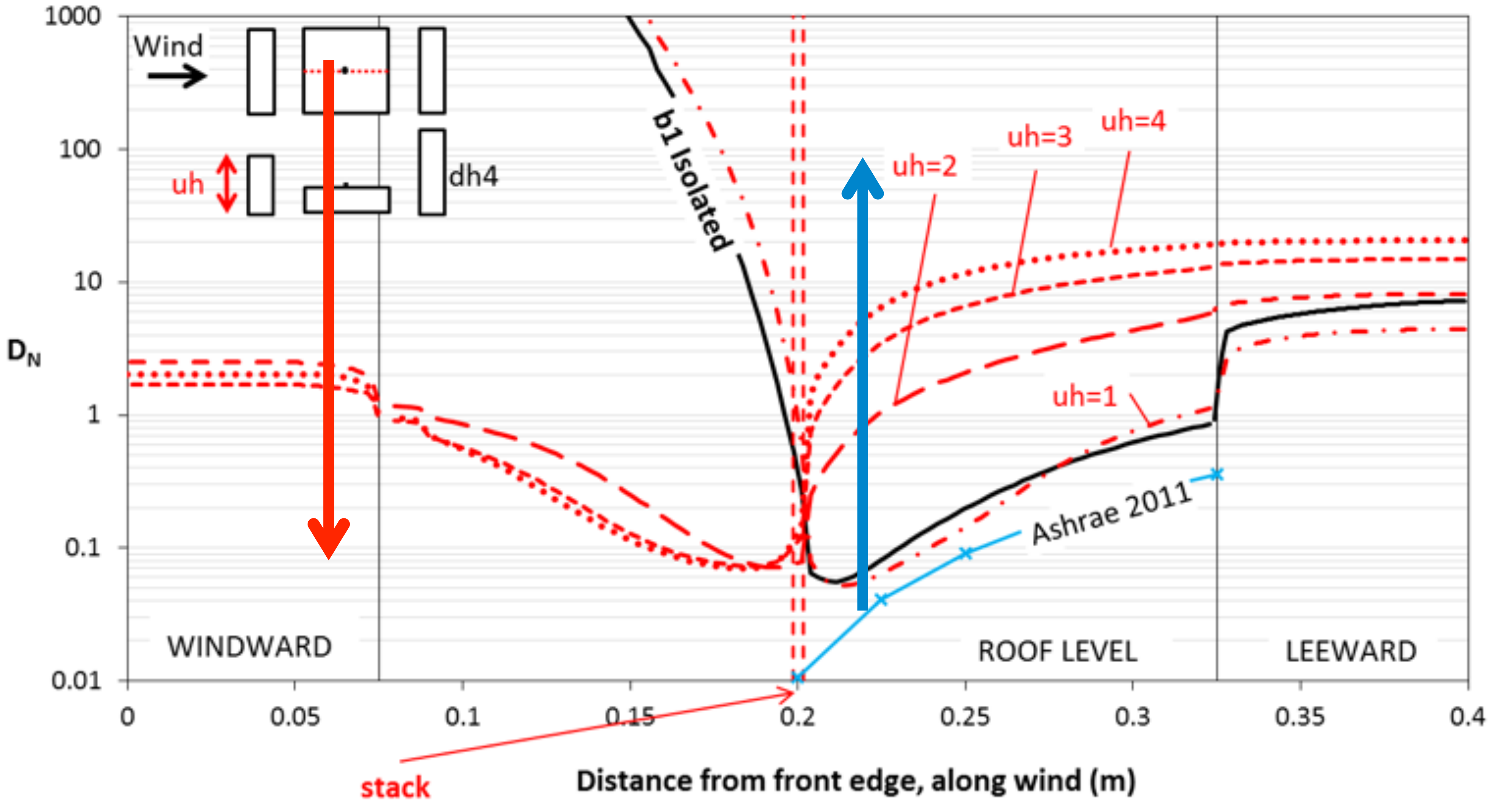
Plan view, uh4

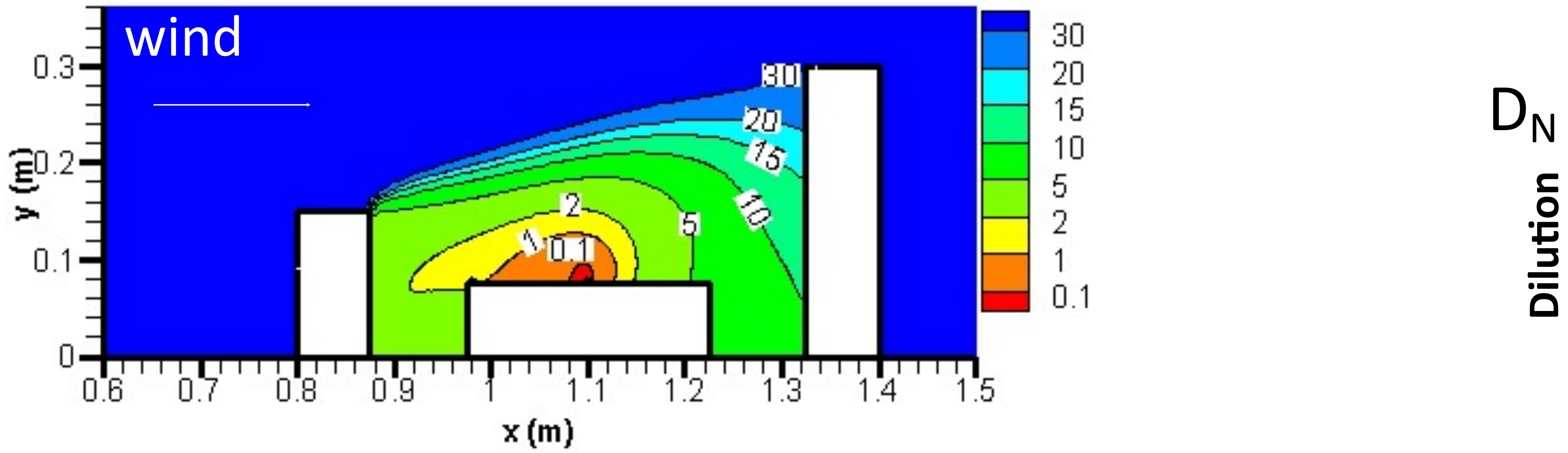
D_N

Dilution

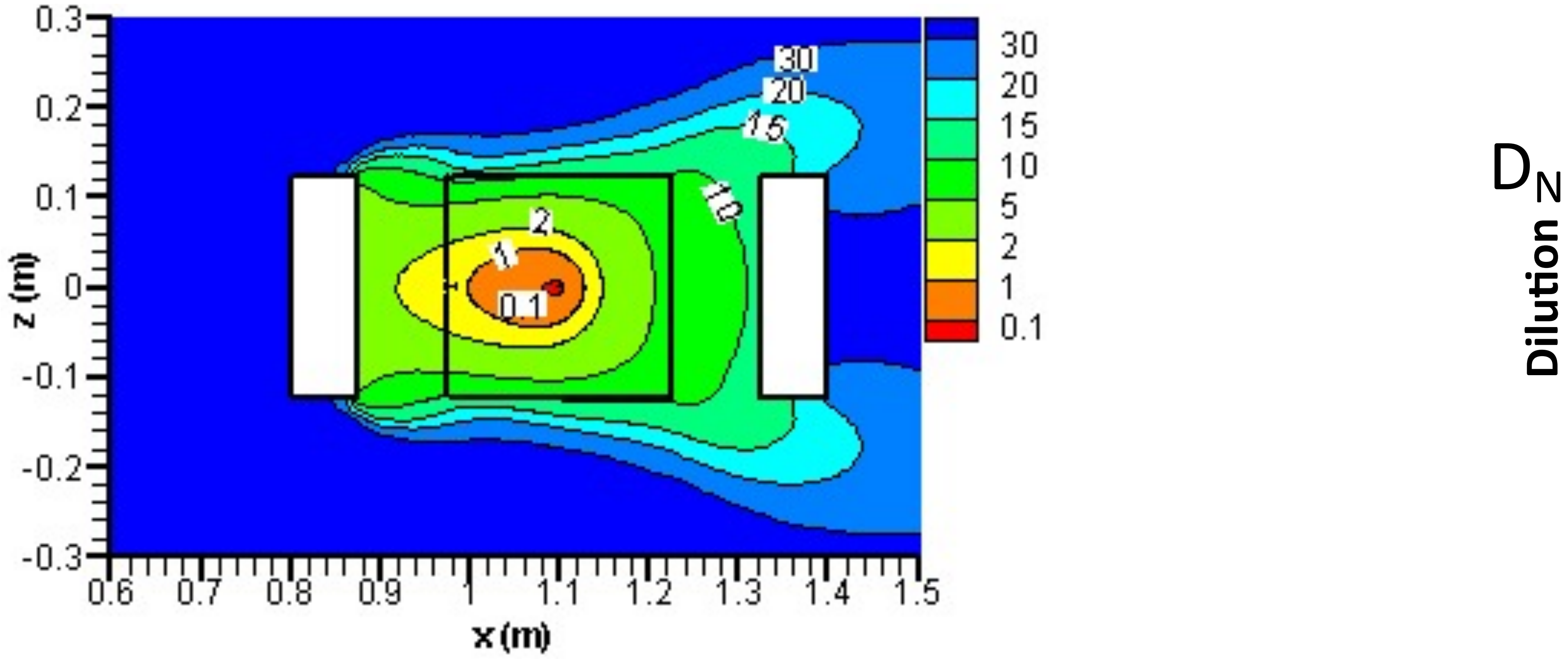
CFD simulations

An emitting building
between two buildings





Elevation, uh2dh4



Plan view, uh2dh4

Design Guidelines

Existing Codes and Standards

Quebec Law :

regulation respecting the quality of the work environment [S-2.1, r.15 (1994)] stipulates that fresh air intakes must be located so that no air already evacuated from an establishment is reintroduced.

Existing Codes and Standards

- For laboratory fume hood exhausts, the American Industrial Hygiene Association (**AIHA**) *Standard* Z9.5 recommends a:
  - minimum stack height of 10 ft above the adjacent roof line; and extending one stack diameter above any architectural screen
  - minimum V_e of 3000 fpm

- The Uniform Plumbing Code (**UPC**) [IAPMO, 1997b] requires exhaust vents to be 3 ft or more above air inlets

- National Fire Protection Association (**NFPA**) *Standard* 45 specifies a minimum stack height of 10 ft to protect rooftop workers

- The Uniform Mechanical Code (**IAPMO 1997a**), widely used in USA, recommends exhausts be at least 3 ft from property lines and 3 ft from openings into buildings

- Petersen and Le Compte (2002) have suggested placing air intakes on building sidewalls

ASHRAE 2011- Guidelines

- The exhaust velocity (V_e) should be maintained above 2000 fpm (even with drains in the stack) to provide adequate plume rise and jet dilution.

- (V_e) should be at least 1.5 times the design wind speed U_H at roof height to avoid stack downwash

- Intakes near vehicle loading zones must be avoided, since these areas may have unacceptable waste

Additional Guidelines

In terms of:

- **Stack** location, height and exhaust momentum ($M=V_e/U_H$) to avoid recirculation areas

- Safe placement of **intakes** on building facades to avoid re-ingestion of pollutants

- **Stack location**
  - Open fetch situation:
    - Stack should be placed near the center of roof (leading edge recirculation zone is avoided, thus, maximizing plume rise)
  - Taller building upstream:
    - Stack should be placed at the leading edge of roof (the roof level concentration decreases significantly, but higher concentrations occur on the leeward wall of the adjacent building) - Depends on distance between the buildings

- **Stack height**

  – For x < 20 m

    - Increase in stack height from 1 m to 3 m reduced the roof level concentrations by a factor of 2

    - To obtain significant (order of magnitude) reduction in concentration, a 7 m stack was required

  – For x > 20 m

    - Increase in stack height from 1 m to 3 m had a negligible effect on roof level concentrations

x: linear distance from stack to sampler

- **Exhaust Momentum**

  – For x < 20 m

    - Increasing M by a factor of 2.5 decreases the concentration by the same factor

Note: higher exhaust speed gives higher dilution due to:

- Larger plume rise
- Increased dilution at stack exit
- Increased entrainment of ambient air (initial dilution)

x: linear distance from stack to sampler

- **Exhaust Momentum** **cont'd**

  – For x > 20 m

    - In the low M range (1.5<M<4.5), which is typical of wind speeds exceeding 5 m/s, increasing exhaust speed may not be beneficial for distant receptors because the plume rise may not be sufficient to avoid them

    - For light wind conditions, doubling the exhaust speed may cause M to be high enough so that concentrations are reduced over the entire roof.

x: linear distance from stack to sampler

Additional Guidelines

In terms of:

- **Stack** location, height and exhaust momentum ($M=V_e/U_H$) to avoid recirculation areas

- Safe placement of **intakes** on building facades to avoid re-ingestion of pollutants

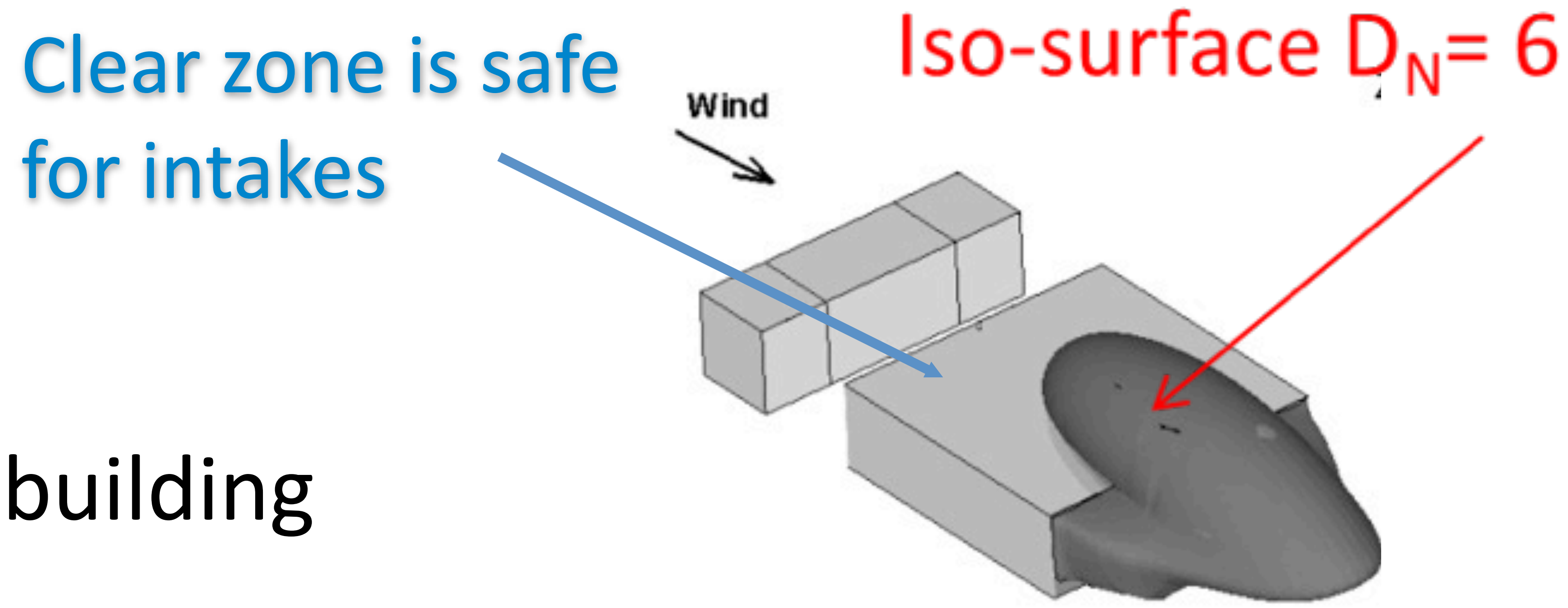
- **Safe placement of intakes**

  – Dilution criterion 3000:1 (to avoid odors and occupational health effects for a large group of chemicals (Wong and Ratcliff, 2003))

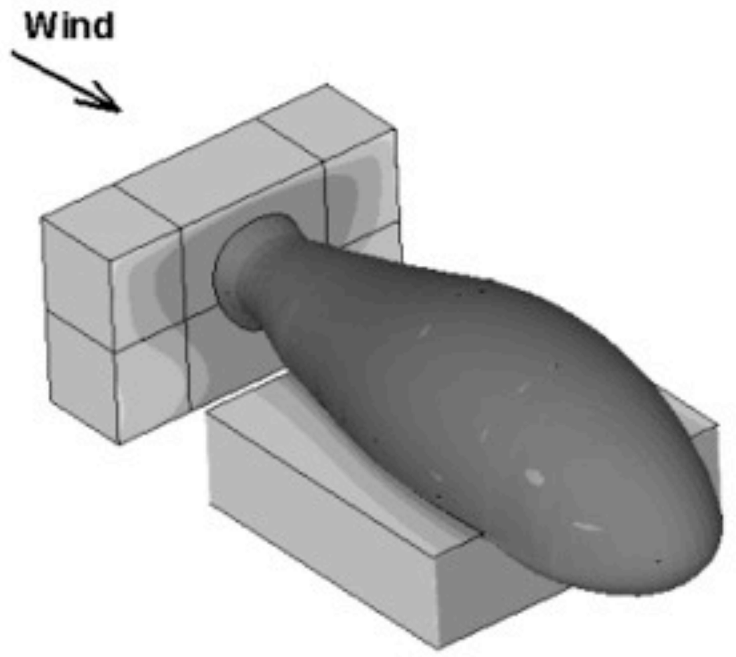
$$D_r = \frac{C_e}{C_r} = \frac{3000}{1} \quad \text{applying} \quad D_N = \frac{D_r Q_e}{U_H H^2}$$

$D_N = 6$

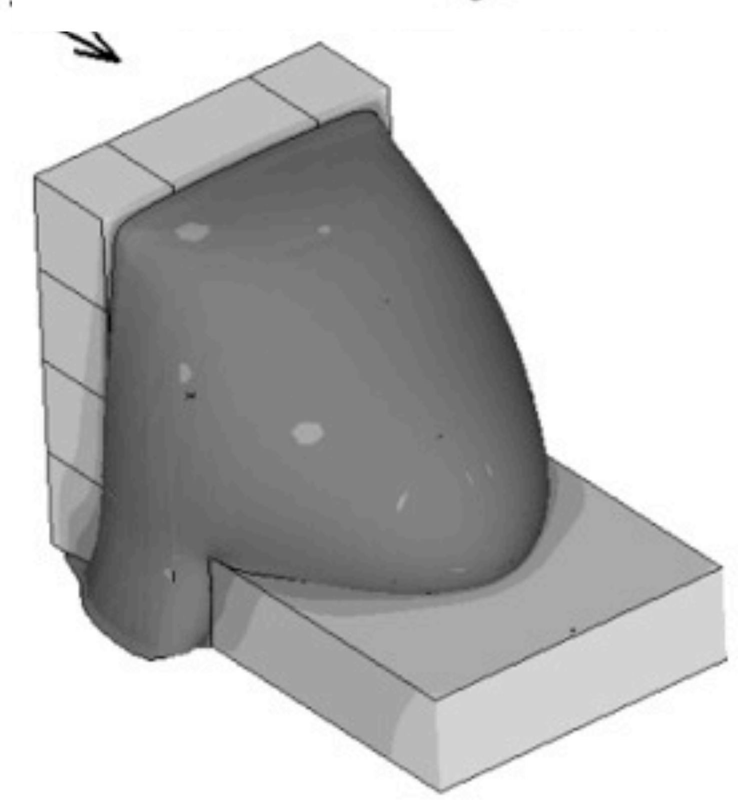
- **Safe placement of intakes with an upstream building**



- Upstream building lower or same height than emitting building

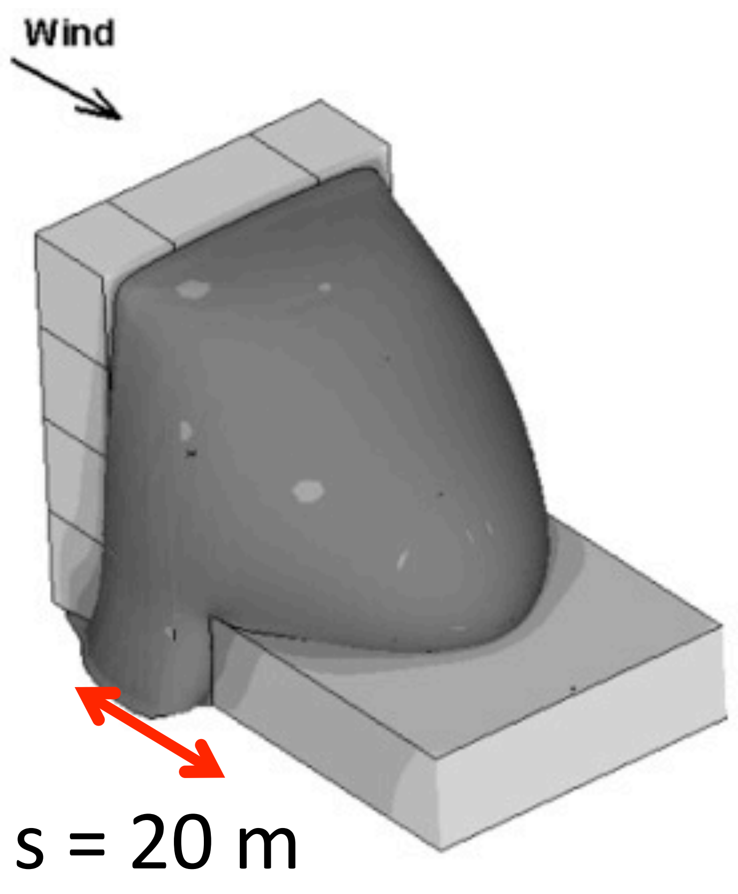


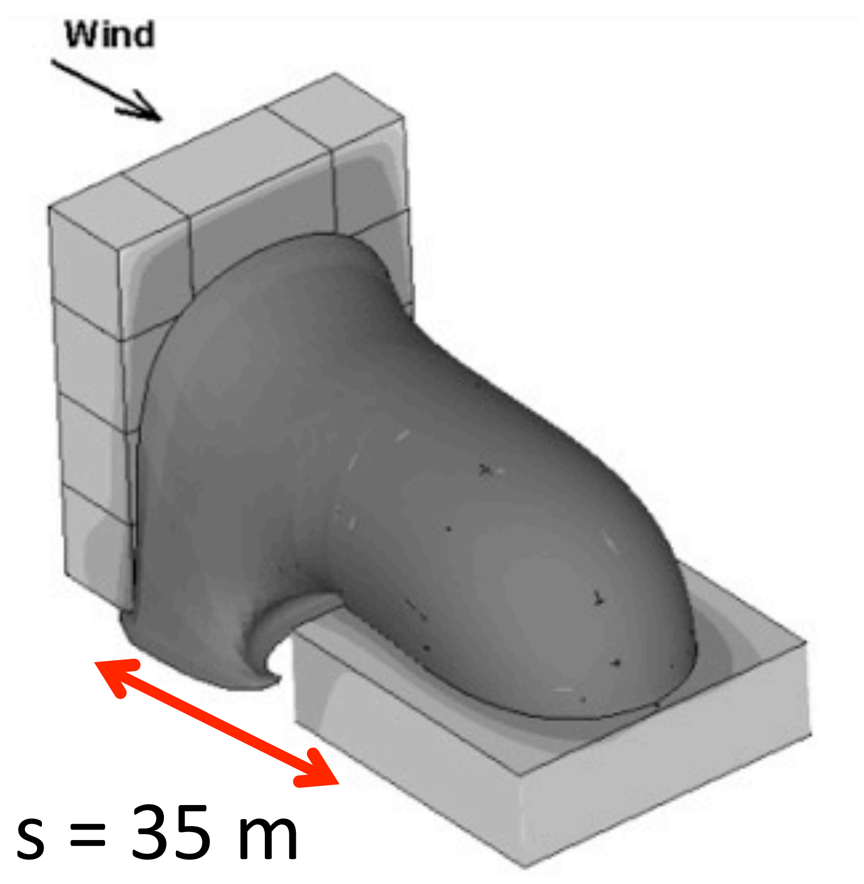
- A medium-tall building (one storey taller than emitting building) located upstream

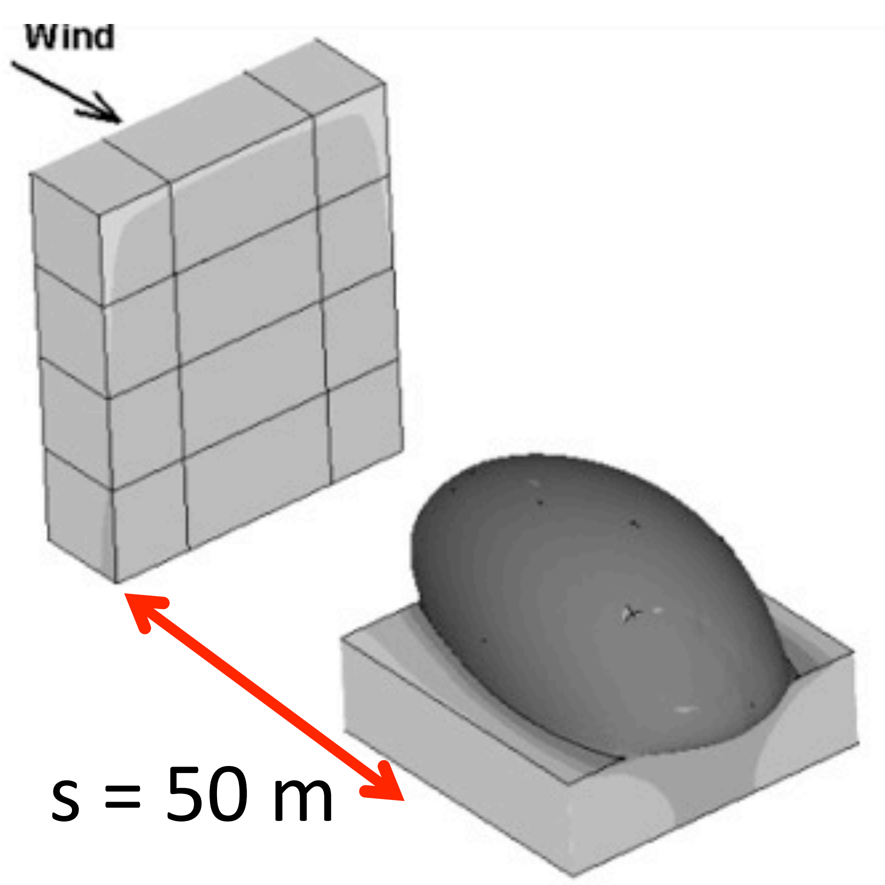


- A tall (two storeys or more taller than emitting building) upstream build

- **Safe placement of intakes for different spacing of the upstream building**



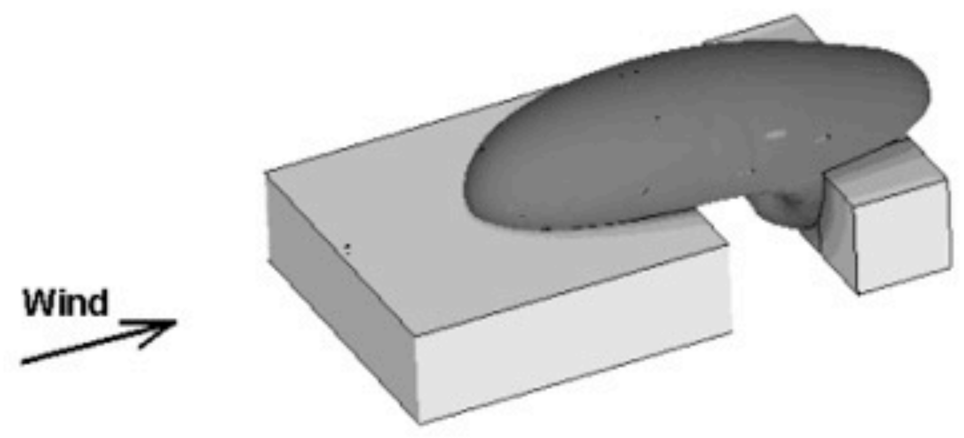




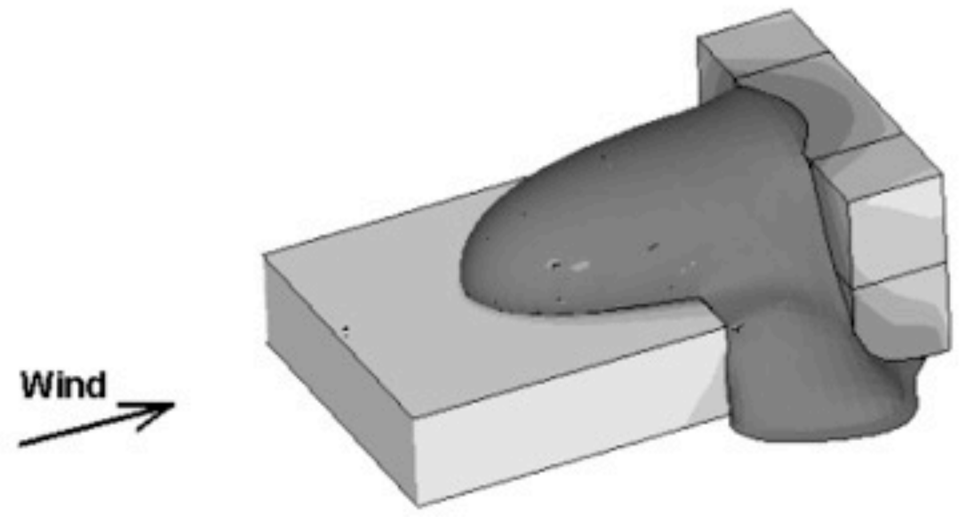
Plume is not trapped within the recirculation

- **Safe placement of intakes with a downstream building**

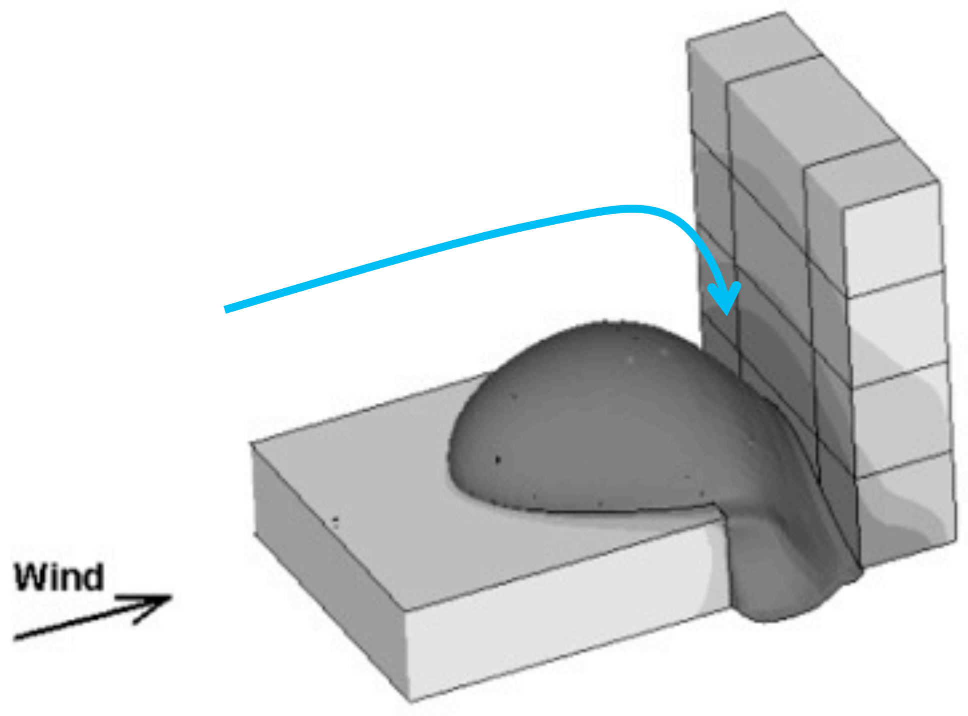
- Downstream building lower or same height than emitting building



- A medium-tall building (one storey taller than emitting building) located downstream

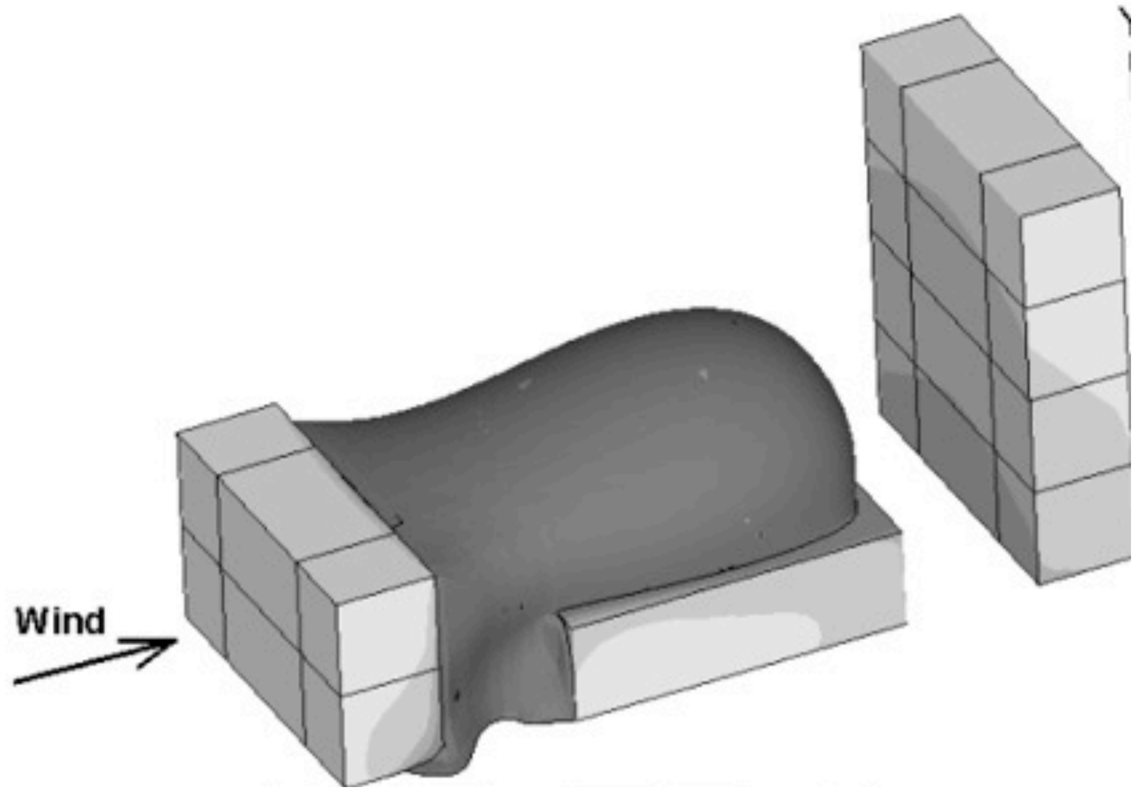


- A tall (two storeys or more taller than emitting building) downstream building

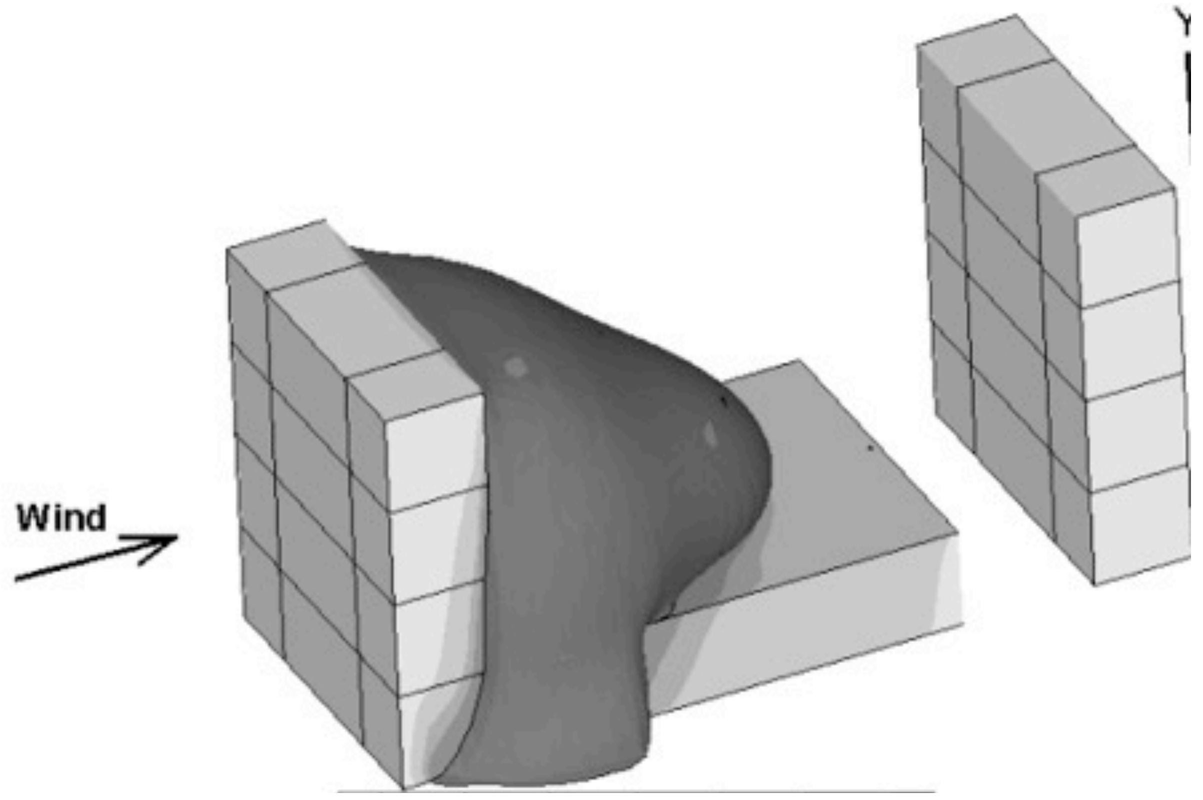


- **Safe placement of intakes for an emitting building between two buildings**

- A medium-tall building located upstream and a taller building located downstream



- An emitting building between two tall buildings



Summary and conclusions

- **Empirical models** (ASHRAE and most EPA) are questionable for the assessment of pollutant concentration in the vicinity of buildings; they may be suitable only for isolated buildings

- **Wind tunnel** test results derived with correct simulation conditions are reliable, particularly when validated with field measurements

- **Field experiments** are costly and time consuming, but indispensable for validation purposes

- **Steady** CFD comparison with wind **tunnel data** show that RANS underestimates dilution within the wake

Summary and conclusions

- A **parametric study** using steady CFD permitted to **quantify** the effect of various adjacent buildings on dispersion

- **Guidelines** to **avoid** re-ingestion of pollutants for non-isolated building configurations were given in terms of stack characteristics and safe intakes locations

Journal papers

Hajra, B., Stahopoulos, T., Bahloul, A. 2013. A wind tunnel study of the effects of adjacent buildings on near-field pollutant dispersion from rooftop emissions in an urban environment. Journal of Wind Engineering and Industrial Aerodynamics , 119, 133-145.

Chavez M., Hajra B, Stathopoulos T., Bahloul A. 2012. Assessment of Near-field Pollutant Dispersion: Effect of Upstream Buildings, Journal of Wind Engineering and Industrial Aerodynamics , vol. 104-106, 509-515

Hajra, B., Stathopoulos, T., Bahloul, A. 2011. The effect of upstream buildings on near-field pollutant dispersion in the built environment. Journal of Atmospheric Environment, 45, 4930-4940.

Chavez M., Hajra B., Stathopoulos T., Bahloul, A. 2011. Near-field pollutant dispersion in the built environment by CFD and wind tunnel simulations, Journal of Wind Engineering and Industrial Aerodynamics , vol. 99, 330-339.

Hajra B, Stathopoulos T, Bahloul A., 2010. Assessment of pollutant dispersion from rooftop stacks: ASHRAE, ADMS and Wind Tunnel simulation. Journal of Building and Environment, 45, 2768-2777.

PhD thesis

Hajra, B., 2012. A Comprehensive Experimental Study of the Effects of Adjacent Buildings on Near Field Pollutant Dispersion. PhD Thesis at Concordia University, Montreal, Canada.

Chavez, M., 2014. A Comprehensive Numerical Study of the Effects of Adjacent Buildings on Near-Field Pollutant Dispersion. PhD Thesis at Concordia University, Montreal, Canada.

Conference papers

Chavez M., Stathopoulos T., Bahloul A. (2014) "CFD flow and dispersion modelling: unsteady RANS, DES and LES performance comparison", Proceedings of The 14th International Conference on Wind Engineering, Hamburg, Germany.

Chavez M., Stathopoulos T., Bahloul A. (2012) "CFD modelling of flow and dispersion in the built environment: different RANS models and a first attempt to use URANS", Proceeding of Seventh International Colloquium on Bluff Body Aerodynamics and Applications, Shangai, China.

Chavez M., Hajra B., Stathopoulos T., Bahloul A. (2011) "Assessment of Near-field Pollutant Dispersion: Effect of Upstream Buildings", Proceedings of The 13th International Conference on Wind Engineering, Amsterdam, Netherlands.

Stathopoulos T., Chavez M., Bahloul A. (2011). " CFD approaches to predicting dilution from exhaust stacks in urban areas" in Sustainability knows no borders : ASHRAE Annual Conference, Montréal, Canada).

Bahloul A. , Chavez M., Hajra B., Stathopoulos T. (2011). " Near field pollutant dispersion around buildings in the urban environment " in Indoor Air : 12th International Conference on Indoor Air Quality and Climate, Austin, USA.

Chavez M., Hajra B., Stathopoulos T., Bahloul A. (2010). "Near-field pollutant dispersion in the built environment by CFD and wind tunnel simulations", in Proceedings of the Fifth International Symposium on computational Wind Engineering / CWE2010, (5th : May 23-27, 2010 : Chapel Hill, North Carolina, USA).

Chavez M., Hajra B., Stathopoulos T., Bahloul A. (2010). "Near-field pollutant dispersion in the built environment by CFD and wind tunnel simulations", Proceedings of The Fifth International Symposium on Computational wind Engineering , North Carolina, USA.

Conference papers cont'd

Bahloul A., Hajra B, Stathopoulos T., (2010). "Dispersion of effluents from building roof stacks: Comparison of various models, CFD and wind tunnel results", Proceedings of the 10th REHVA world congress (CLIMA 2010) , Antalya, Turkey.

Bahloul A., Stathopoulos T., Hajra B., (2009) "Estimation of Pollutant Concentrations from Building roof stacks: Comparison of various models", Proceedings of the 9th International Conference on Healthy Buildings , Syracuse, New York, USA.

Bahloul A., Stathopoulos T., Hajra B. (2009) "Étude comparative des modèles de dispersion des émissions polluantes des cheminées des immeubles", Le croisement des générations : échanger connaissances et expériences : Congrès de l'Association québécoise pour l'hygiène, la santé et la sécurité du travail/ AQHSST , Montreal, Canada.

Bahloul A. , Stathopoulos T., Hajra B., Gupta A. (2008). " A Comparative study of ADMS, ASHRAE and Wind Tunnel Simulation for Rooftop Dispersion of Airborne Pollutants" in Indoor Air 2008 : Proceedings of the 11th International Conference on Indoor Air Quality and Climate, Copenhagen, Denmark.

Technical reports

Bahloul, A. Stathopoulos, T., Chavez, M., Hajra, B. (2014). A Wind Tunnel Study of the Effect of Adjacent Buildings on Near-Field Pollutant Dispersion from Rooftop Emissions. Report 0099-7590(a), IRSST.

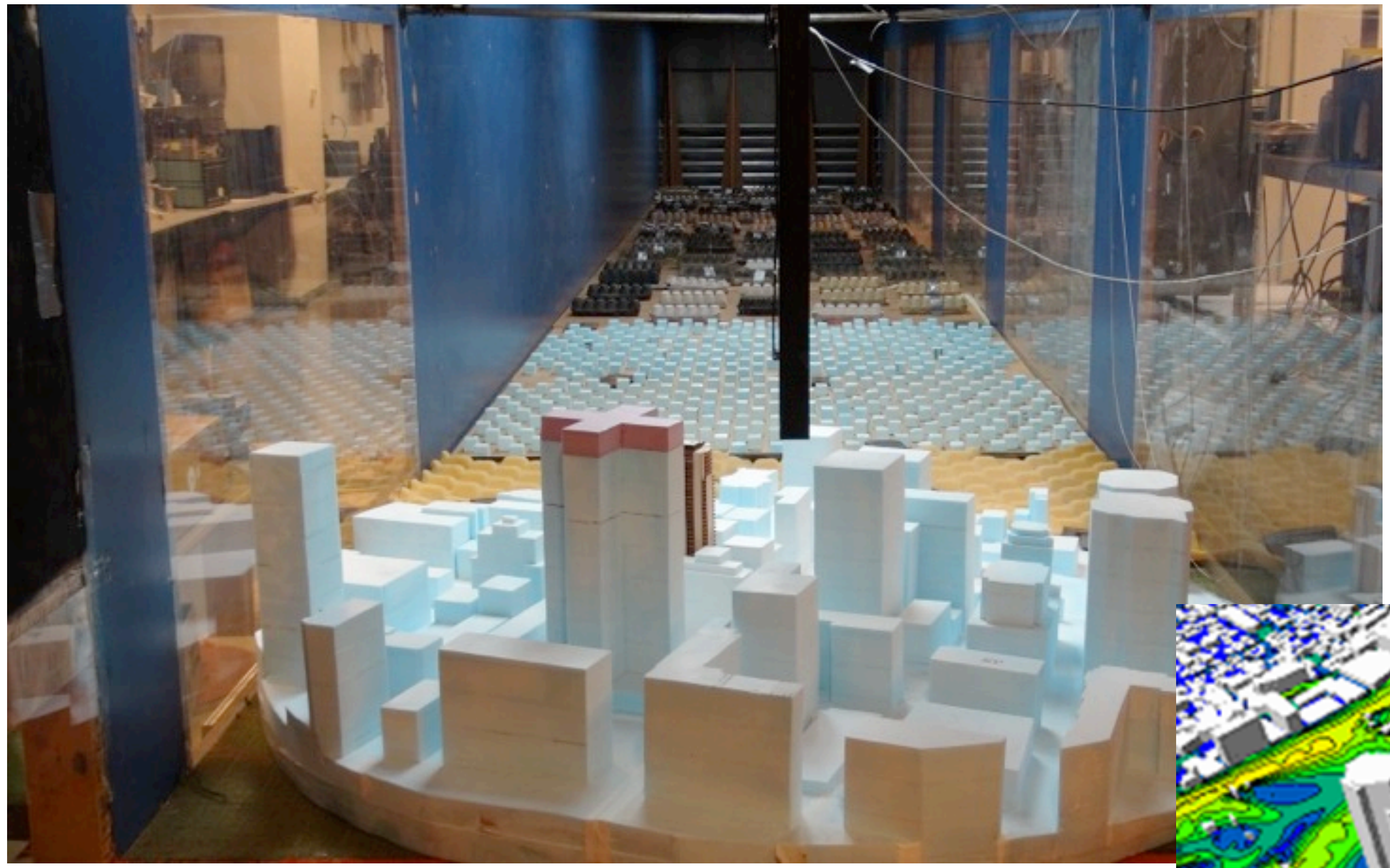
Bahloul, A. Stathopoulos, T., Chavez, M., Hajra, B. (2014). The impact of adjacent buildings on the dispersion of emissions from buildings: A numerical (CFD) and experimental approach in a wind tunnel. Report 0099-7590(b), IRSST.

Bahloul, A. Stathopoulos, T., M., Hajra, B. (2008). Analytical evaluation of the dispersion of polluting emissions from building stacks. Report 0099-6120, IRSST.

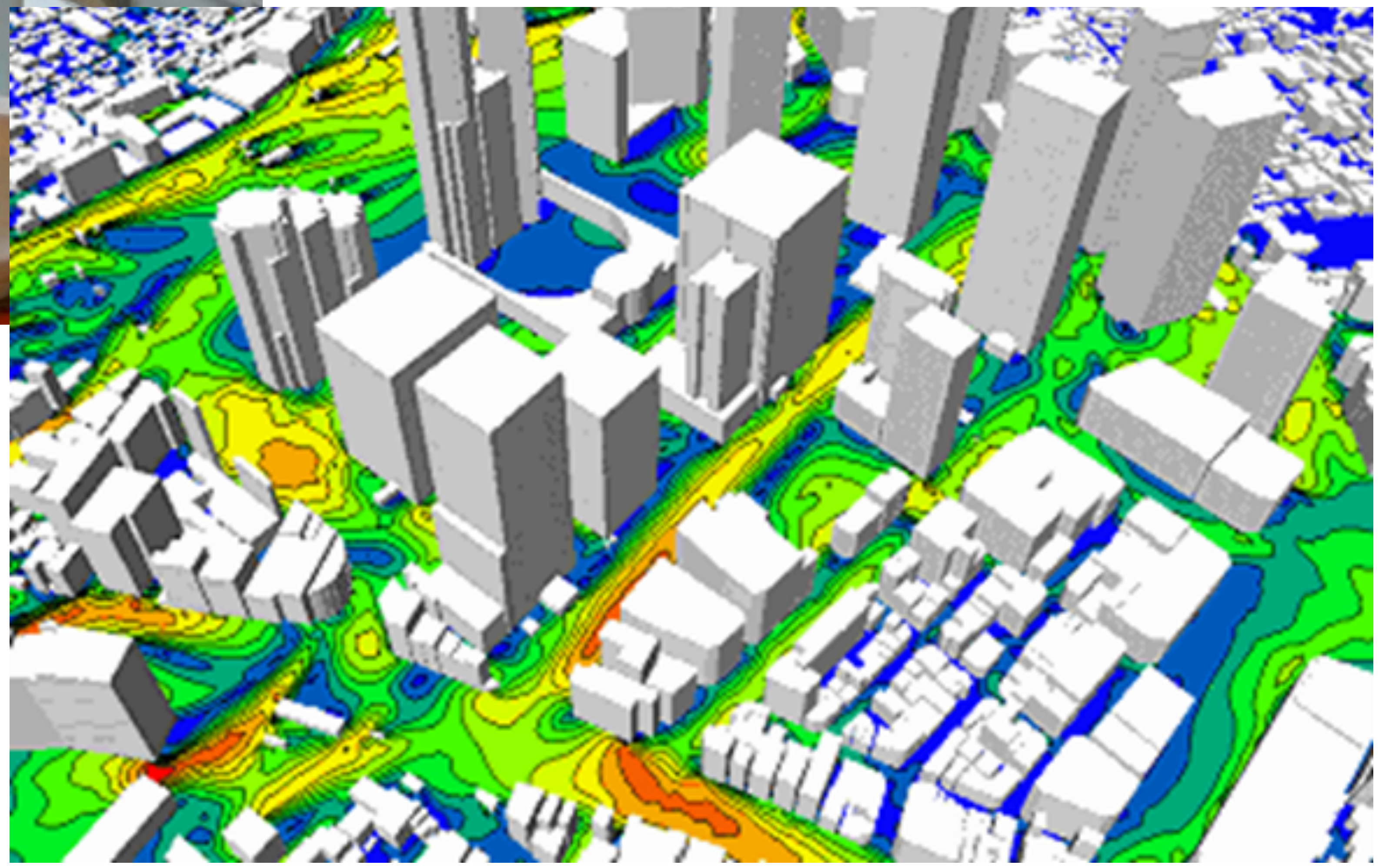
Future research

1. Complex configurations with realistic geometries

Pollutant aerodynamics in **actual neighbourhoods** or critical part of cities



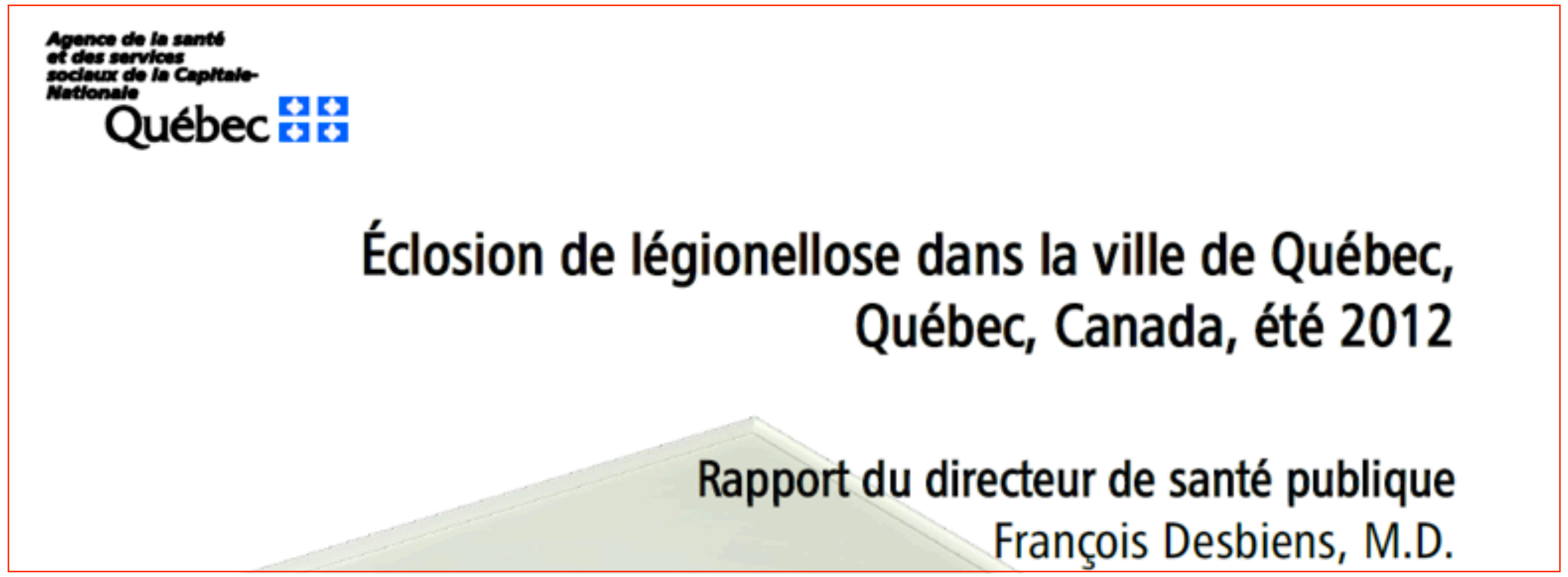
Wind tunnel at Concordia University



www.aij.or.jp/jpn/publish/cfdguide/index_e.htm

Future research

2. Particle tracking using biphasic approach (e.g. dispersion of droplets)


Agence de la santé et des services sociaux de la Capitale-Nationale

Québec

Éclosion de légionellose dans la ville de Québec, Québec, Canada, été 2012

Rapport du directeur de santé publique

François Desbiens, M.D.

In summer 2012, at least **180 people were infected and 13 killed** in what has been the deadliest outbreak of **Legionnaire's** disease in Canada, in 25 years (Desbiens, 2012)