BUILDING DESIGN AND ENGINEERING APPROACHES
TO AIRBORNE INFECTION CONTROL
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Natural Ventilation for Infection Control in Health Care Settings:

Theory

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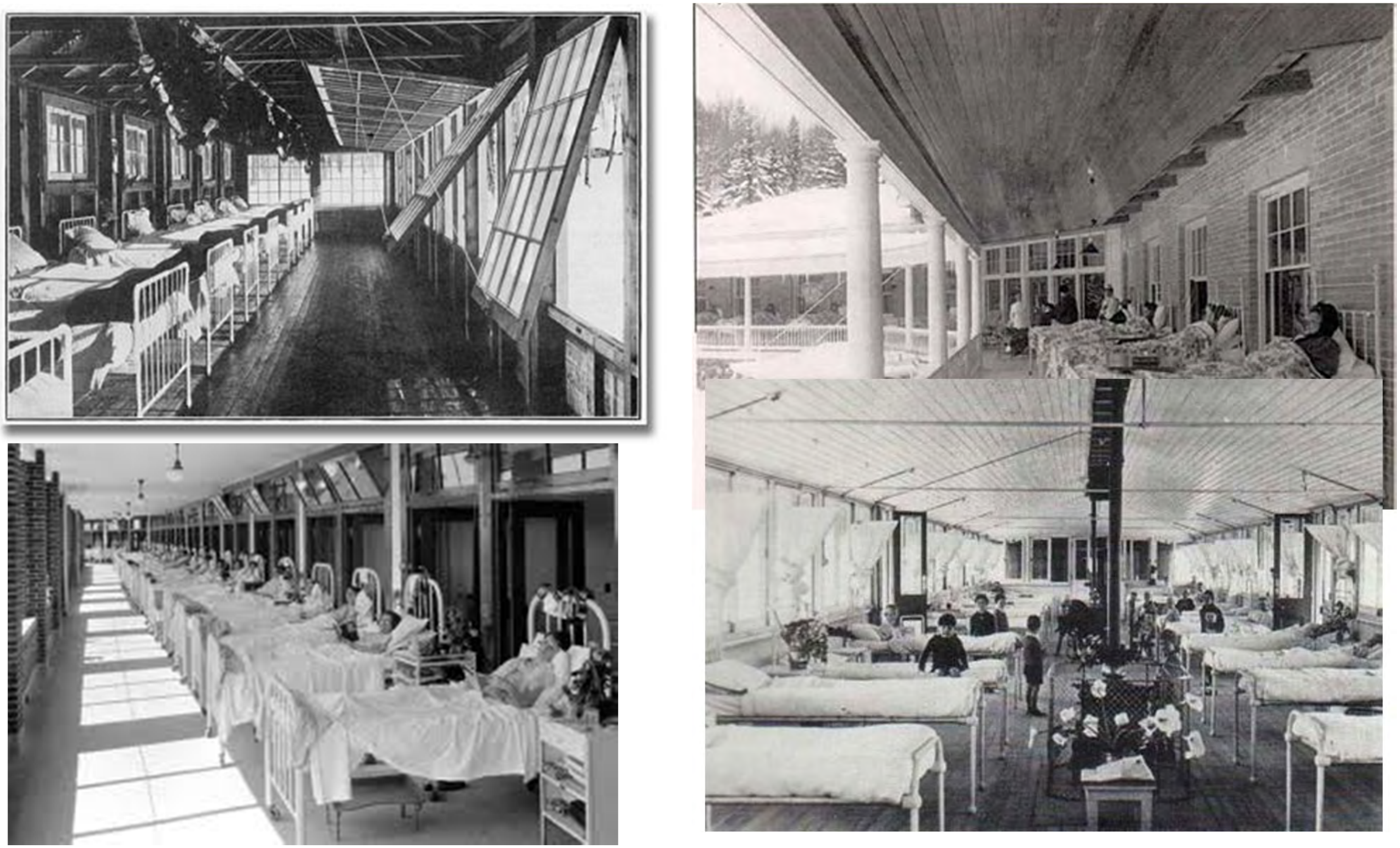
Natural Ventilation for Infection Control in Health Care Settings



Principles of ventilation and infection control (source: Nielsen, 2009)

Ventilation systems	Room air distribution system
Mechanical ventilation	Mixing ventilation
	Vertical ventilation
	Displacement ventilation
	Personalized ventilation
Natural ventilation	Mixing ventilation
	Displacement ventilation

Keys to Natural Ventilation for Infection Control in Healthcare Settings

- Air change rate
  - Ensure adequate average flow and minimum flow specifications are met
  - Approximate measurements under all weather and building operational conditions
  - Measurements , Verification
- Air distribution:
  - Flow direction:
    - Away from infected - verify
    - Ensure and verify consistency under all ventilation regimes
  - Flow of infectious agents directly out of building
  - Avoid flow toward other patients, especially susceptibles
- Management plan

Natural Ventilation: Theory Definitions

Purpose of ventilation: What is ventilation? Natural (Passive), Mechanical

Types of natural ventilation (Driving forces):

- Buoyancy (stack effect; thermal)
- Pressure driven (wind driven; differential pressure)

Applications

- Supply of outdoor air – removal of pollutants (e.g., infectious agents)
- Convective cooling
- Physiological cooling

Issues

- Weather-dependence: wind, temperature, humidity
- Thermal conditions, comfort/health
- Outdoor air quality/pollution
- Immune compromised patients
- Building configuration (plan, section)
- Management of openings
- Measurement and verification

What is ventilation?

Definitions covering ventilation and the flow of air into and out of a space include:

- **Purpose provided (intentional) ventilation:** Ventilation is the process by which ‘clean’ air (normally outdoor air) is intentionally provided to a space and stale air is removed. This may be accomplished by natural or mechanical means.
- **Air infiltration and exfiltration:** In addition to intentional ventilation, air inevitably enters a building by the process of ‘air infiltration’. This is the uncontrolled flow of air into a space through adventitious or unintentional gaps and cracks in the building envelope. The corresponding loss of air from an enclosed space is termed ‘exfiltration’.

Three elements of ventilation

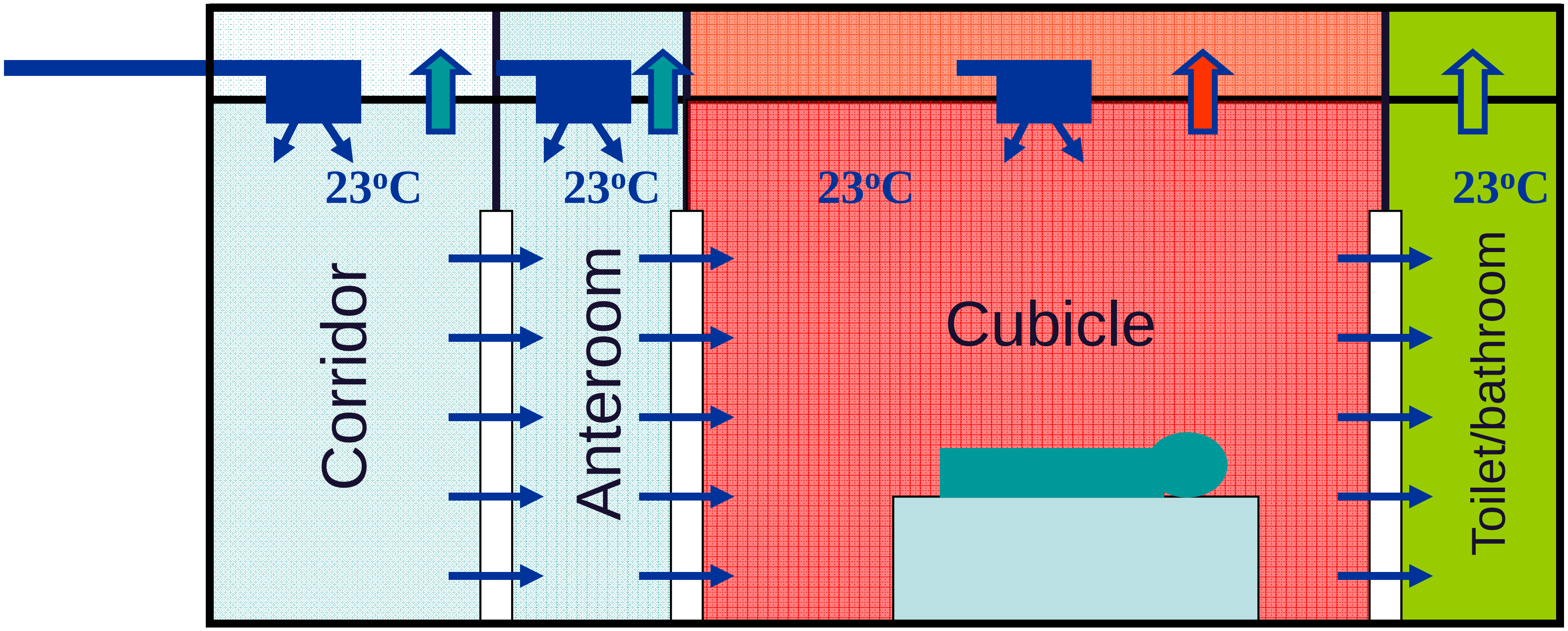
(source: Yuguo Li, personal communication)

Element	Description	Requirements/ Guideline	Design or Operation	Buildings	Cities
Primary	External air flow rate	Minimum ACH Minimum L/s-p	Fan, duct, openings or streets	ASHRAE 62 1-12 ACH	?
Secondary	Overall flow direction between zones	Flow clean to “dirty” spaces	Pressure control through airflow imbalance Prevailing winds	Positive/ negative 2.5-15 Pa Isolation/ smoke control	Dirty industry downwind Buy upwind
Tertiary	Air distribution within a space	Ventilation effectiveness, no short-circuiting	Use of CFD Smoke visualization	Ventilation strategies	Urban planning

Isolation room ventilation

Goal: ~12 ach or 160 l/s-p (?)

Suspended ceilings



The purpose is Not to have a 2.5 Pa negative pressure, but no air leaks to the corridor!

Recommended negative pressure is – 10 Pa with wind, -2.5 Pa without wind

Courtesy of Yuguo Li

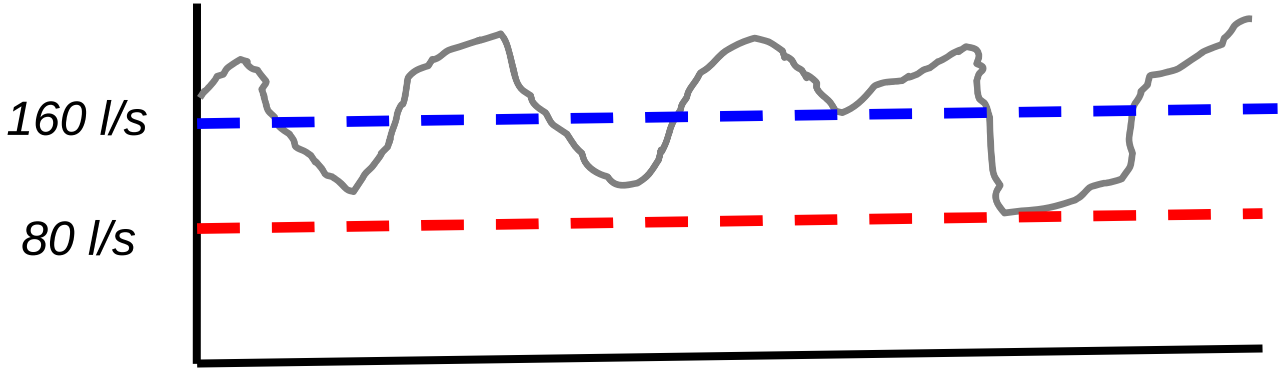
NatVent for healthcare

- Intake/reception areas
  - Administrative measures, Triage potential cases
- General areas
  - Ensure at least 2 air changes per hour (ACH)
- Patient rooms
  - Ensure at least 2 air changes per hour (ACH), one-pass
- Isolation rooms/wards
  - Ensure 6 ACH, design and operate for 12 ACH, 160 L/s-p
  - Vent to outside; Ideally a free-standing structure or unconnected directly to other areas
- Procedure rooms
  - Always ventilated to outside, Free-standing if possible

WHO 2009 NatVent Guideline – key ideas

Courtesy of Yuguo Li

- **For natural ventilation, a minimum hourly averaged ventilation rate of 160 L/s/patient for airborne precaution rooms (with a minimum of 80 L/s/patient).**



- When natural ventilation alone cannot satisfy the requirements, mechanically assisted natural ventilation system should be used.

- **Overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.**

HB2009 Seven conjectures

(source: Yuguo Li, HB2009, Syracuse, Sept 2009)

1. *Ventilation can reduce infection risk in a room.*
2. ***Airflow can transport infection risk from one location to another****.*
3. *Airflow can reduce infection risk at source.*
4. ***Infection risk quickly reduces as moving away from the source in fully mixing ventilated rooms.***
5. ***There exists a certain ventilation rate value below which the overall infection risk is more significant than that at no ventilation****.*
6. *There exists a certain ventilation rate* ***above which*** *the reduction of overall infection risk is insignificant as compared to other control methods.*
7. *There exists a certain ventilation rate above which the overall* ***infection risk is absent****.*

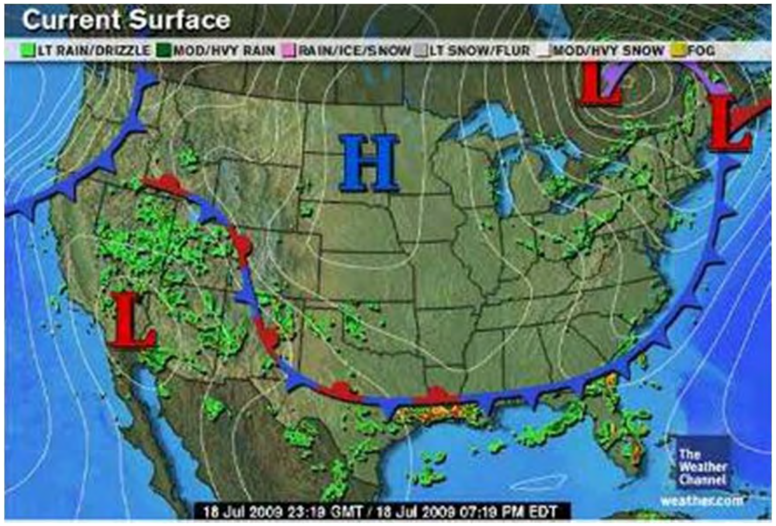
Types of natural ventilation

Stack effect (buoyancy)

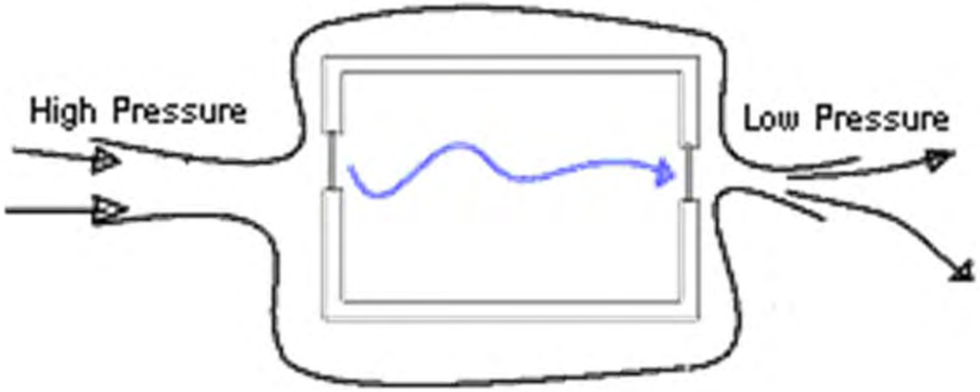
- Warm air is lighter (less dense) than cold air
- Warm air rises, cold air falls
- Intentional chimneys (stacks) can create larger differences between top and bottom, increasing the air flow rate

Wind-driven (pressure)

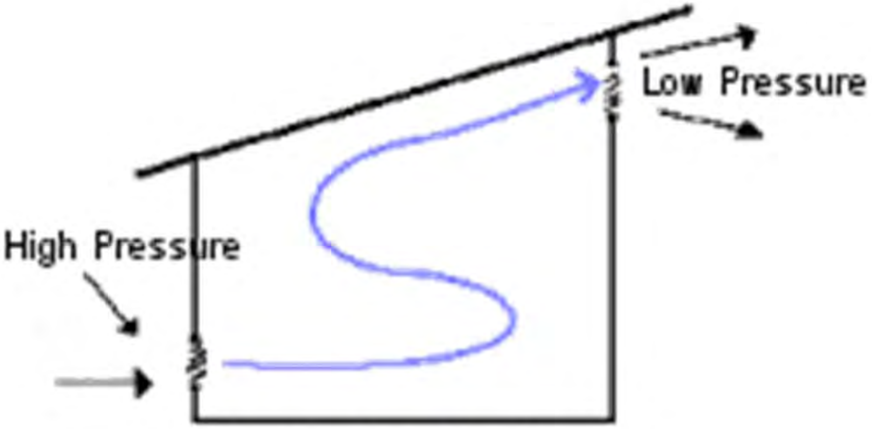
- Pressure differences result in air mass movement
- “Packets” of air flow from higher to lower air pressure regimes



Wind driven vs. Stack effect



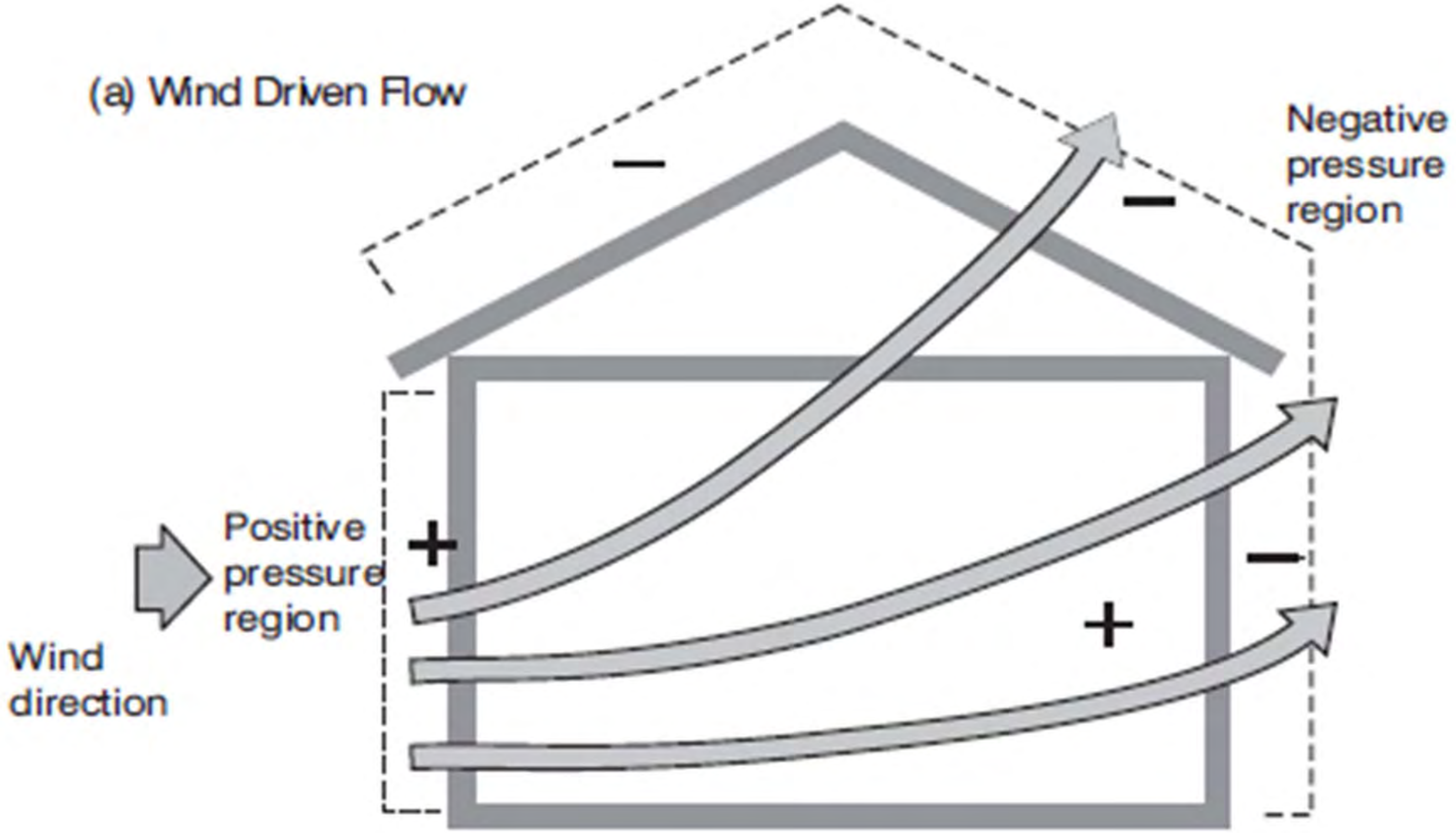
Cross Ventilation



Stack Ventilation

Natural Driving Mechanisms – <u>Pressure</u>: Wind-driven air flow

Natural Driving Mechanisms – Pressure: Wind-driven air flow



Wind Pressure as a function of angle of incidence on wall

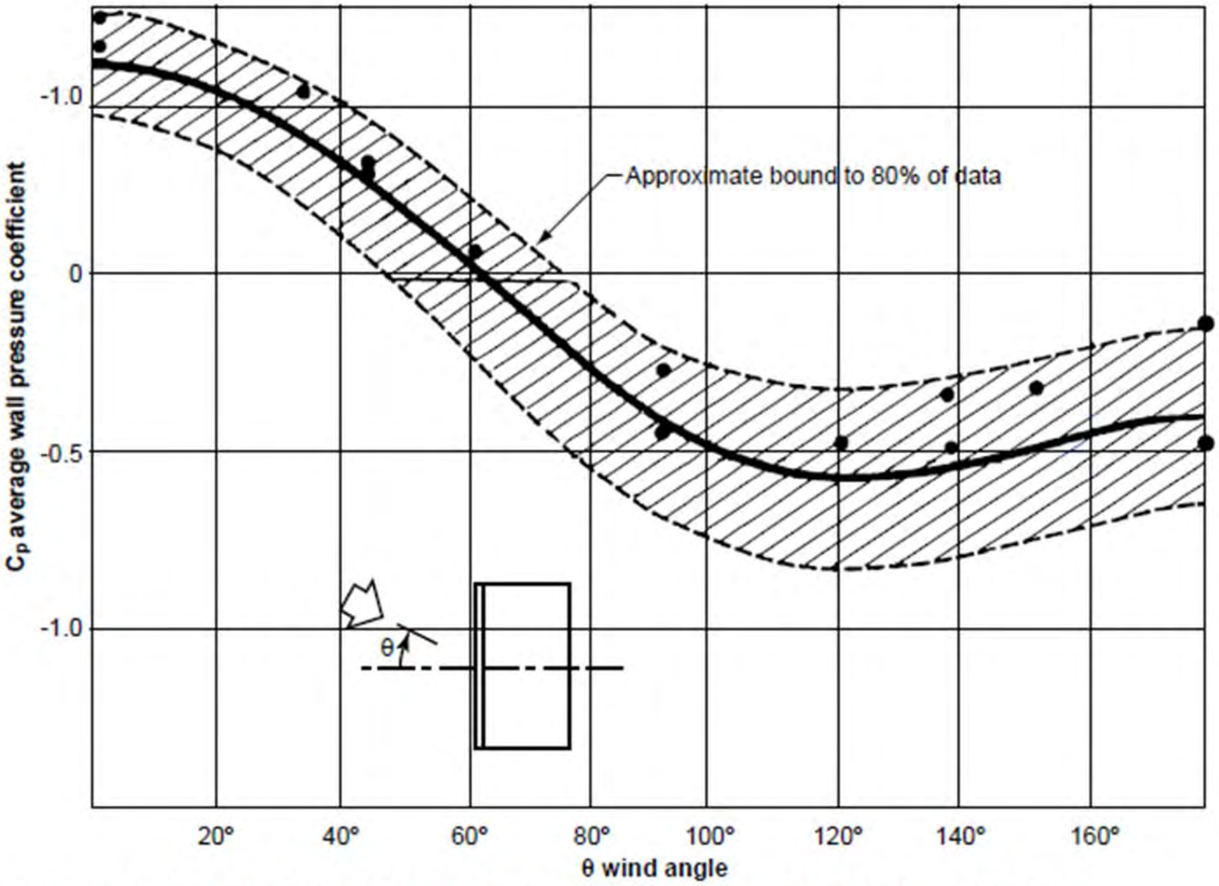
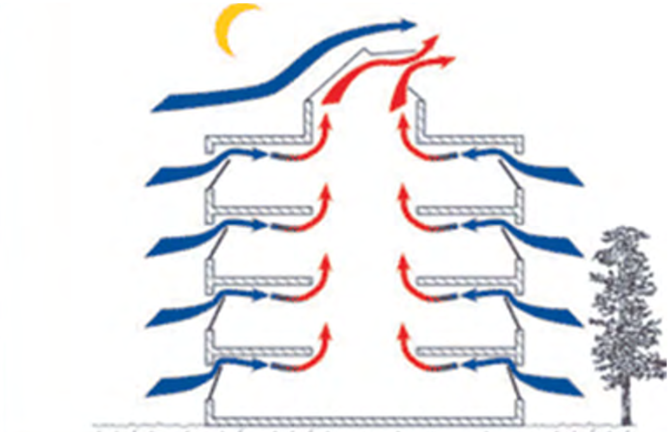
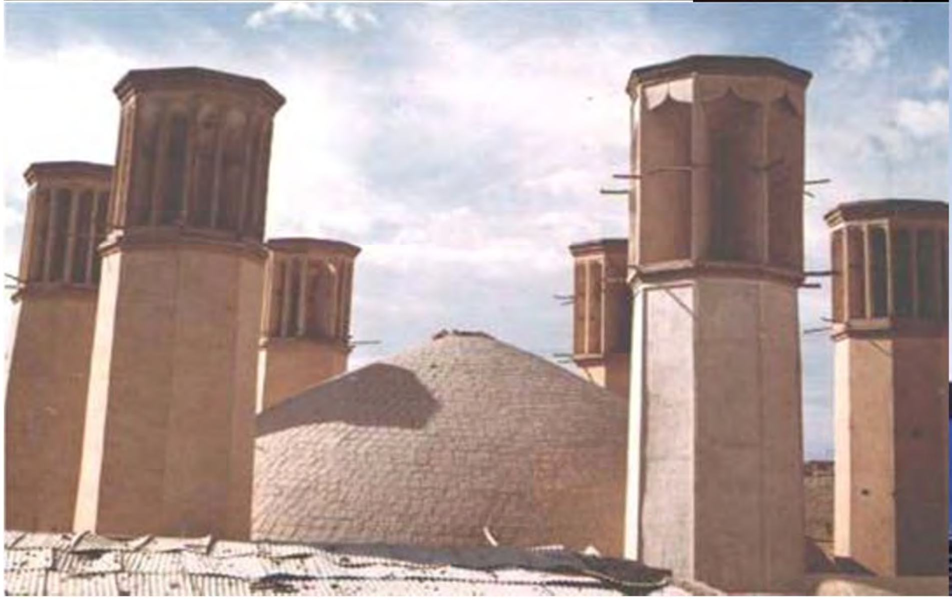


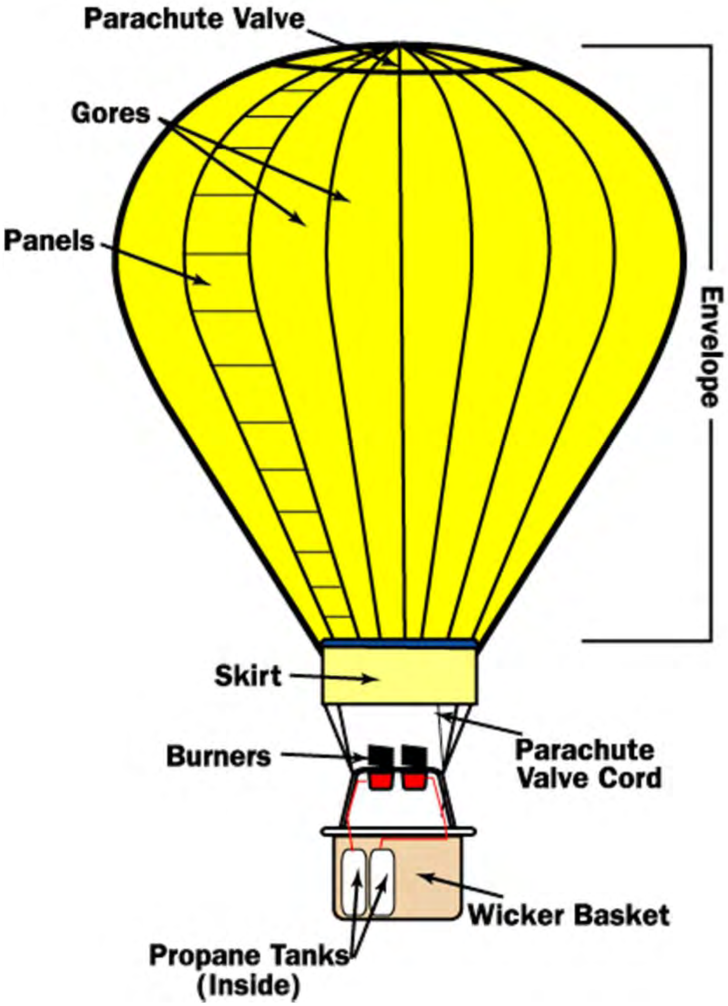
Figure 3. Typical Wall-averaged Wind pressure Coefficients for Low-rise Buildings
(Swami & Chandra, 1987)

Natural driving mechanisms -- <u>Buoyancy</u>
Stack effect

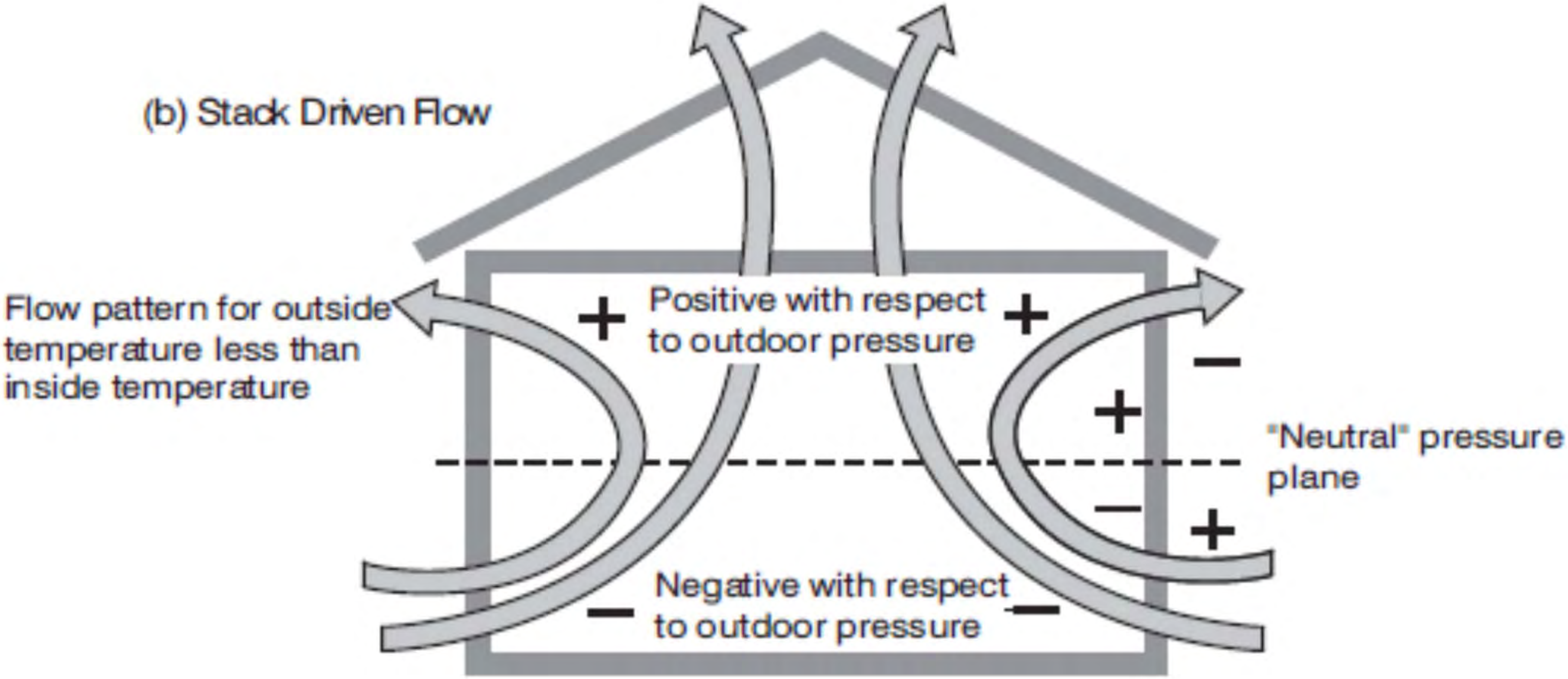




Hot air = buoyancy



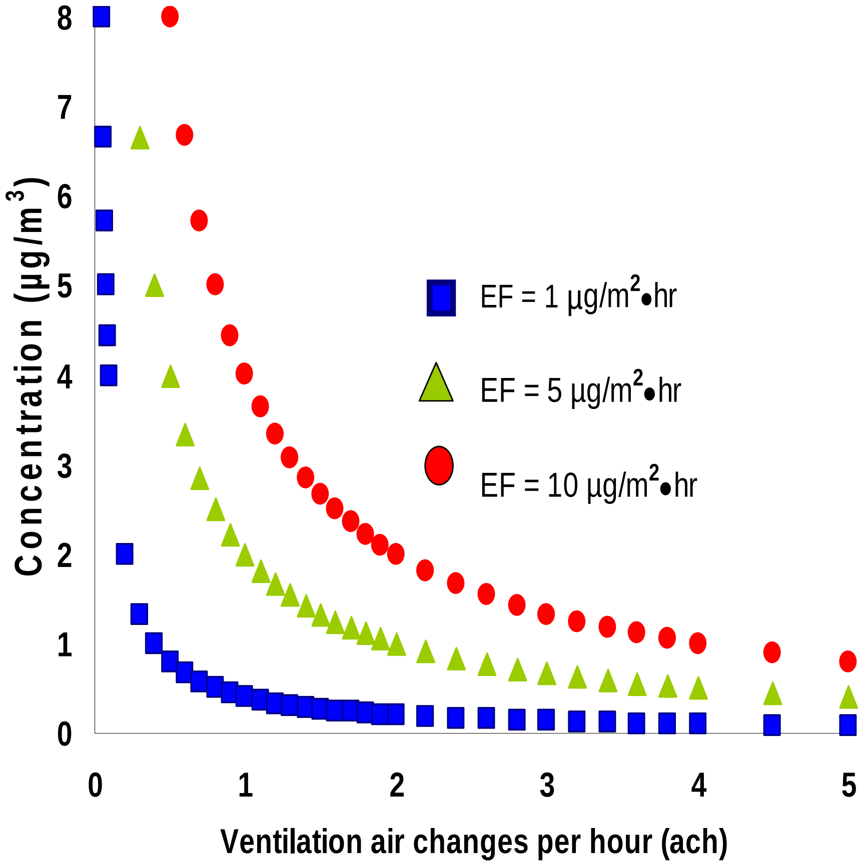
Natural driving mechanisms -- Buoyancy Stack effect

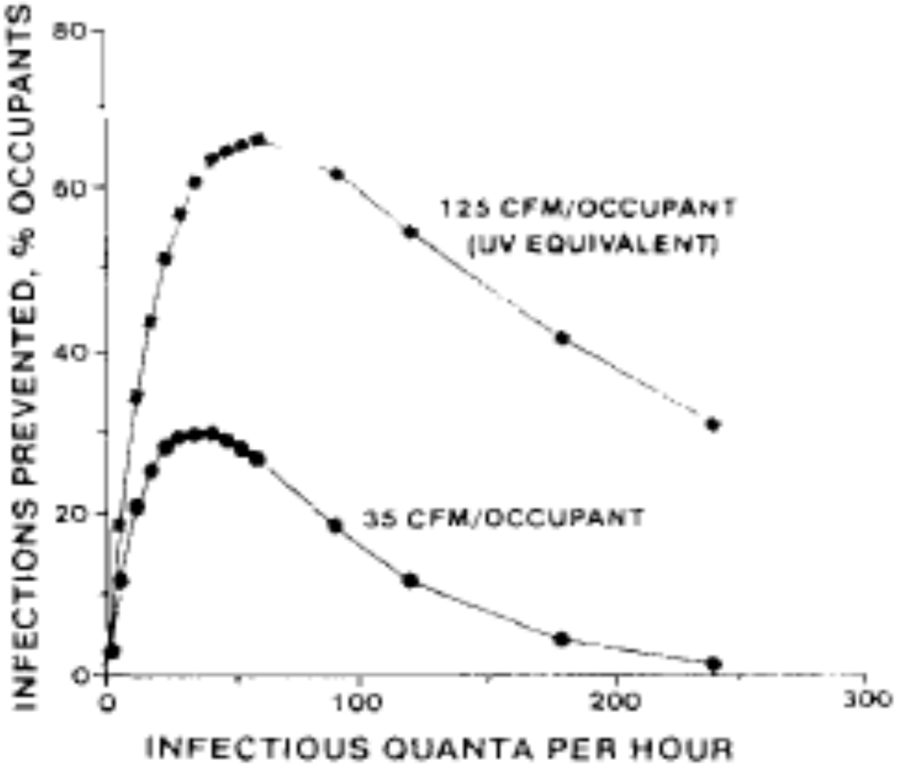


Applications: Supply of outdoor air

- Supply of outdoor air … removal of pollutants
  - In air changes per hour (AER or h^{-1}) or liters per second per person (l/s-p)
  - What happens if you have a very tall space?
- Pollutant concentration = source strength/removal rate
  - Removal rate includes dilution/exhaust plus deposition on surfaces or chemical interactions/transformation
  - Chemicals: source strength expressed as mg of pollutant / m^2-h or mg/h
  - Dilution/exhaust rate expressed as dilution ventilation (air changes per hour, ach, AER, h^{-1})
  - Removal rate ("Deposition velocity": $gcm^{-1}s^{-1}$)

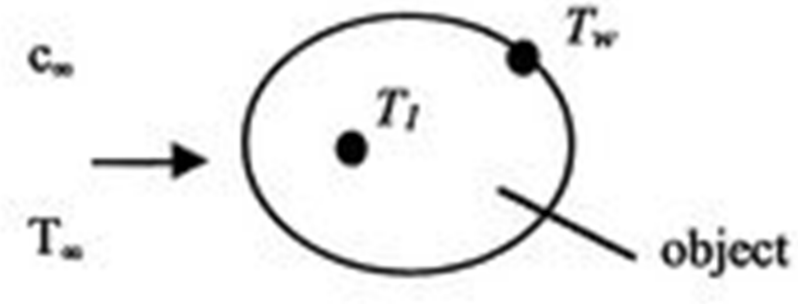
Pollutant concentration as a function of outdoor air exchange rate





Applications: Convective cooling

- **convection** /con·vec·tion/ (kon-vek´shun) the act of conveying or transmission, specifically transmission of heat in a liquid or gas by bulk movement of heated particles to a cooler area.
- Air flow around a person can be caused by the higher temperature of the person's skin relative to the air around it, giving rise to an air flow known as the "thermal plume," air movement predominantly in an upward direction.
- Or, it may be caused by forced air movement, as from a fan or wind.



Temperature variation in an object cooled by a flowing liquid

Convective cooling

Physiological cooling

Physiological cooling

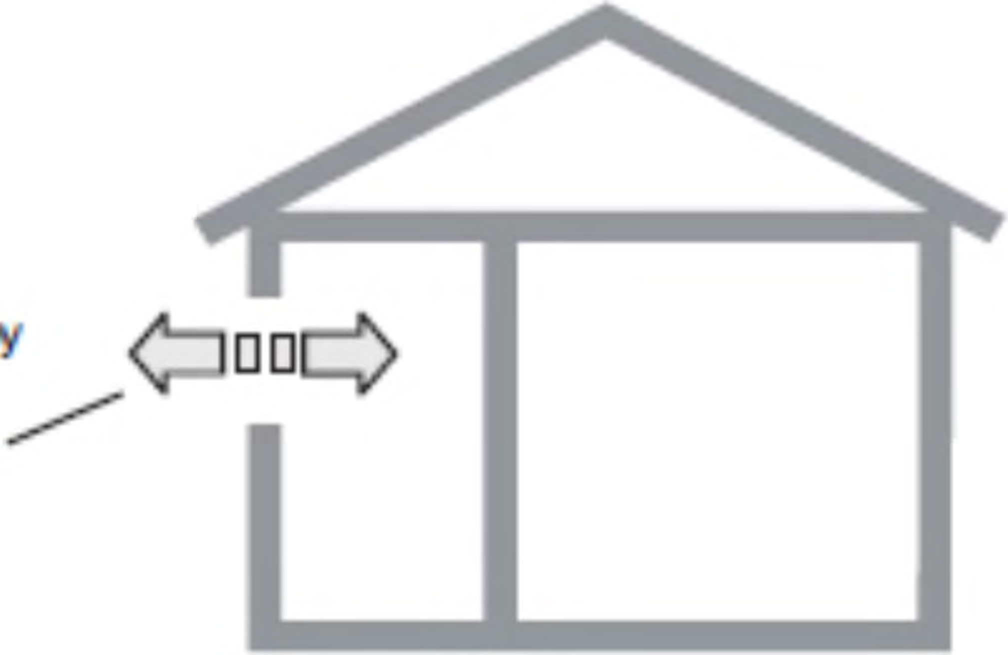
Applications: Physiological cooling

“Ectothermic cooling”

- Vaporization:
  - Getting wet in a river, lake or sea.
- Convection:
  - Entering a cold water or air current.
  - Building a structure that allows natural or generated air flow for cooling.
- Conduction:
  - Lie on cold ground.
  - Staying wet in a river, lake or sea.
  - Covering in cool mud.
- Radiation:
  - Find shade.
  - Enter a cave or hole in the ground shaped for radiating heat (Black box effect).
  - Expand folds of skin.
  - Expose skin surfaces.

Convective + Physiological cooling

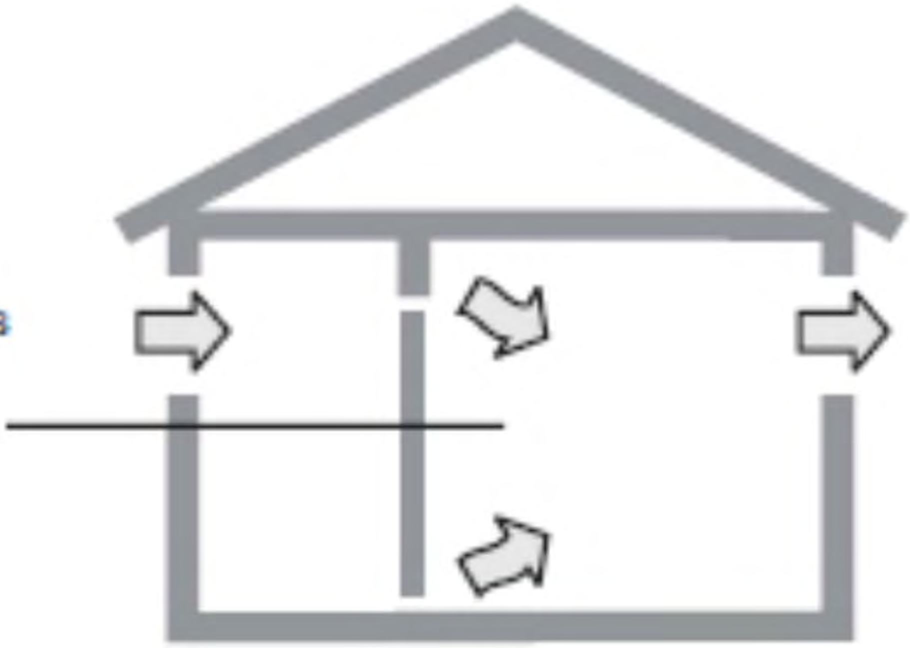
Single-sided ventilation



Air exchange is driven by turbulent fluctuations. Ventilation rates can be very small unless openings are large

(a) Single sided - sealed enclosure

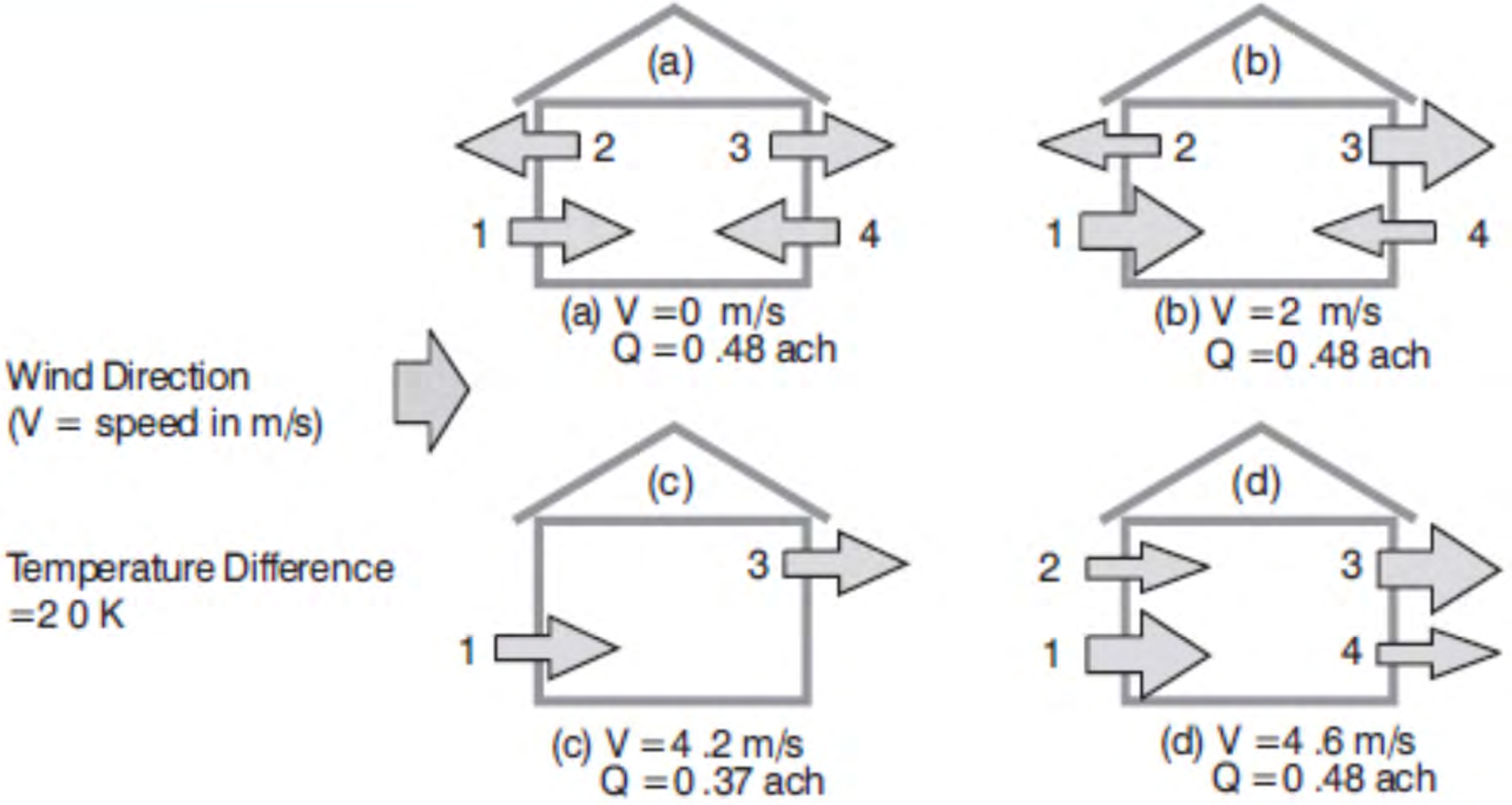
Cross-flow ventilation



'Cross flow' ventilation takes place through internal leakage paths or internal doors

(a) 'Single sided' unsealed enclosure

Influence of wind and temperature (stack effect) on ventilation and air flow pattern

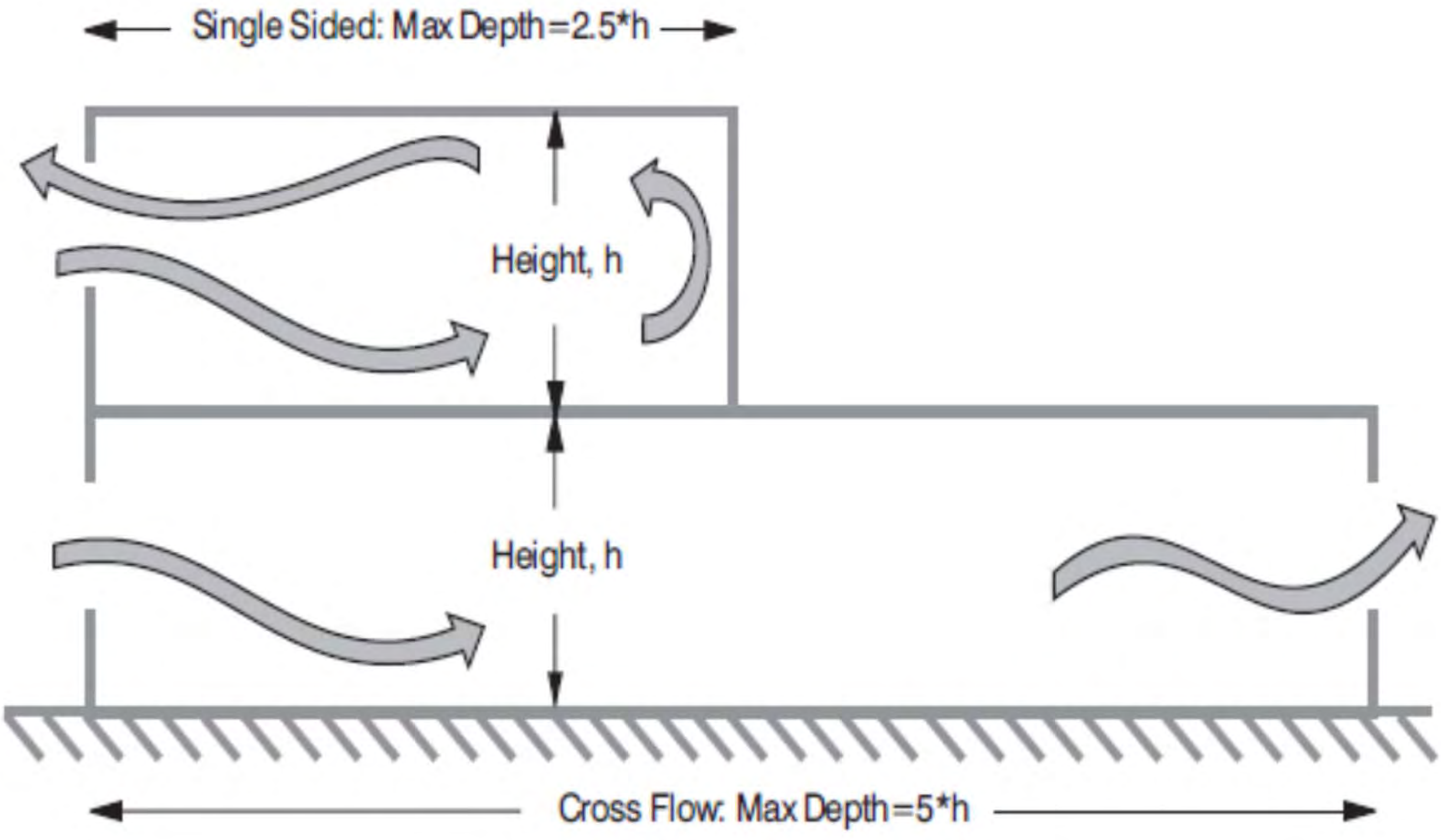


Influence of wind and temperature (stack effect) on ventilation rate and air flow pattern

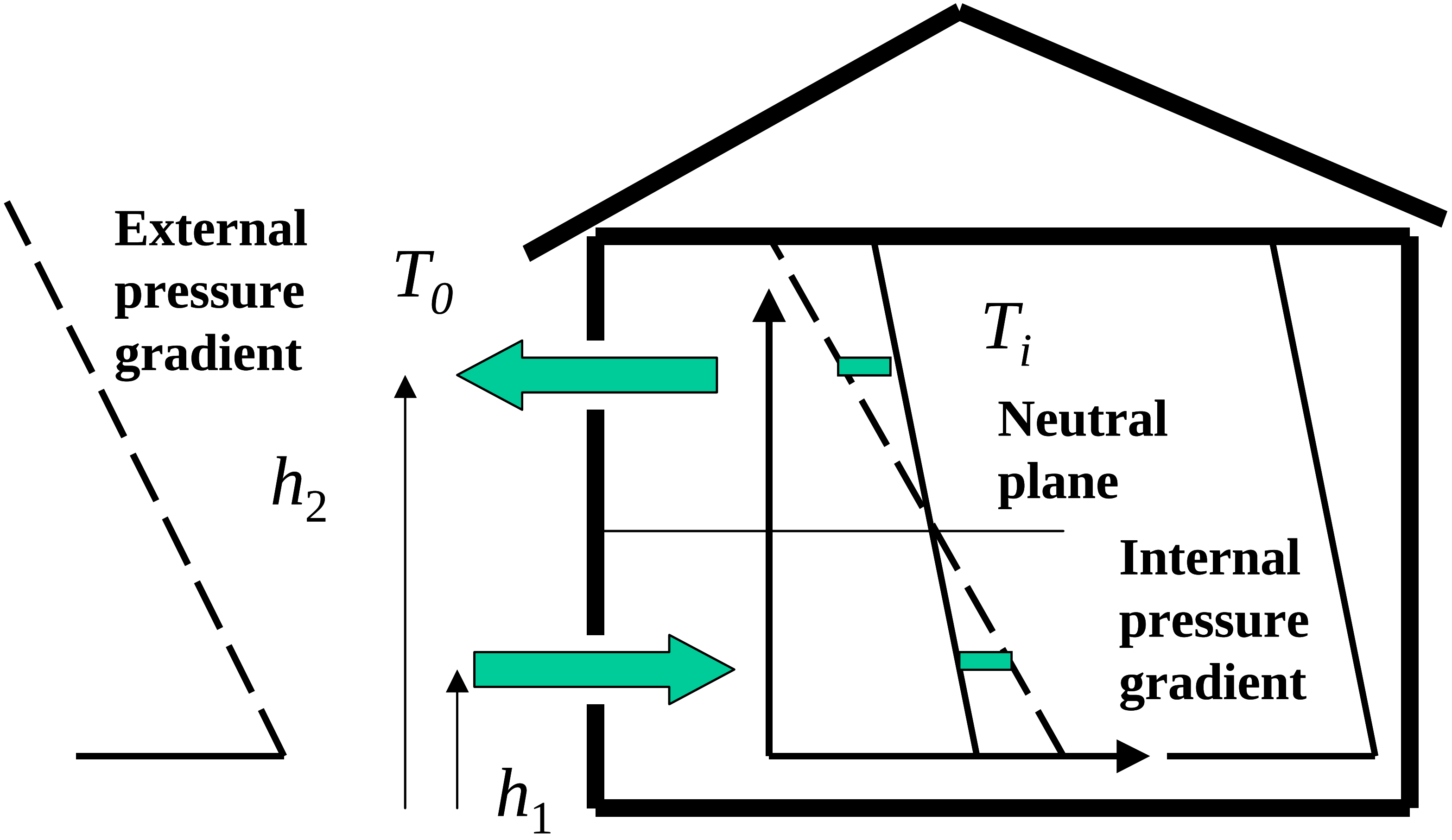
(source: AIVC, 2009)

Single-sided vs. Cross flow ventilation

(source: AIVC, 2009)

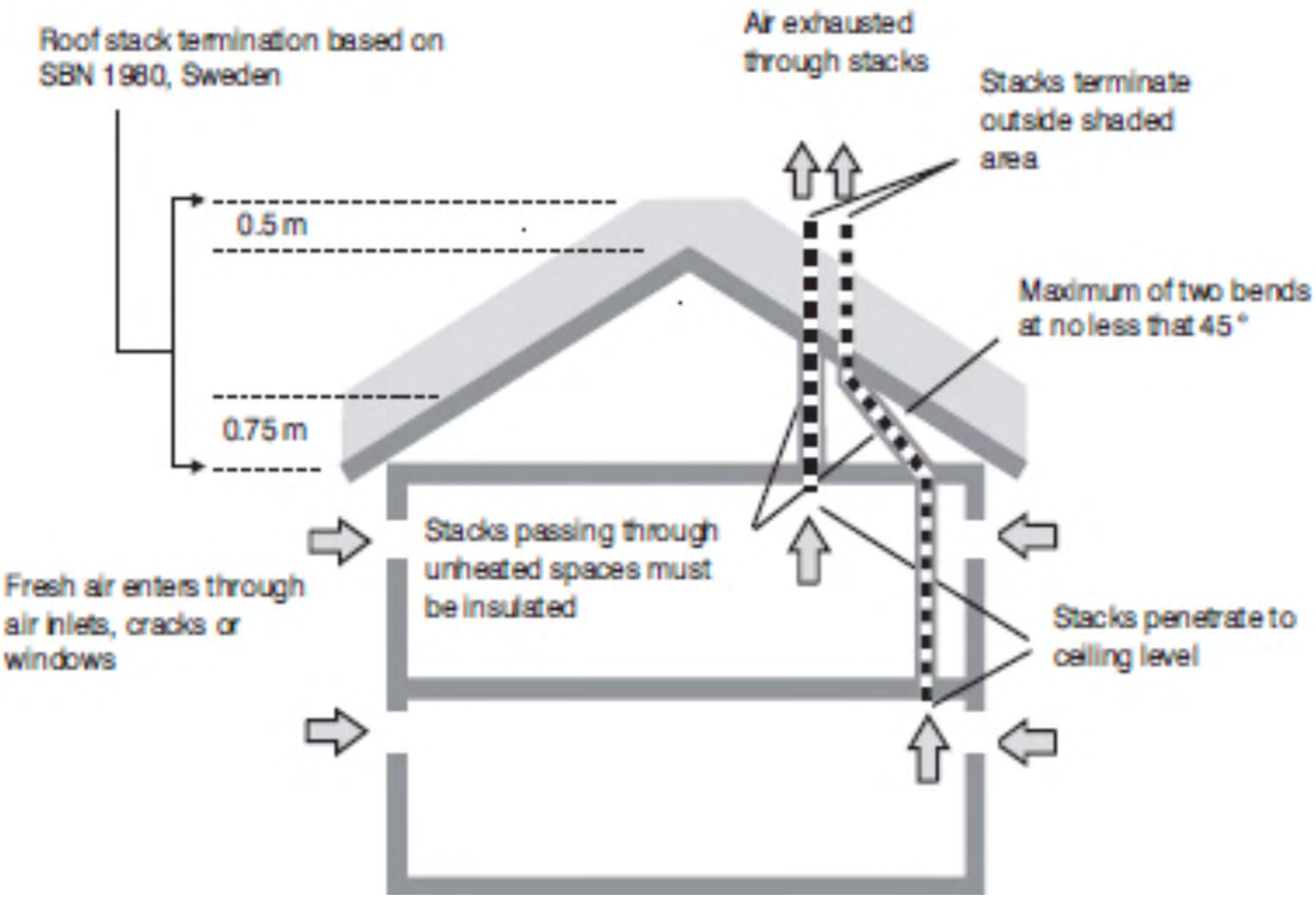


Concept of the neutral level



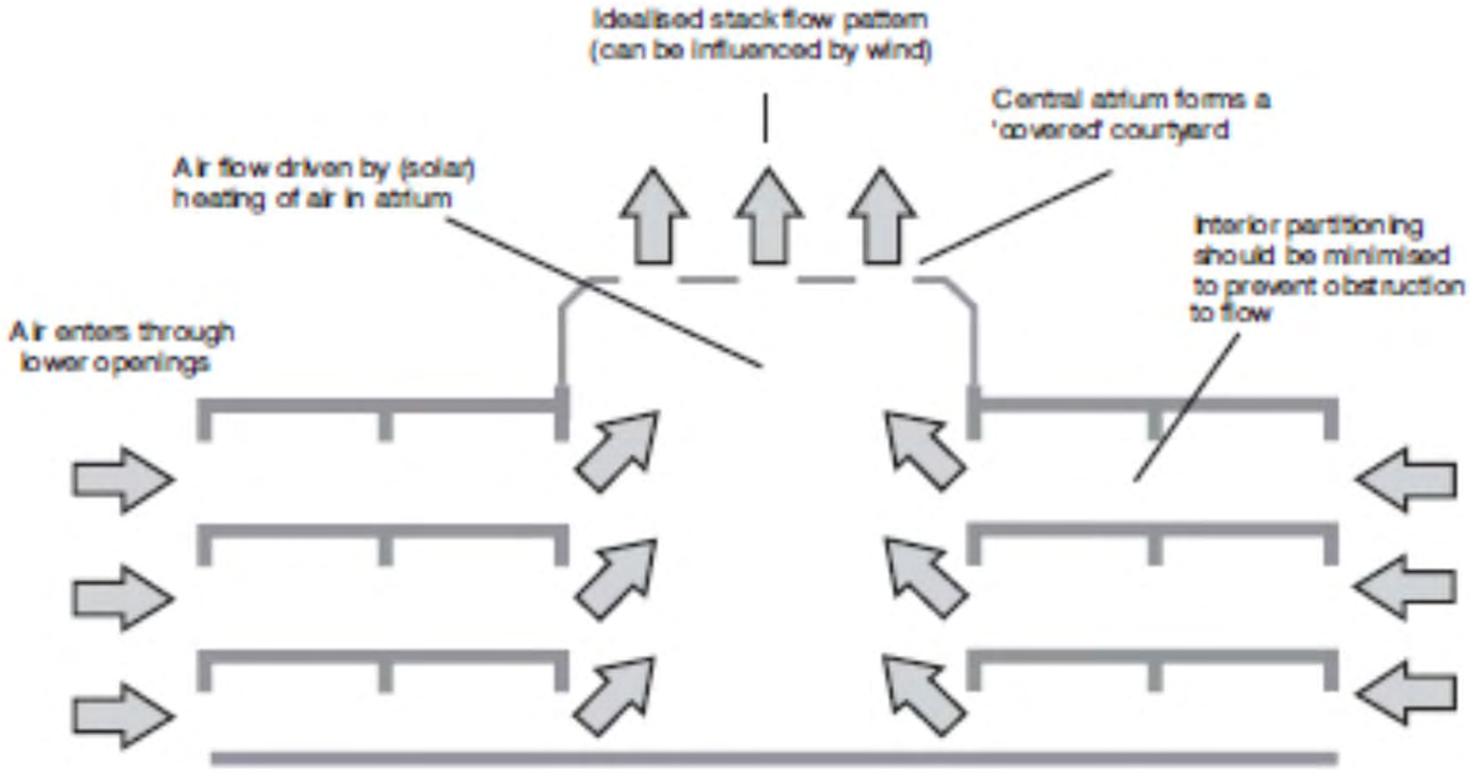
Stack ventilation (dwellings)

(source: AIVC 2009)

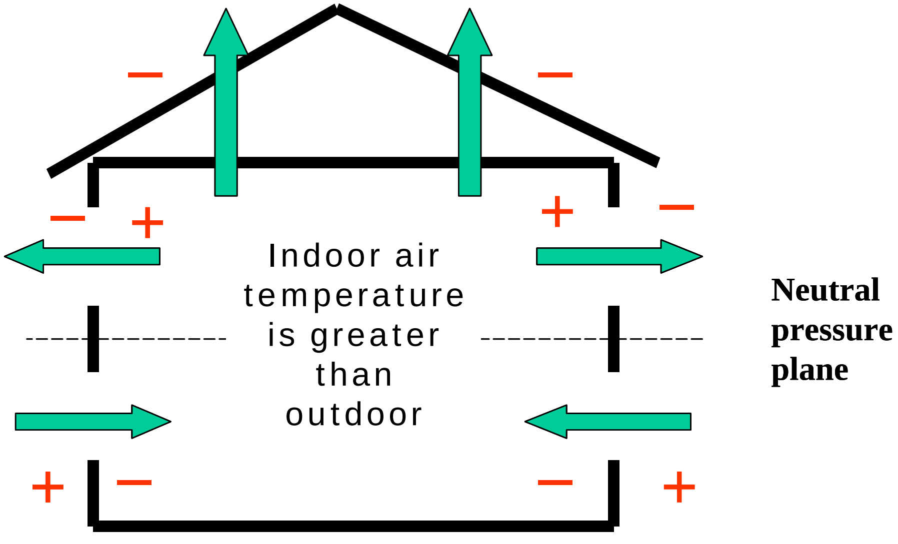


Stack ventilation (atrium)

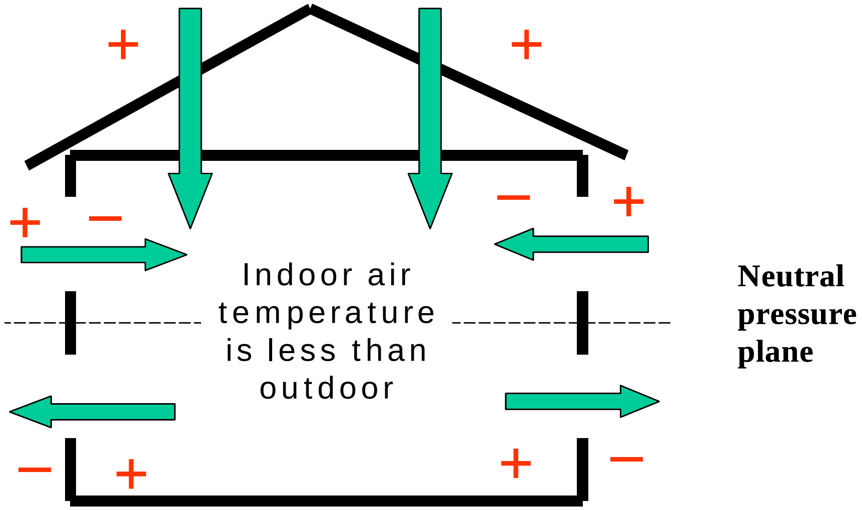
(source: AIVC 2009)



Stack driving flows in a building



(A)



(B)

Indoor air warmer than outdoor

Indoor air cooler than outdoor

Natural ventilation in buildings

By Francis Allard, Mat Santamouris, Servando Alvarez, European Commission.

Directorate-General for Energy, ALTENER Program

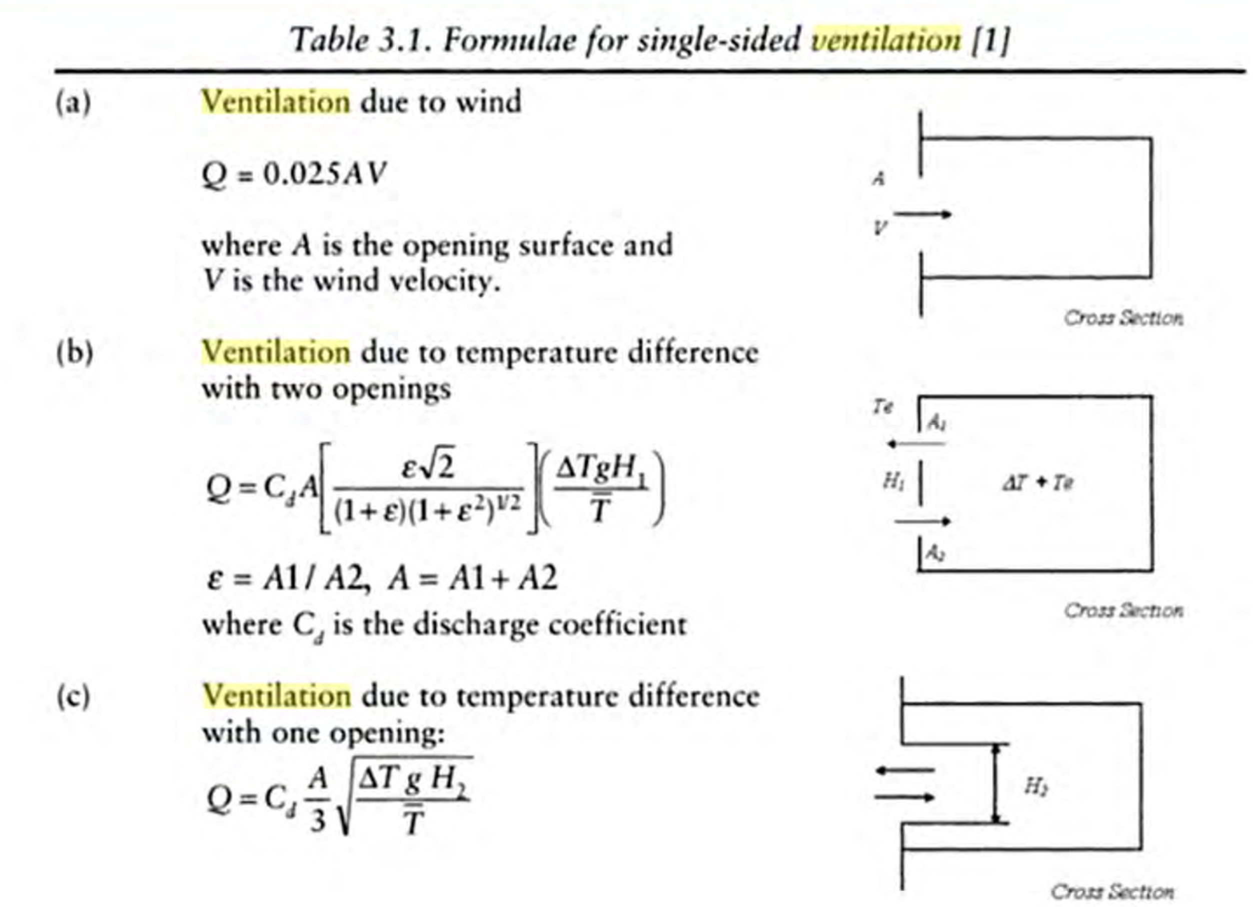


Table 3.1. Formulae for single-sided ventilation [1]

(a) Ventilation due to wind

$Q = 0.025AV$

where A is the opening surface and
V is the wind velocity.

(b) Ventilation due to temperature difference with two openings

$$Q = C_d A \left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\varepsilon^2)^{1/2}}\right]\left(\frac{\Delta T g H_1}{\bar{T}}\right)$$

$\varepsilon = A1/A2, \quad A = A1 + A2$

where C_d is the discharge coefficient

(c) Ventilation due to temperature difference with one opening:

$$Q = C_d \frac{A}{3}\sqrt{\frac{\Delta T\, g\, H_2}{\bar{T}}}$$

http://books.google.com/books?hl=en&lr=&id=1tdQMyhPA2gC&oi=fnd&pg=PR9&dq=Natural+ventilation+theory&ots=mFzmfd4mct&sig=XA3zksH_OBkkS8tILbxmwJqbWyo

Natural ventilation in buildings

Francis Allard, Mat Santamouris, Servando Alvarez, European Commission. Directorate-General for Energy, ALTENER Program

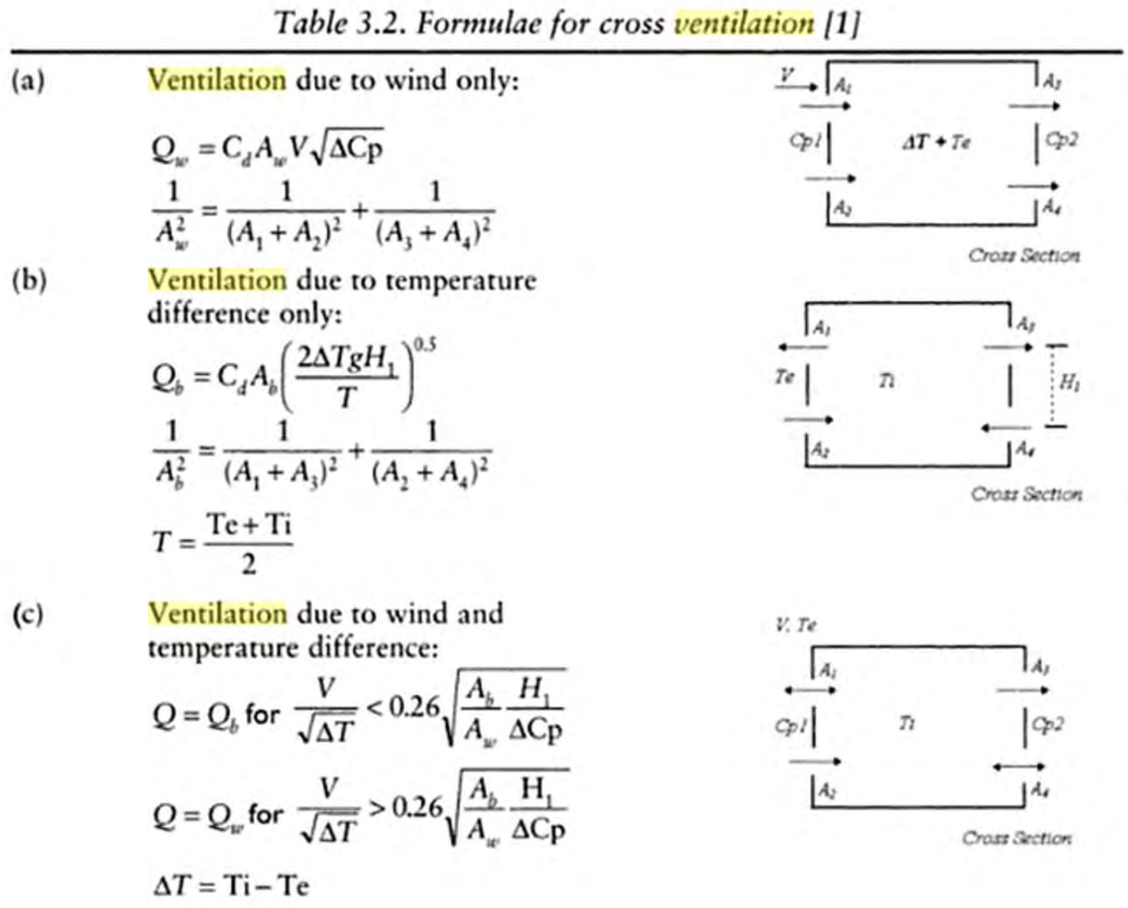


Table 3.2. Formulae for cross ventilation [1]

(a) Ventilation due to wind only:

$$Q_w = C_d A_w V \sqrt{\Delta Cp}$$

$$\frac{1}{A_w^2} = \frac{1}{(A_1 + A_2)^2} + \frac{1}{(A_3 + A_4)^2}$$

(b) Ventilation due to temperature difference only:

$$Q_b = C_d A_b \left(\frac{2 \Delta T g H_1}{T} \right)^{0.5}$$

$$\frac{1}{A_b^2} = \frac{1}{(A_1 + A_3)^2} + \frac{1}{(A_2 + A_4)^2}$$

$$T = \frac{Te + Ti}{2}$$

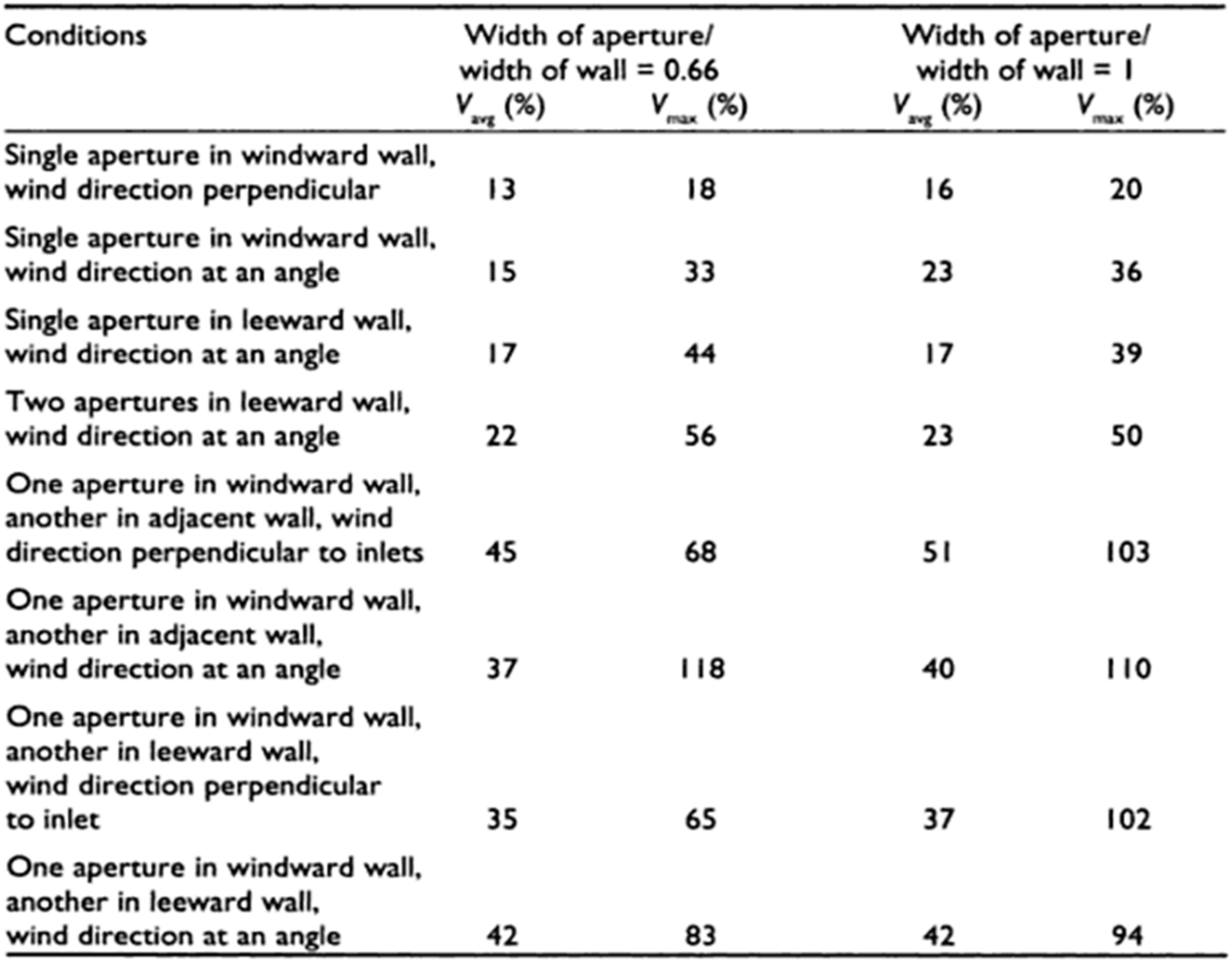
(c) Ventilation due to wind and temperature difference:

$$Q = Q_b \text{ for } \frac{V}{\sqrt{\Delta T}} < 0.26 \sqrt{\frac{A_b}{A_w} \frac{H_1}{\Delta Cp}}$$

$$Q = Q_w \text{ for } \frac{V}{\sqrt{\Delta T}} > 0.26 \sqrt{\frac{A_b}{A_w} \frac{H_1}{\Delta Cp}}$$

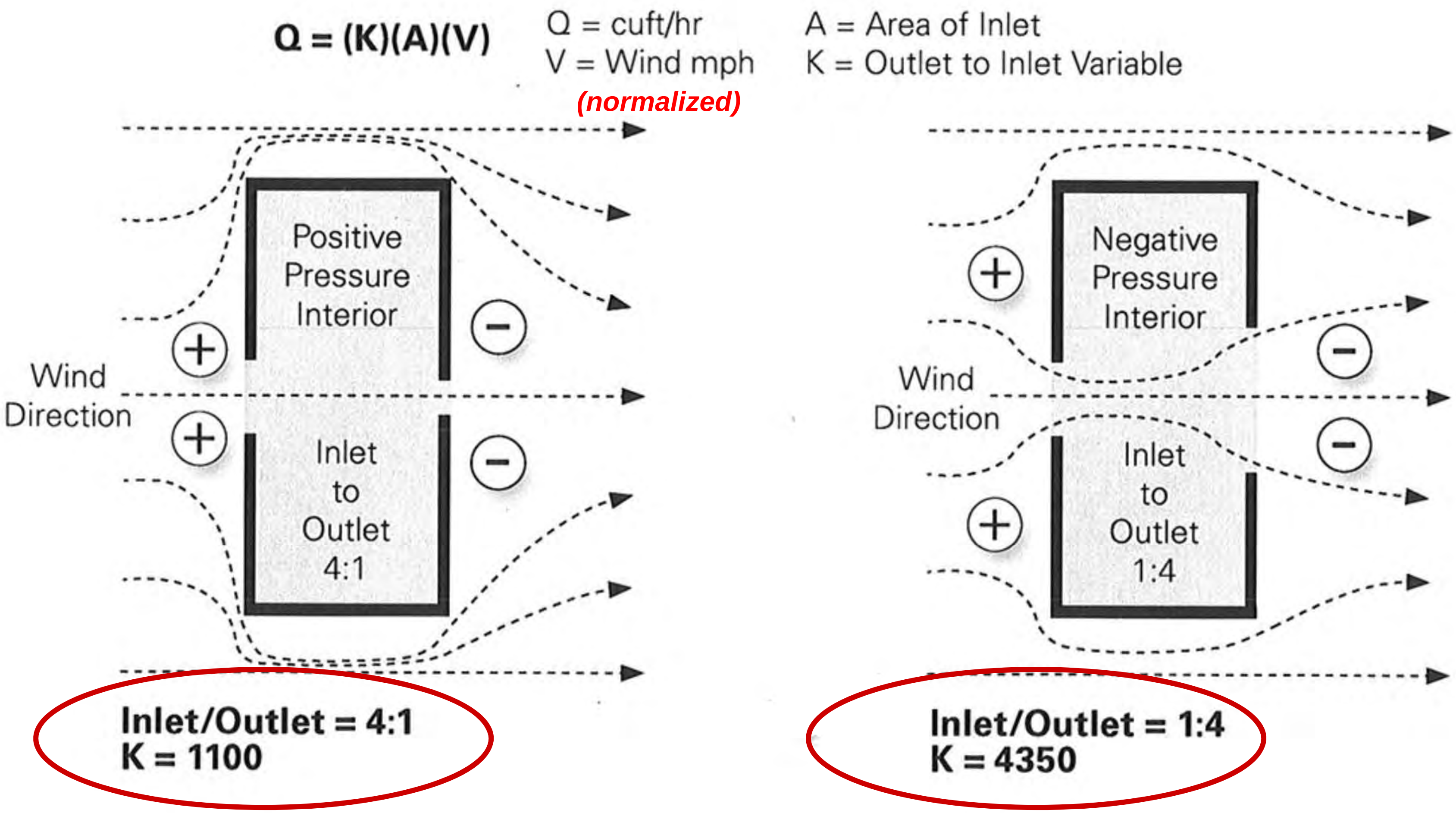
$$\Delta T = Ti - Te$$

Indoor air velocities for naturally ventilated spaces under different wind directions and different number of apertures and locations



Conditions	Width of aperture/ width of wall = 0.66		Width of aperture/ width of wall = 1	
	V_{avg} (%)	V_{max} (%)	V_{avg} (%)	V_{max} (%)
Single aperture in windward wall, wind direction perpendicular	13	18	16	20
Single aperture in windward wall, wind direction at an angle	15	33	23	36
Single aperture in leeward wall, wind direction at an angle	17	44	17	39
Two apertures in leeward wall, wind direction at an angle	22	56	23	50
One aperture in windward wall, another in adjacent wall, wind direction perpendicular to inlets	45	68	51	103
One aperture in windward wall, another in adjacent wall, wind direction at an angle	37	118	40	110
One aperture in windward wall, another in leeward wall, wind direction perpendicular to inlet	35	65	37	102
One aperture in windward wall, another in leeward wall, wind direction at an angle	42	83	42	94

Simple formulation for Vent Calculation



Q = (K)(A)(V)

Q = cuft/hr

V = Wind mph

(normalized)

A = Area of Inlet

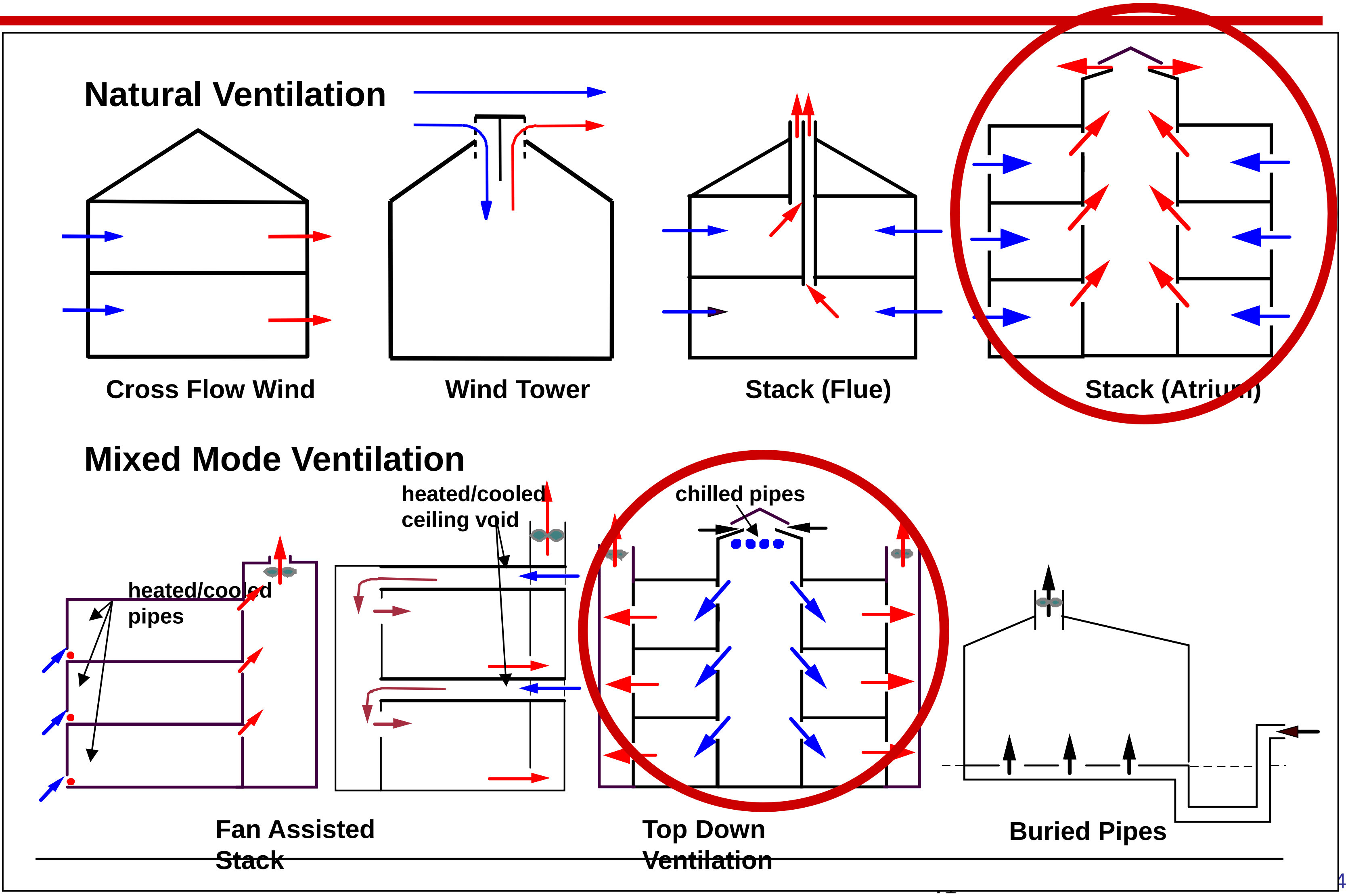
K = Outlet to Inlet Variable

Inlet/Outlet = 4:1
K = 1100

Inlet/Outlet = 1:4
K = 4350

Natural and Mixed Mode Ventilation Mechanisms

the strengths and weaknesses of the various schemes;
emphasize the various applications of theory to practice here



Courtesy of Martin Liddament via Yuguo Li

Stack Effect

- The efficiency of solar chimneys can be improved by:
- Increasing the stack height.
- Increasing the temperature difference between collector and ambient air.

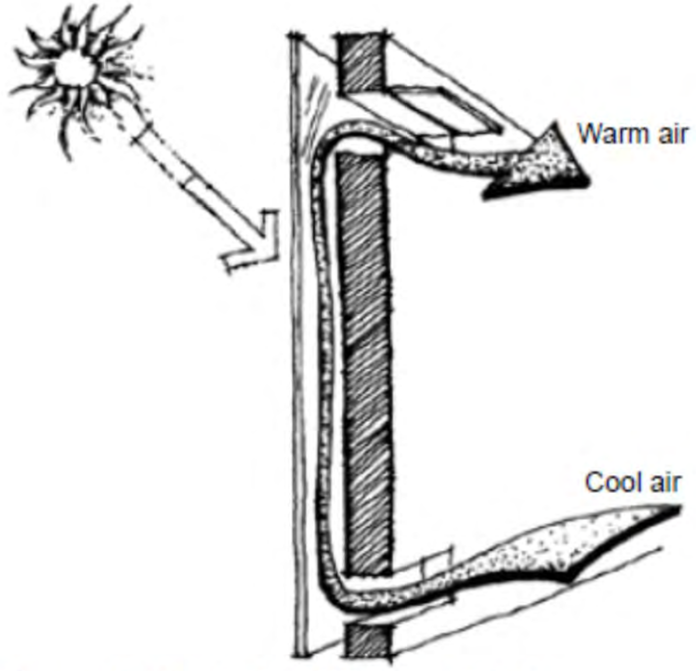
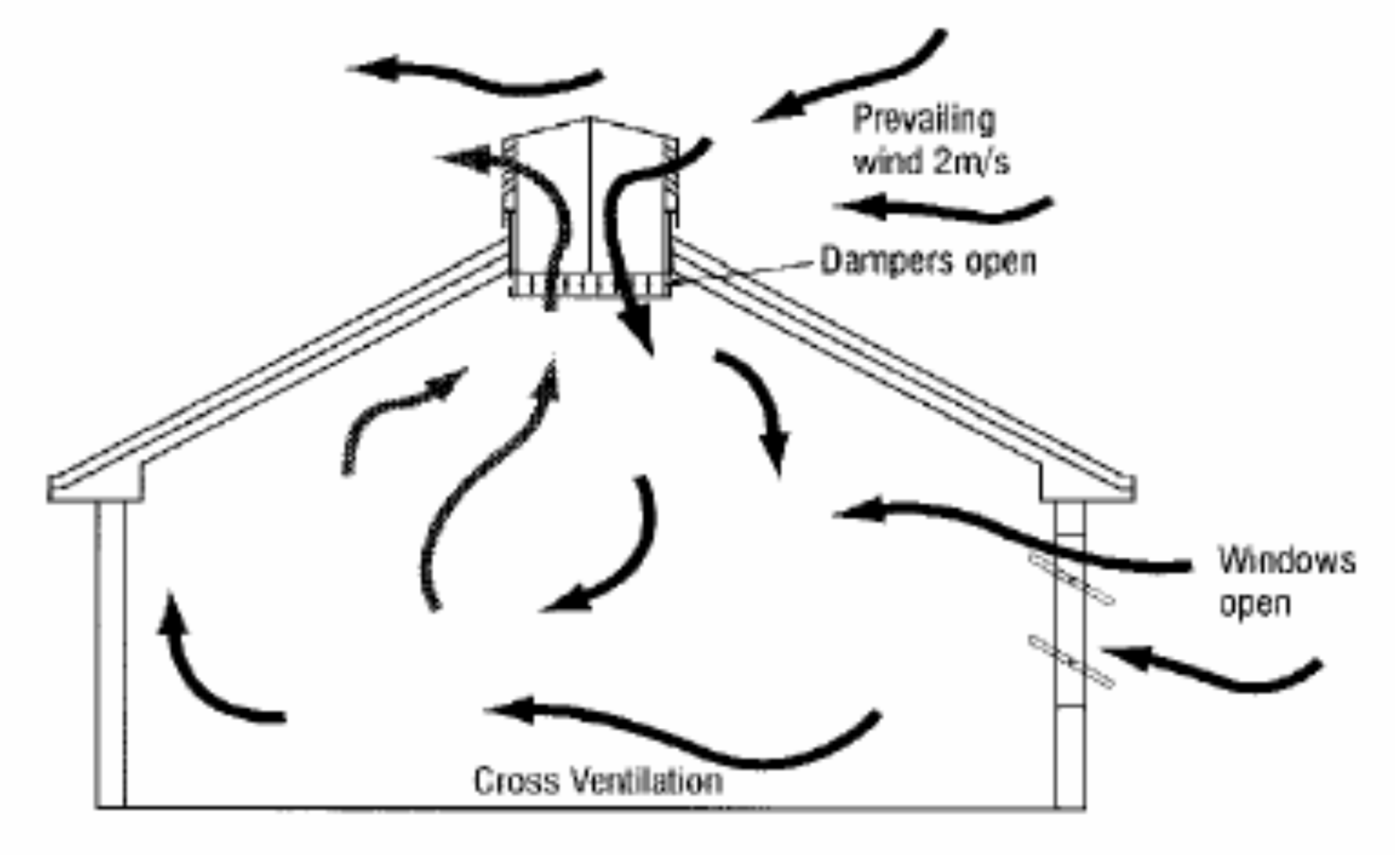


Figure 4. The Solar Chimney Effect

Windcatcher ventilation



Wind Tower Ventilation

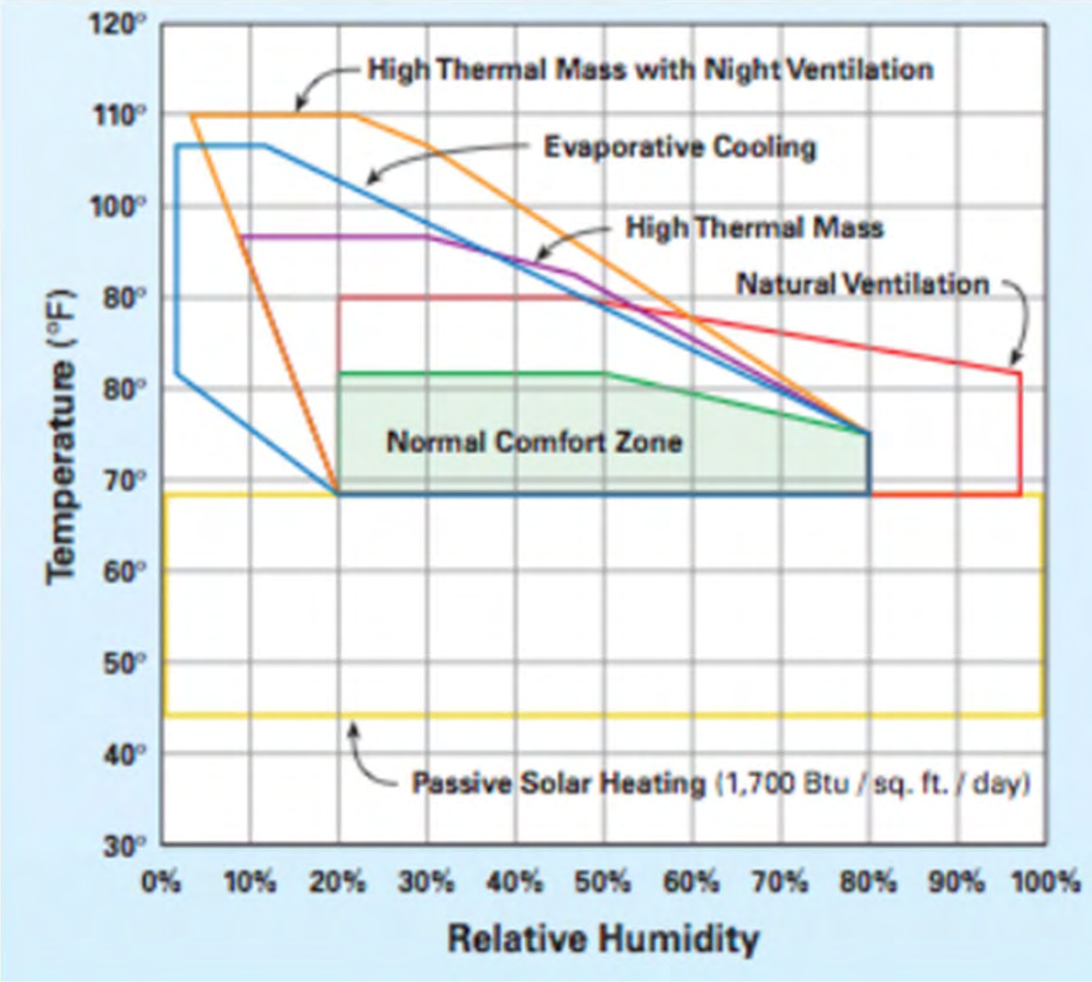
Not in handout materials (copyright limitation)

BRE’s Environmental Office Building

- ***Low energy fans for use on still air days***
- ***Glass for solar heating of thermal chimney***

Design strategies for Natural Ventilation as a thermal control strategy

- *Overall building design strategy must match the climate conditions and the need for high outdoor air ventilation rates*
- *Natural ventilation can work in outdoor Temperature range from 40 F (5 C) up to 110 F (43 C), but Relative Humidity is a critical factor*



Natural Ventilation Issues

- Weather-dependence: wind, temperature, humidity
- Thermal conditions: comfort, health
- Outdoor air quality/pollutants
- Immune compromised patients
- Building configuration (plan, section)
- Management of openings
- Measurement of ventilation rate(s)

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Building and Environment 39 (2004) 1157–1170

www.elsevier.com/locati

How to use natural ventilation to cool narrow office buildings

E. Gratia*, I. Bruyère , A. De Herde

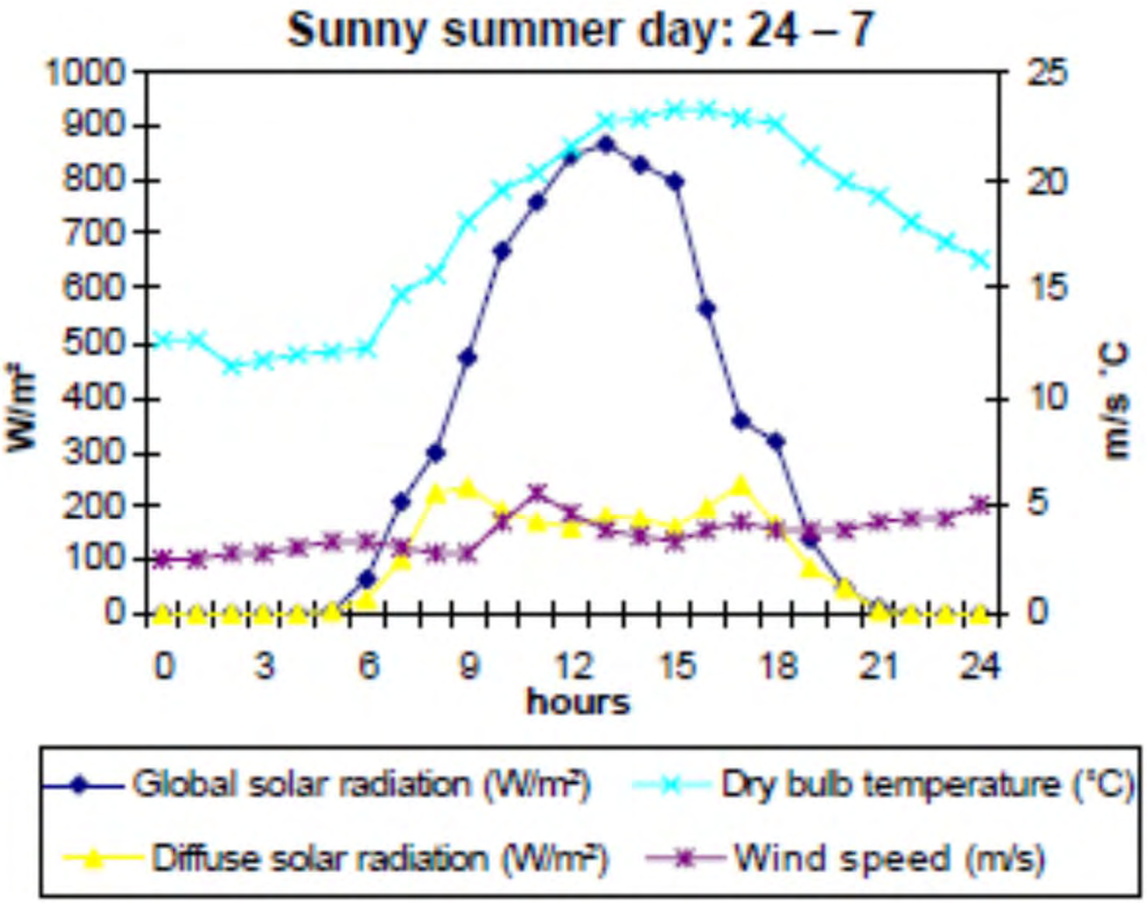
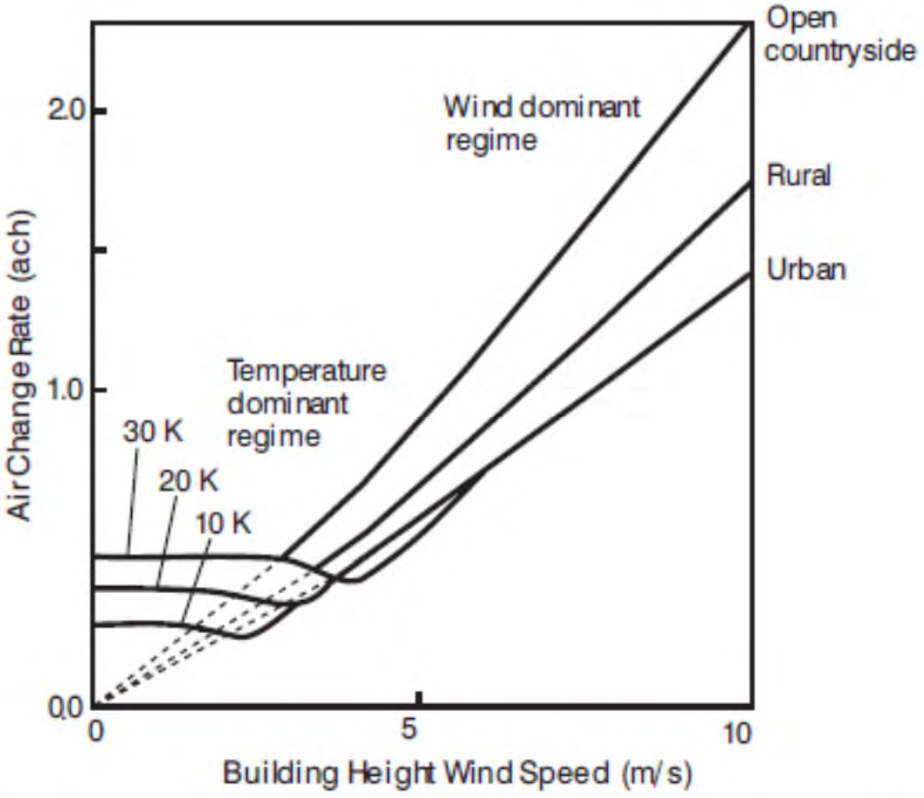


Fig. 7. Climatic data of the sunny summer day.

Impact of wind and temperature difference on natural ventilation



Impact of wind and temperature difference on natural ventilation

Natural ventilation in buildings

Francis Allard, Mat Santamouris, Servando Alvarez, European Commission. Directorate-General for Energy, ALTENER Program

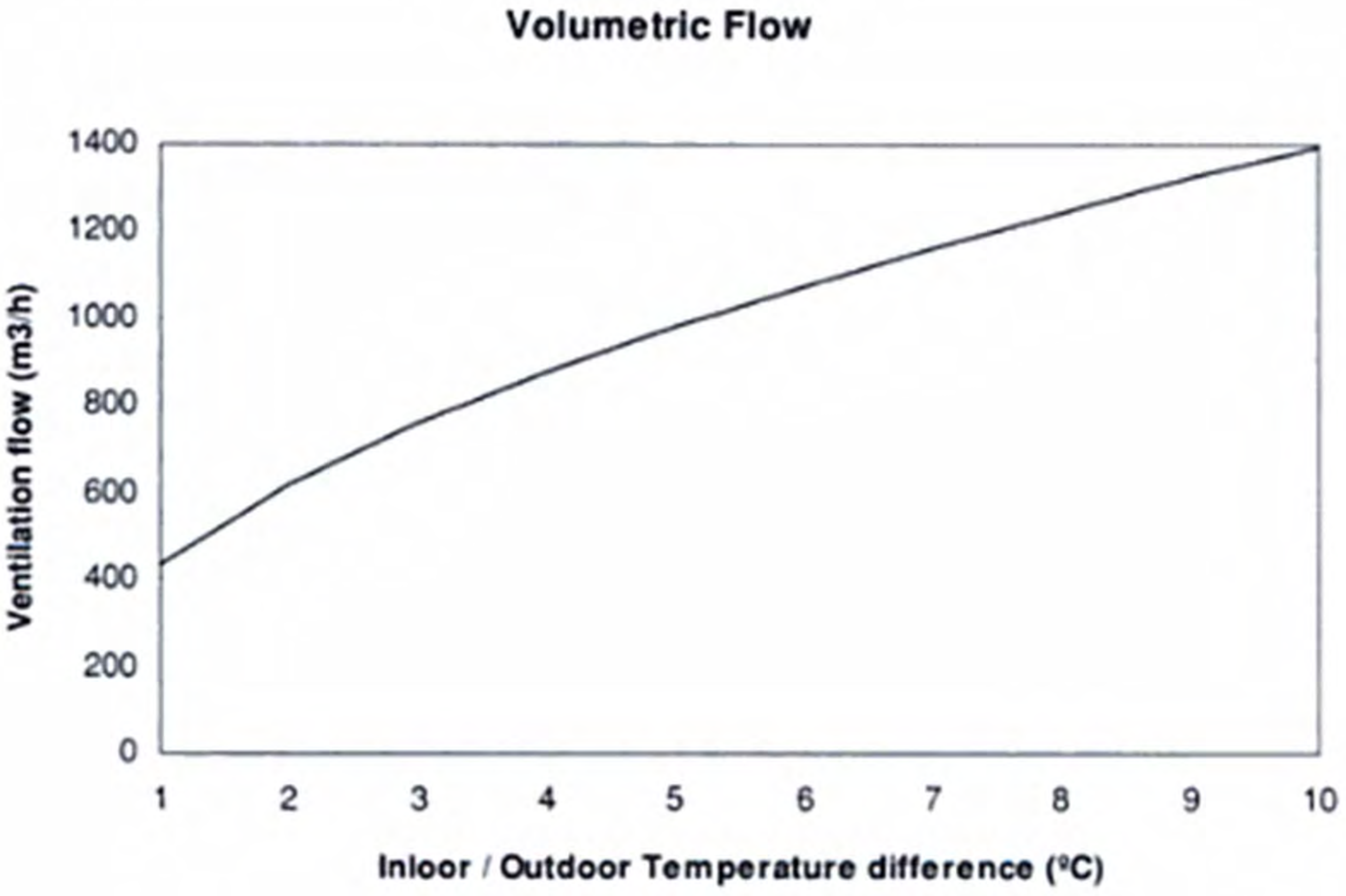
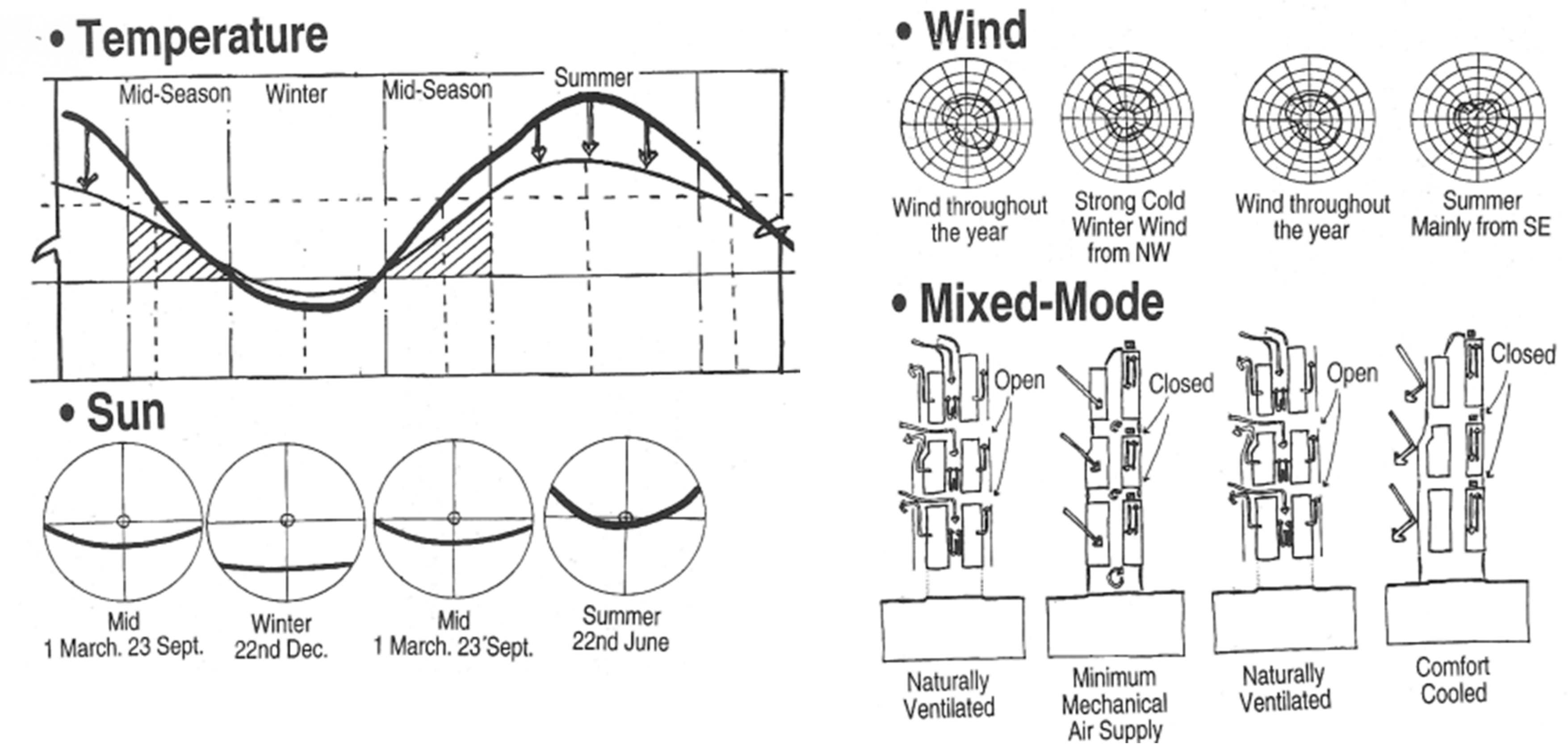


Figure 2.33. Airflow as a function of the temperature difference

Weather conditions and ventilation mode

Armoury Tower – Shanghai, China



Wind Towers, **1999. Battle McCarthy Consulting Engineers**

Not in handout materials (copyright limitation)

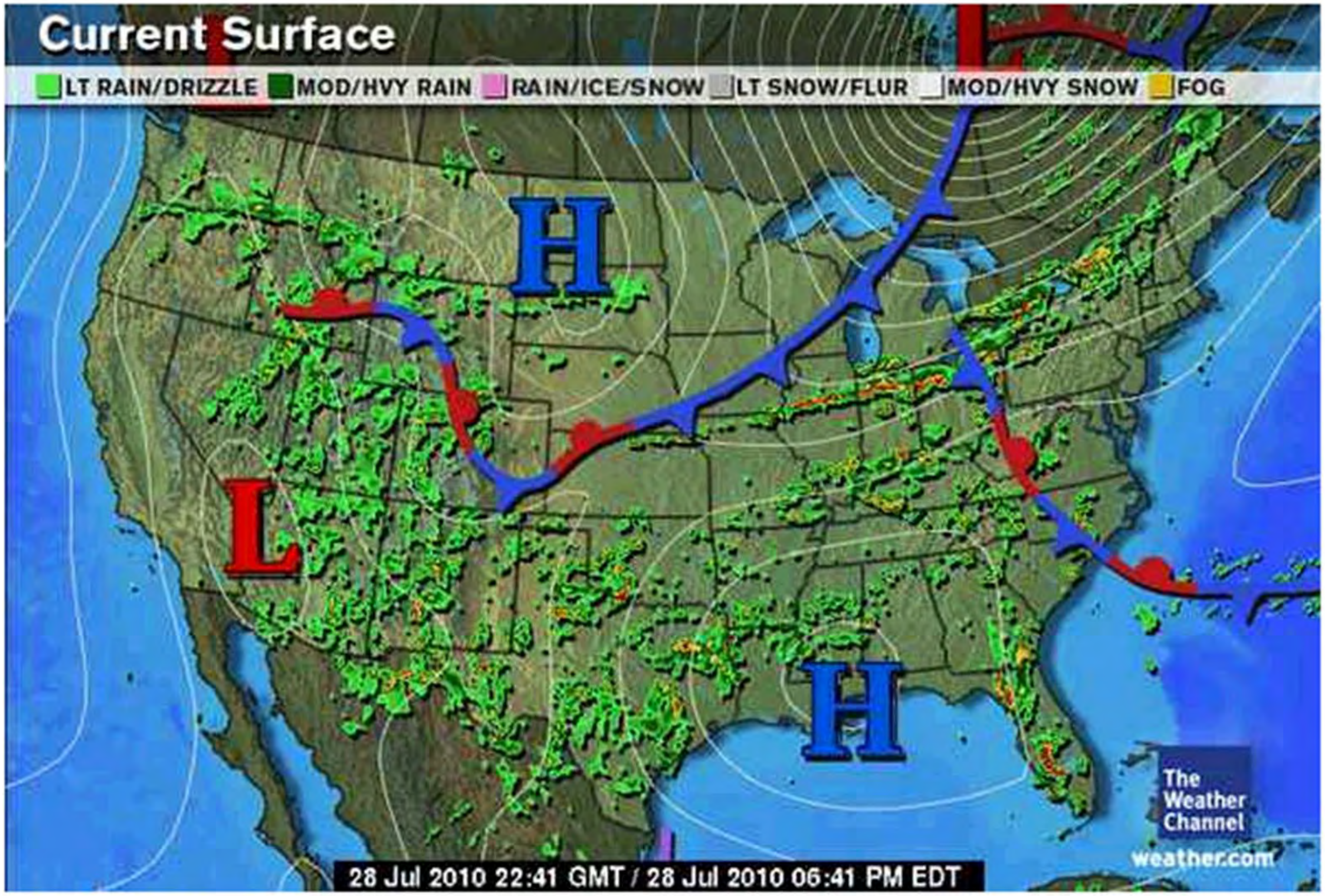
Climate Typology (oversimplified!)
What is your climate type?

Climate type	*Diurnal swing*	*Steady daily cycle*	*Seasonal variation*	*No seasonal variation*
Hot humid		Singapore		
Hot dry	Low desert			
Temperate humid		London	Milan, Italy	
Temperate dry	High desert			Quito, Ecuador
Temperate seasonal -- Temp	Boston	Lima, Peru	Montreal, Canada	
Temperate seasonal – RH	San Francisco Mt. Fuji			
Cold humid				
Cold dry	Bogotá			Bogotá

Wind: direction and velocity are neither stable nor consistent – almost anywhere

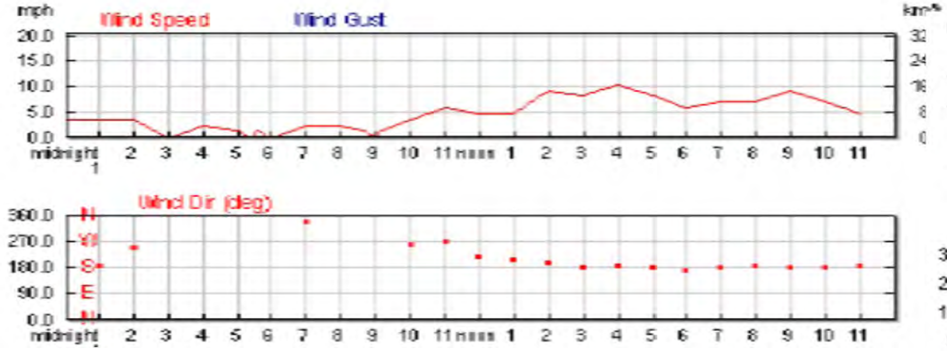
- Selected data from almost any city will show daily cycles and variations in wind direction and velocity
- Seasonal variations are more reliable, but daily variations are still the rule rather than the exception
- Even with many predictable situations, wind direction will change over the diurnal cycle – California coast is an example.
- Relying on wind alone can result in both under and over-ventilation relative to a design objective.

Weather – “wait a minute and it will change”

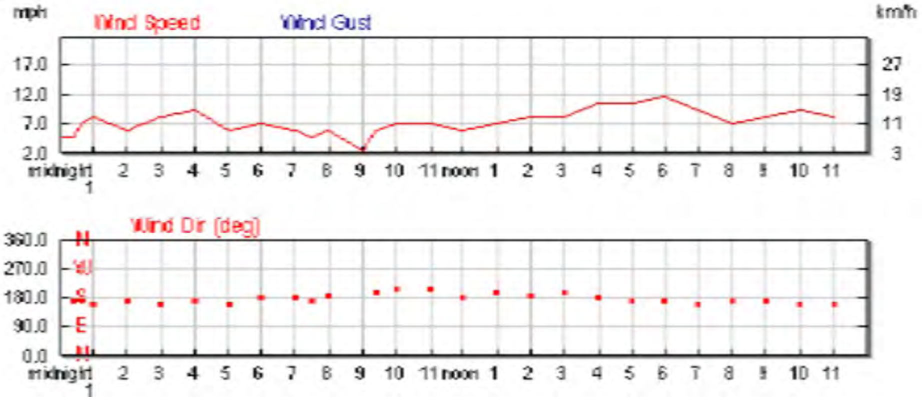


Lima, Peru: wind speed and direction

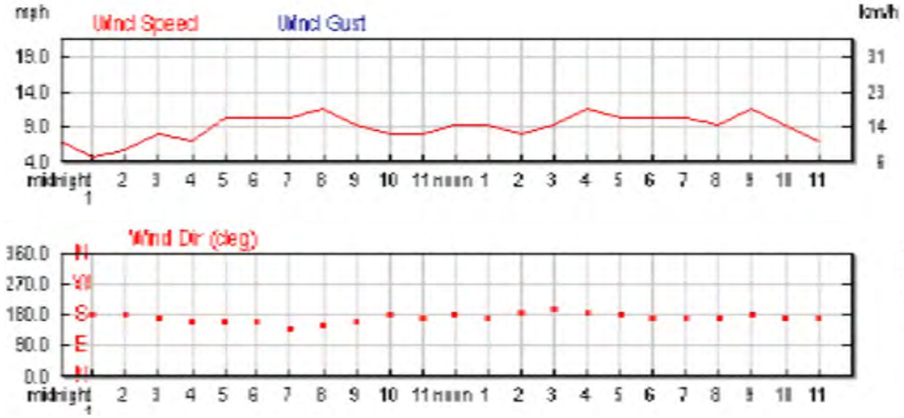
May 1, 2008



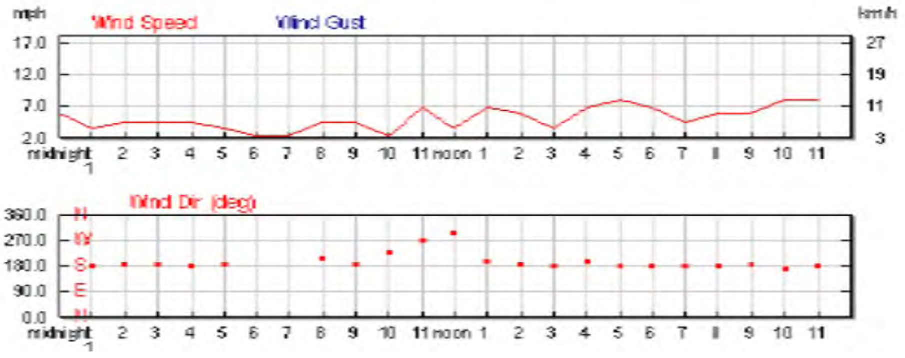
January 1, 2009



September 1, 2008

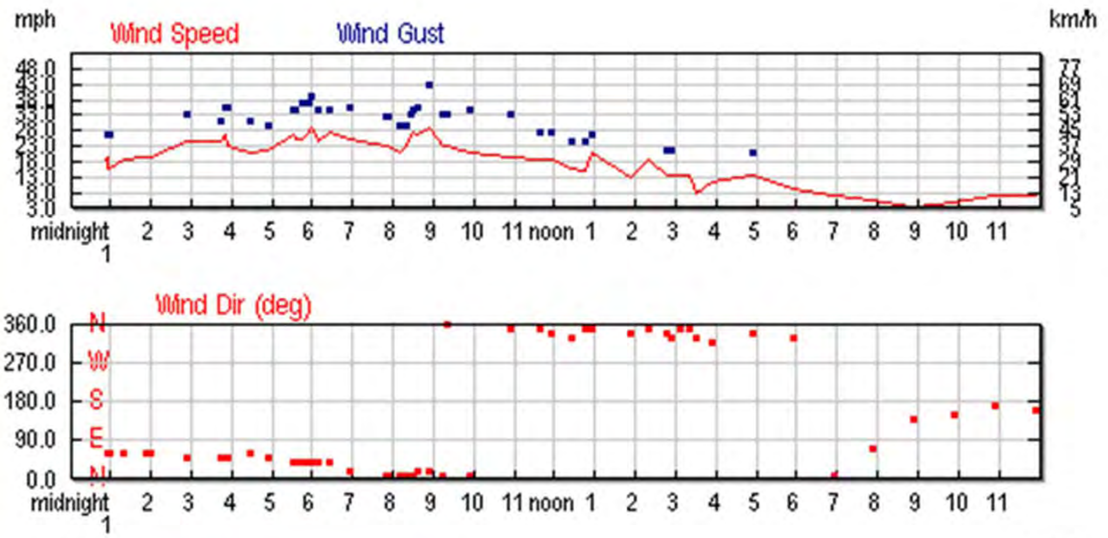


March 1, 2009



Boston, MA

July 24, 2009



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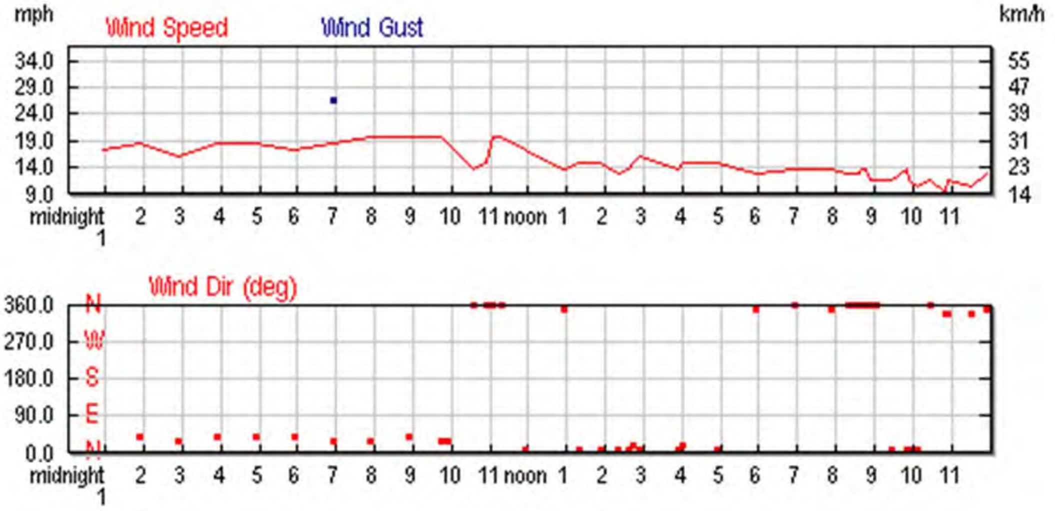
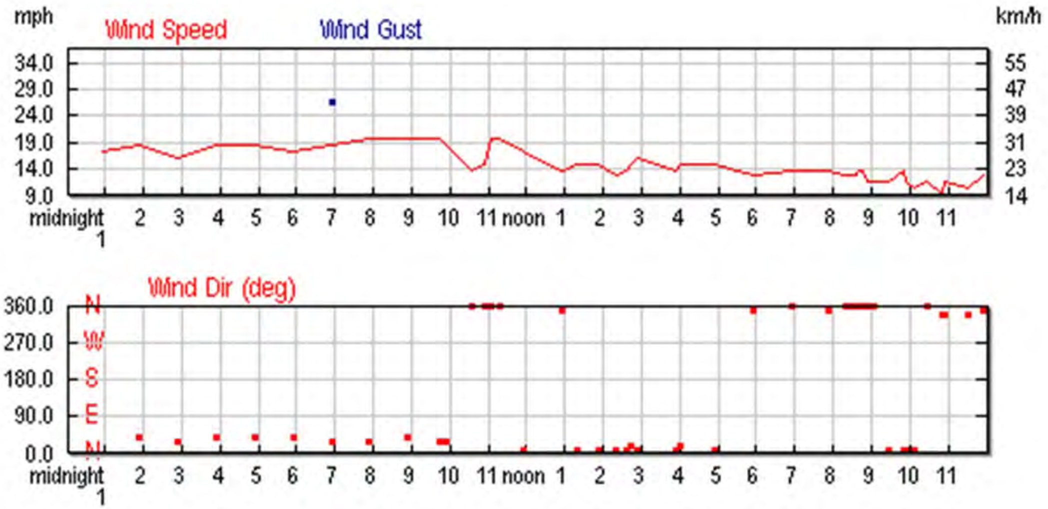
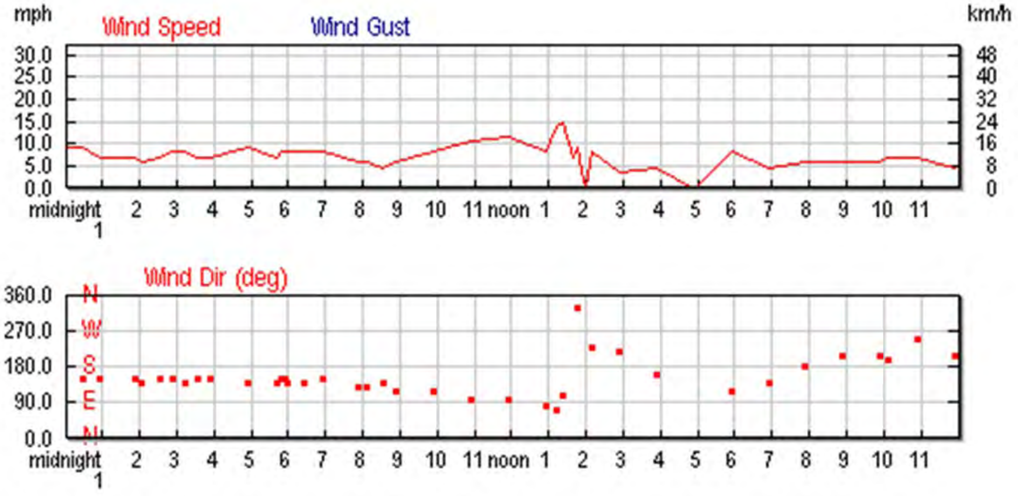


Boston, MA

January 1, 2009

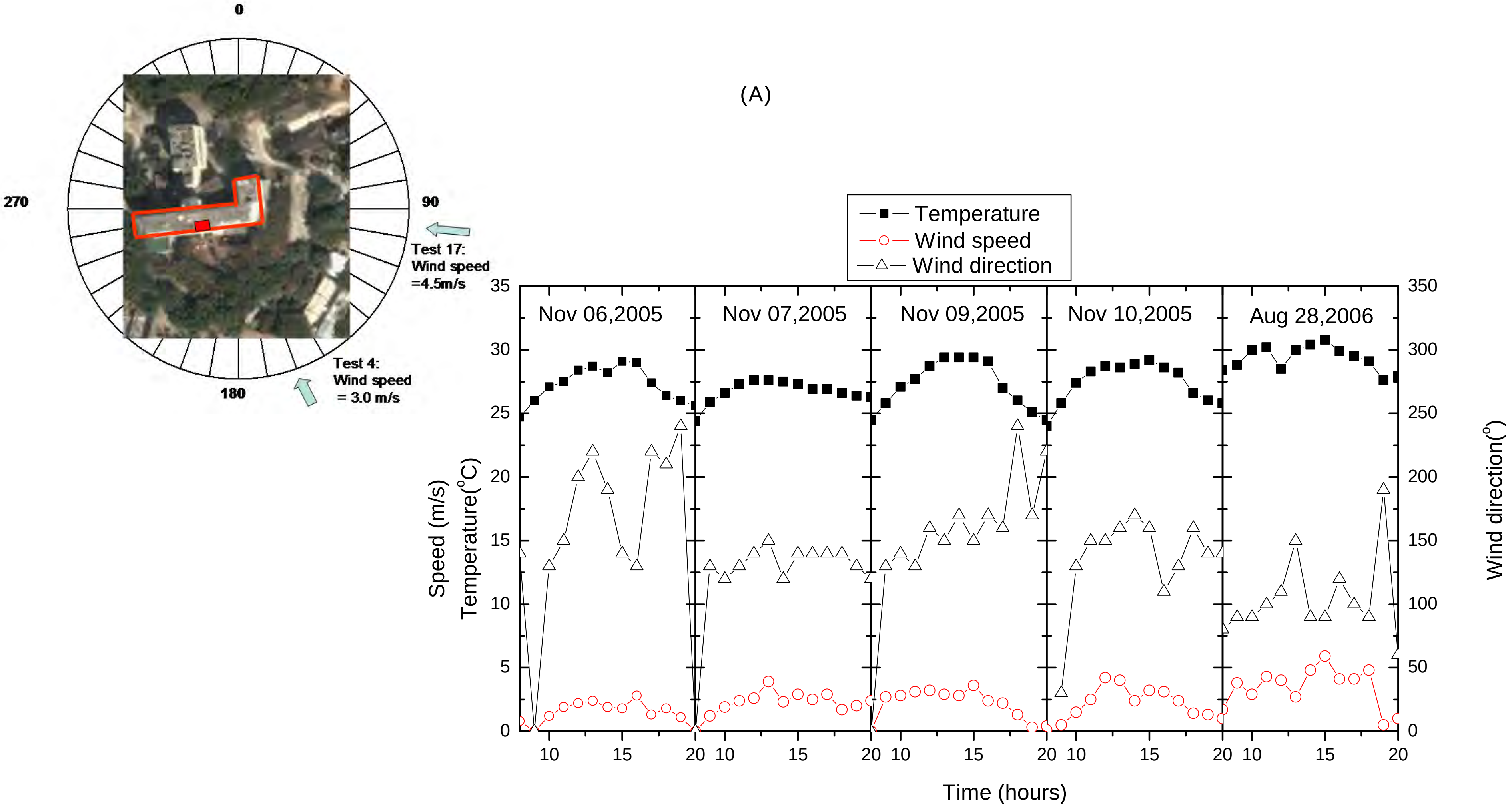


October 1, 2008



Grantham Hospital Study, Hong Kong

Yuguo Li, WHO 2009



Outdoor air quality becomes indoor air quality at high ventilation rates

- The higher the outdoor air ventilation rate, the higher the indoor/outdoor pollutant concentration
- The effect of the building on reducing outdoor pollutants varies by pollutant and by building ventilation pathways
- Where outdoor air pollution is high, natural ventilation must be considered not only as a means for reducing concentrations from indoor sources (infectious airborne agents as well as chemicals emitted indoors), but also as a means of delivering <u>un-cleaned</u> outdoor air.
- With highly susceptible health care facility occupant populations, consideration must be given to the effects of outdoor pollutants on the occupants' health.

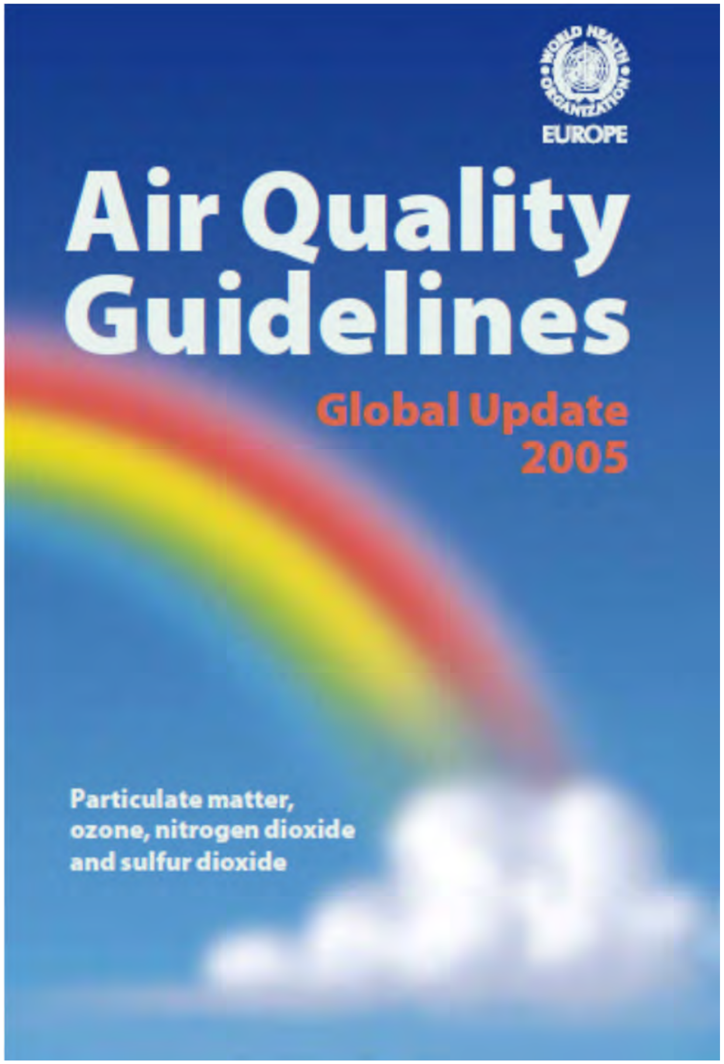
Air Quality Guidelines: Global Update
WHO, 2005

Chapter 2.

Global ambient air pollution concentrations and trends

Bjarne Sivertsen

http://www.who.int/phe/health_topics/outdoorair_aqg/en/



EUROPE

Air Quality Guidelines

Global Update
2005

Particulate matter,
ozone, nitrogen dioxide
and sulfur dioxide

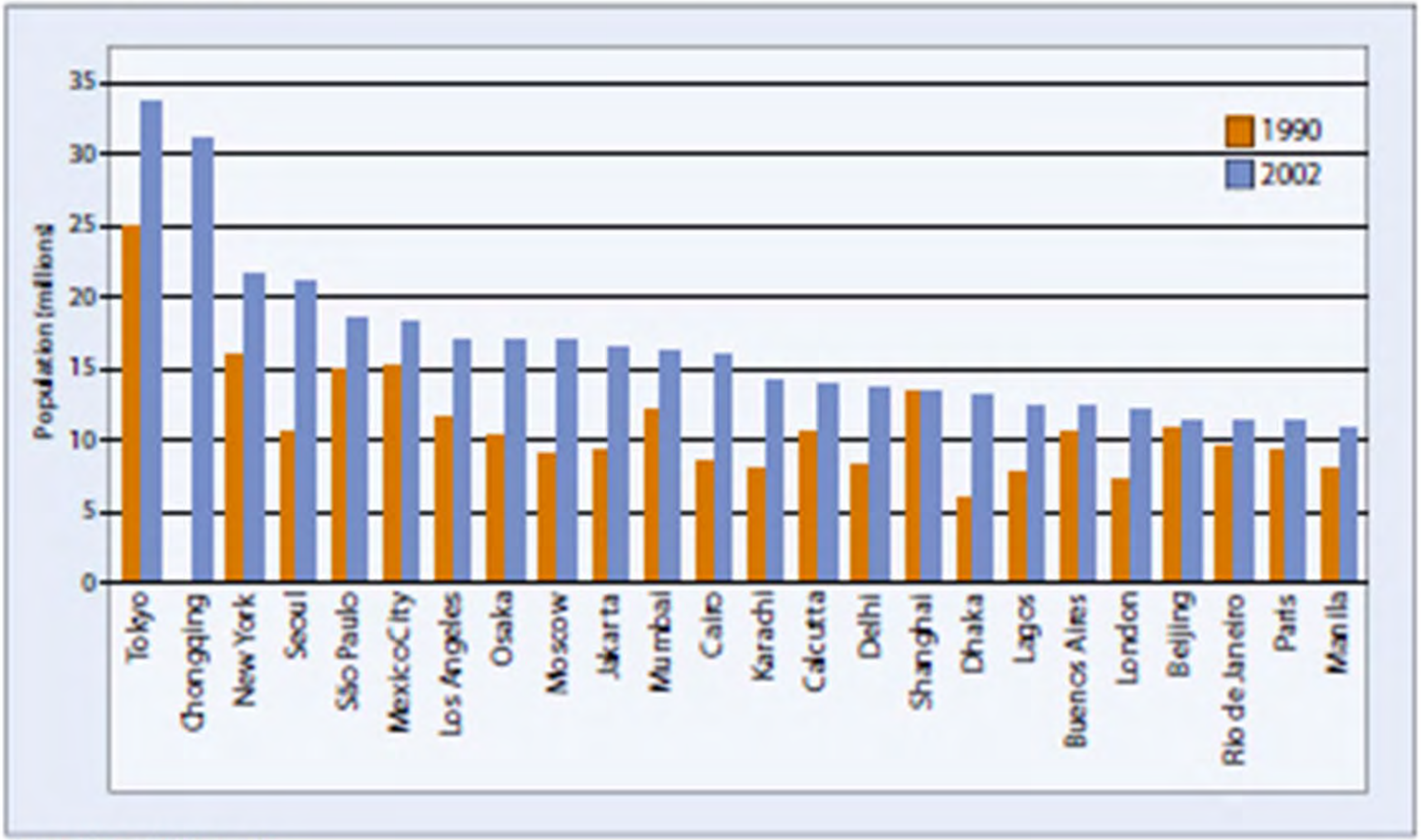
Ranges of annual average concentrations of outdoor air pollutants by continent based on selected urban data

Region	PM_{10}	Nitrogen dioxide	Sulfur dioxide	Ozone (1-hour maximum concentration)
Africa	40–150	35–65	10–100	120–300
Asia	35–220	20–75	6–65	100–250
Australia/New Zealand	28–127	11–28	3–17	120–310
Canada/United States	20–60	35–70	9–35	150–380
Europe	20–70	18–57	8–36	150–350
Latin America	30–129	30–82	40–70	200–600

(source: World Health Organization, 2005. *Air Quality Guidelines: Global Update*)

Where are the people who will arrive in naturally-ventilated health care facilities?

Fig. 2. The 24 megacities in the world with populations (including suburbs) exceeding 10 million in 2002

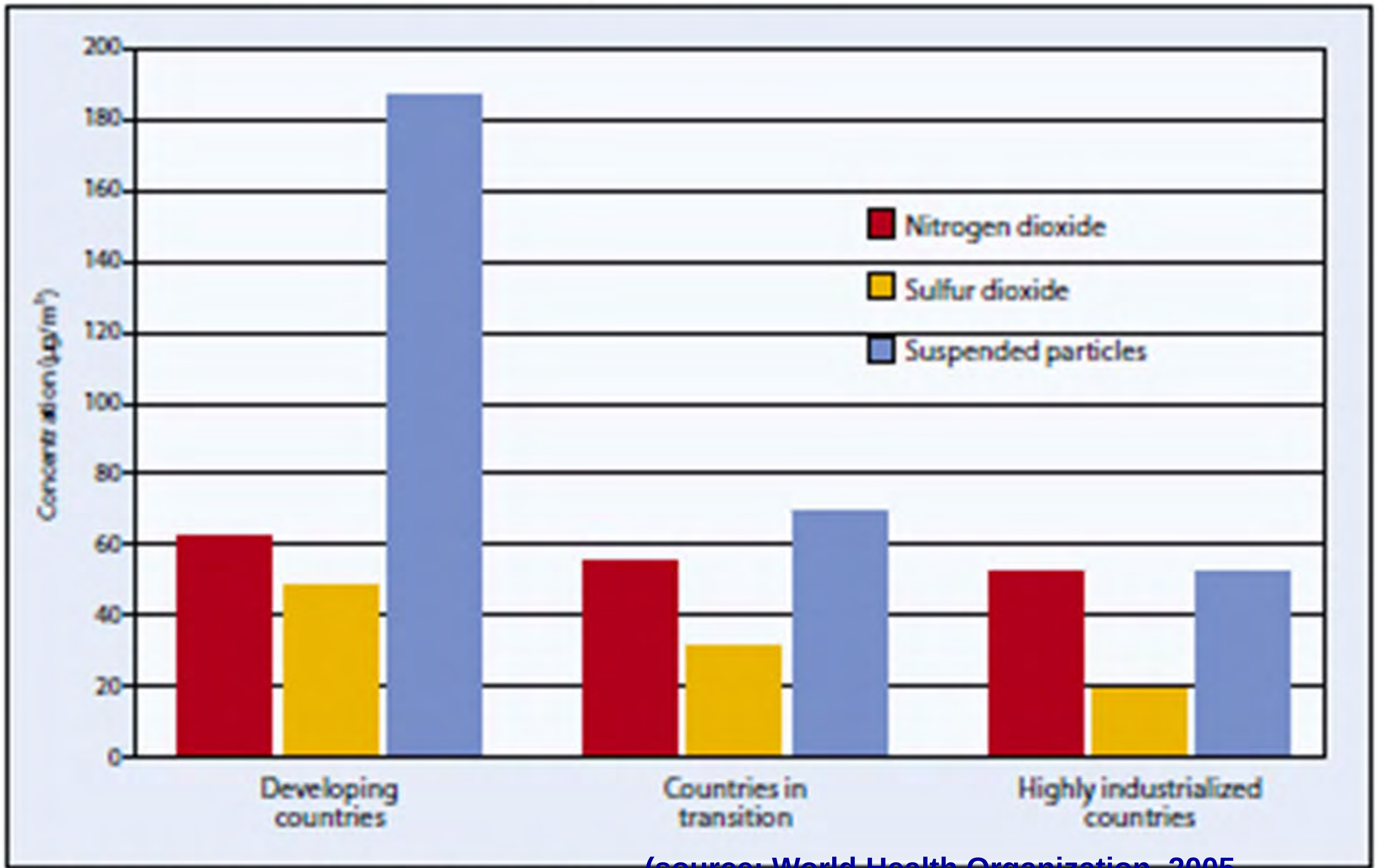


Source: United Nations (4).

(source: World Health Organization, 2005.

Pollutant concentrations by national level of development

Fig. 3. Typical annual average concentrations of nitrogen dioxide, sulfur dioxide and suspended particles in different parts of the world

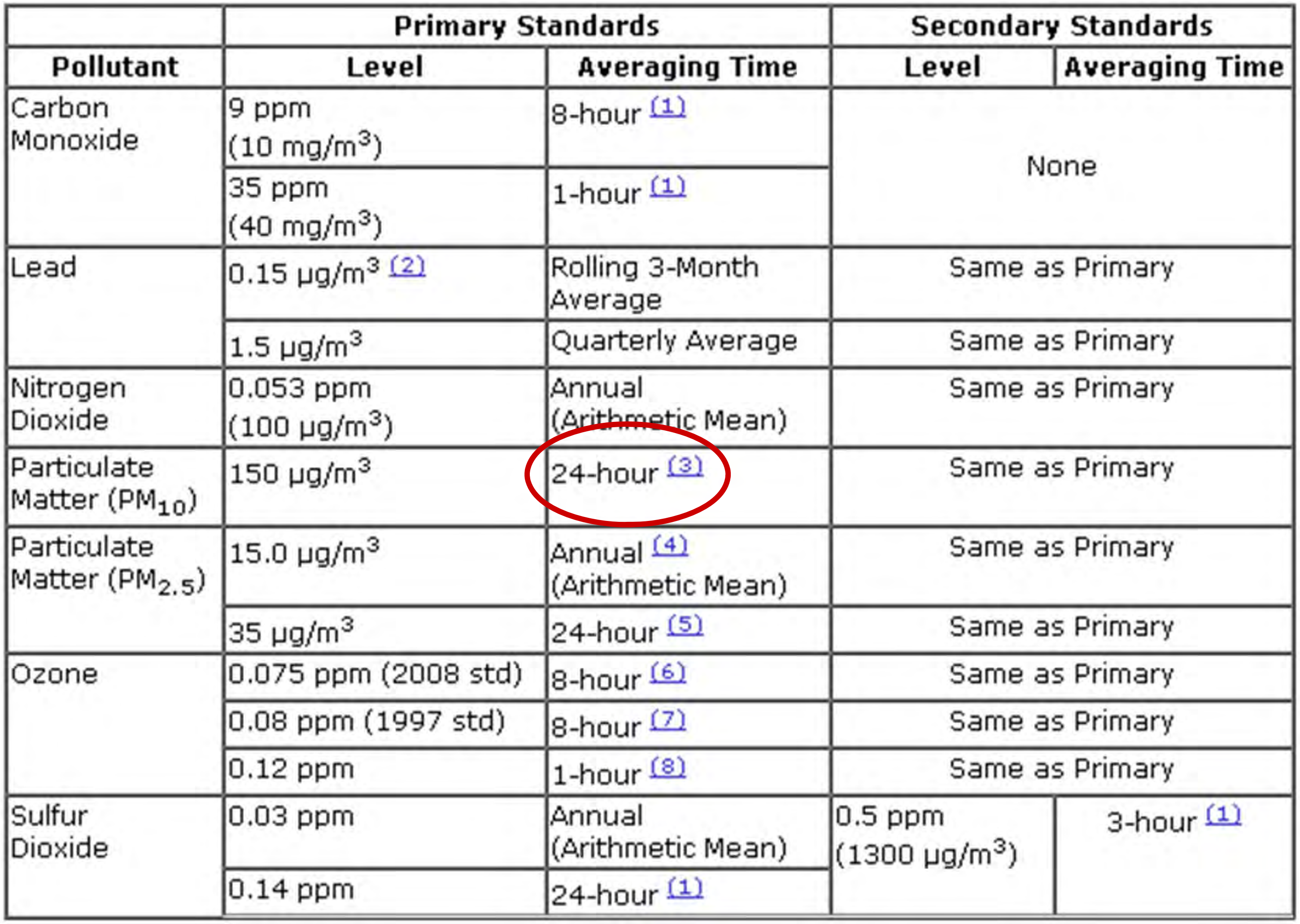


(source: World Health Organization, 2005.

Source: United Nations Human Settlements Programme (5).

U.S. EPA National Ambient Air Quality Standards

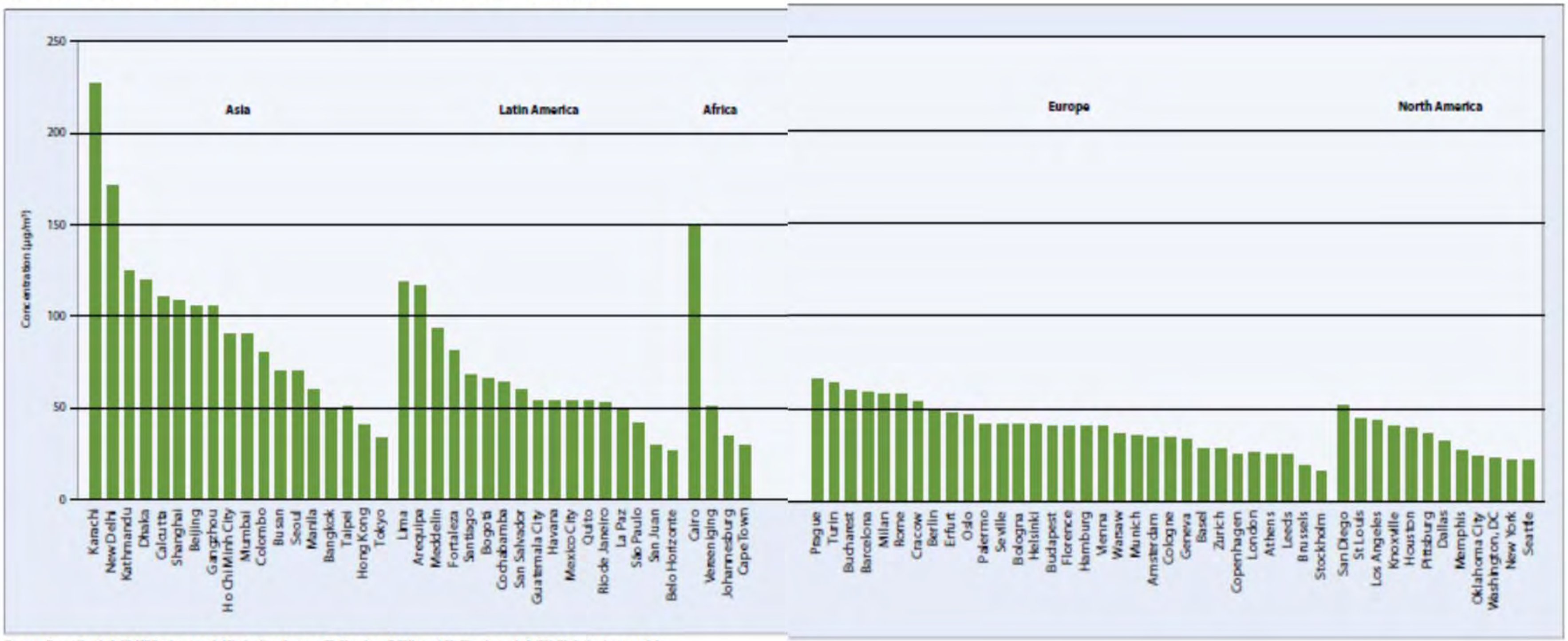
(NAAQS) http://www.epa.gov/air/criteria.html



	Primary Standards		Secondary Standards	
Pollutant	**Level**	**Averaging Time**	**Level**	**Averaging Time**
Carbon Monoxide	9 ppm (10 mg/m^3)	8-hour (1)	None	
	35 ppm (40 mg/m^3)	1-hour (1)		
Lead	0.15 µg/m^3 (2)	Rolling 3-Month Average	Same as Primary	
	1.5 µg/m^3	Quarterly Average	Same as Primary	
Nitrogen Dioxide	0.053 ppm (100 µg/m^3)	Annual (Arithmetic Mean)	Same as Primary	
Particulate Matter (PM_{10})	150 µg/m^3	24-hour (3)	Same as Primary	
Particulate Matter ($PM_{2.5}$)	15.0 µg/m^3	Annual (4) (Arithmetic Mean)	Same as Primary	
	35 µg/m^3	24-hour (5)	Same as Primary	
Ozone	0.075 ppm (2008 std)	8-hour (6)	Same as Primary	
	0.08 ppm (1997 std)	8-hour (7)	Same as Primary	
	0.12 ppm	1-hour (8)	Same as Primary	
Sulfur Dioxide	0.03 ppm	Annual (Arithmetic Mean)	0.5 ppm (1300 µg/m^3)	3-hour (1)
	0.14 ppm	24-hour (1)		

Average annual PM_{10} concentrations in selected cities world wide (part 1)

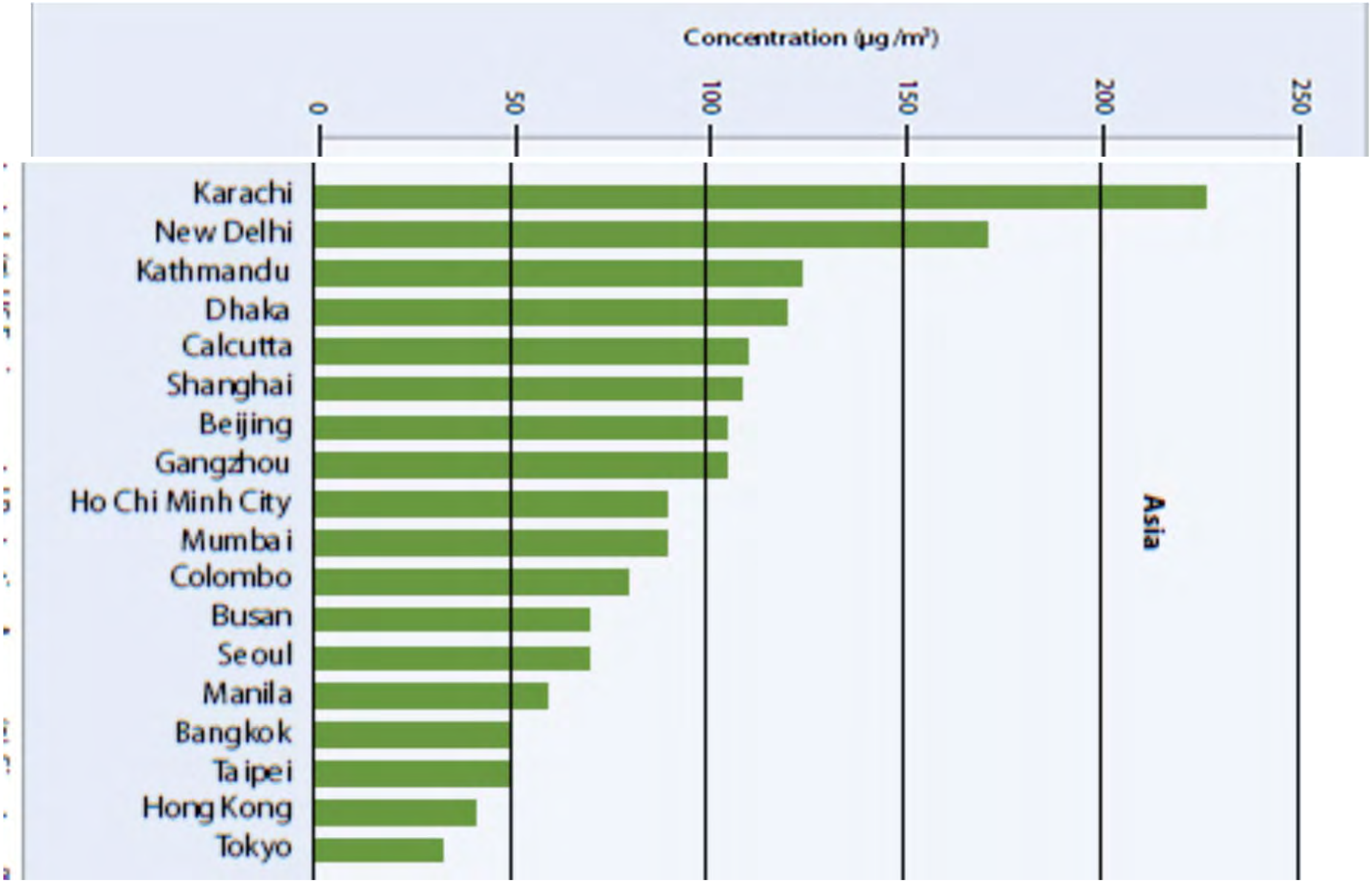
Fig. 4. Annual average PM_{10} concentrations observed in selected cities worldwide



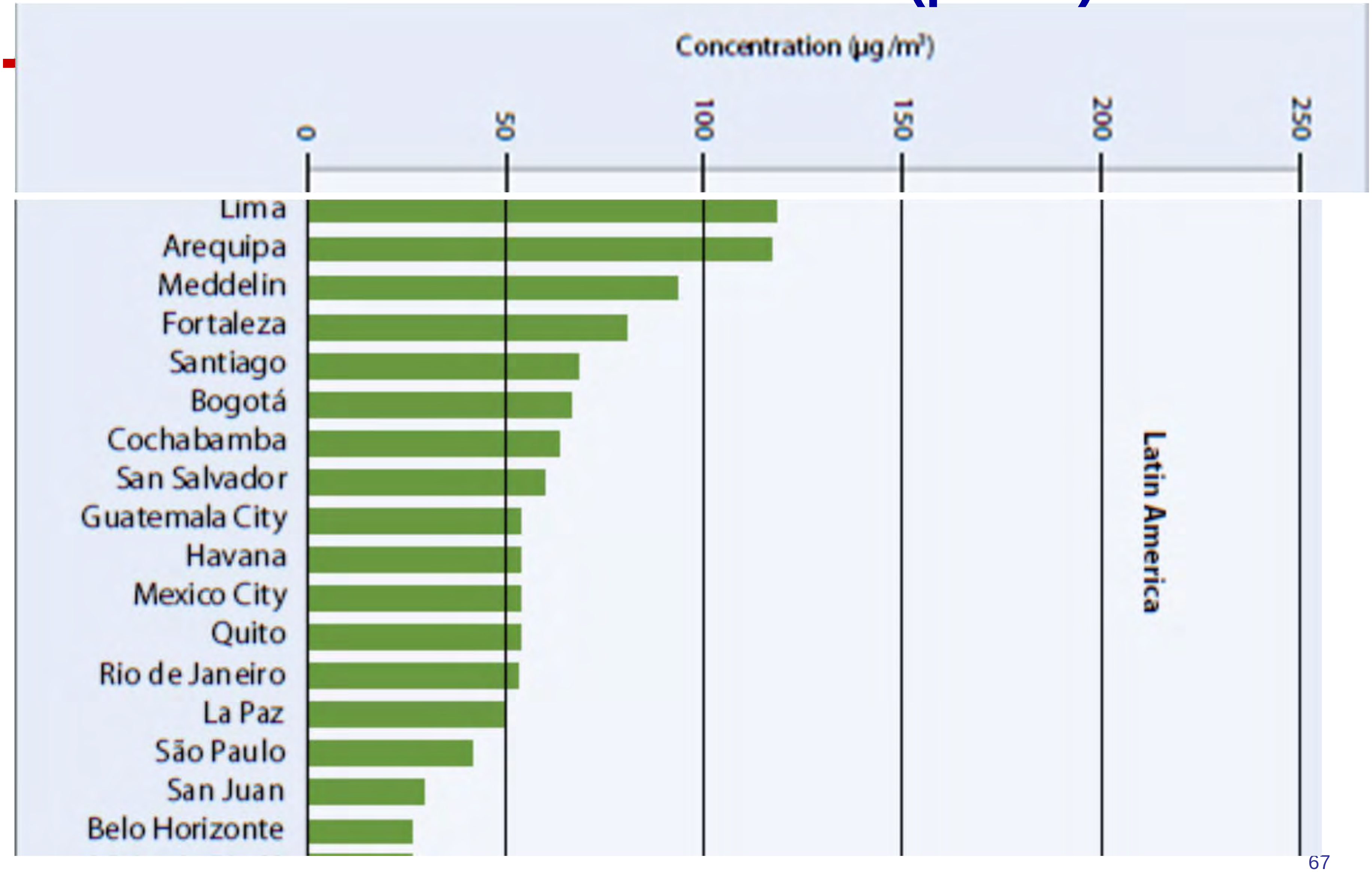
Sources: Bourotte et al. (7); US Environmental Protection Agency (8); Sivertsen & El Seoud (9); Sivertsen et al. (10); State Environmental Protection Agency (11); CAFE (12); Department of Environment and Heritage (13); Department of Environmental Affairs and Tourism (14); US Environmental Protection Agency (15).

(source: World Health Organization, 2005.

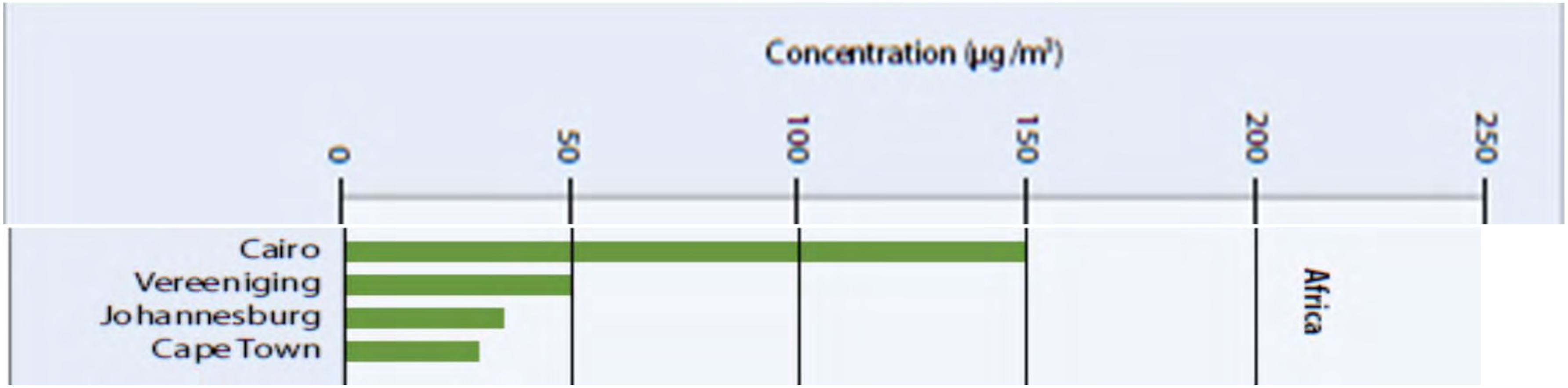
<u>Average annual</u> PM$_{10}$ concentrations in selected cities world wide (part 2)



Average annual PM_{10} concentrations in selected cities world wide (part 3)

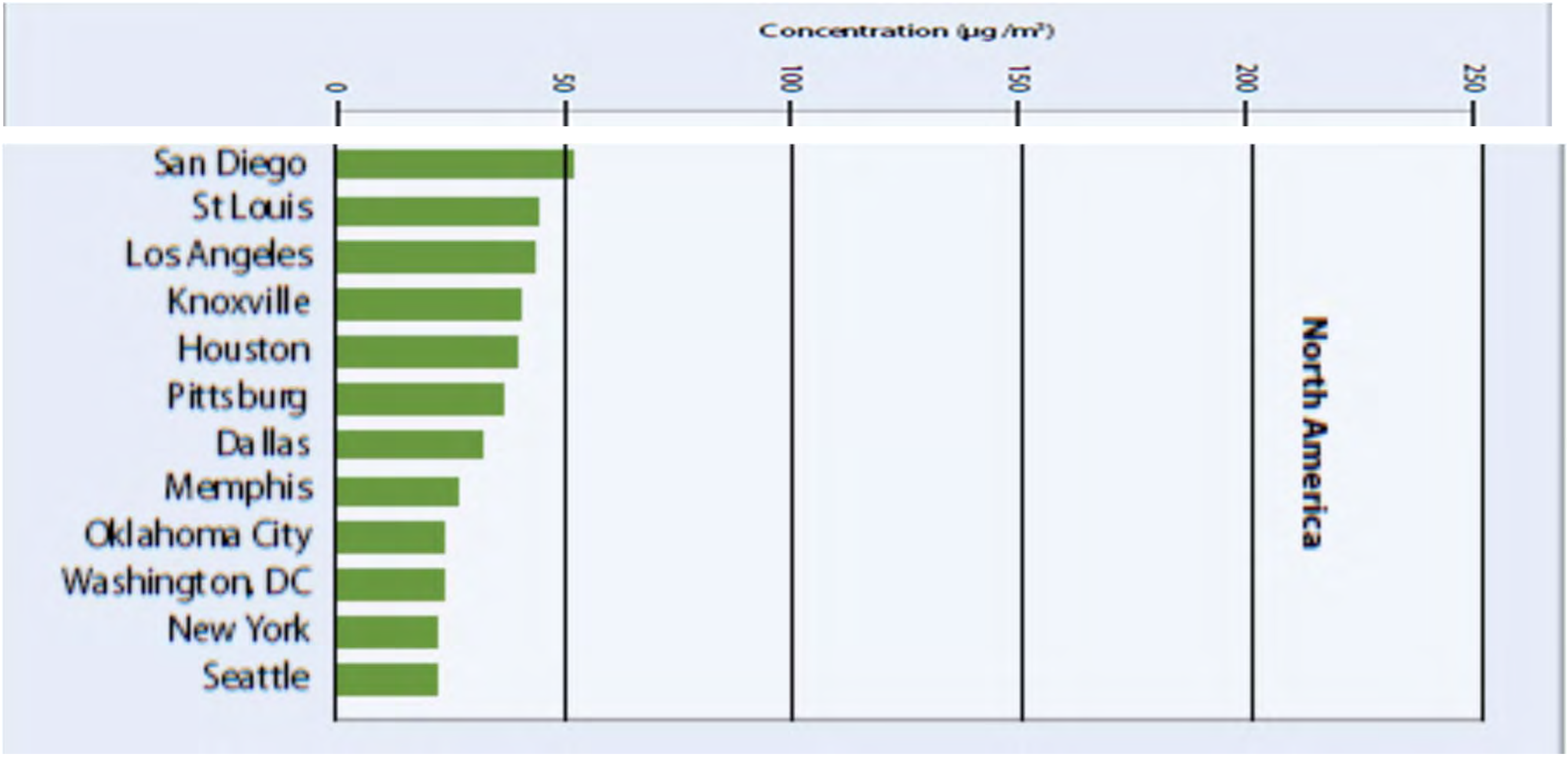


Average annual PM$_{10}$ concentrations in selected cities world wide (part 4)

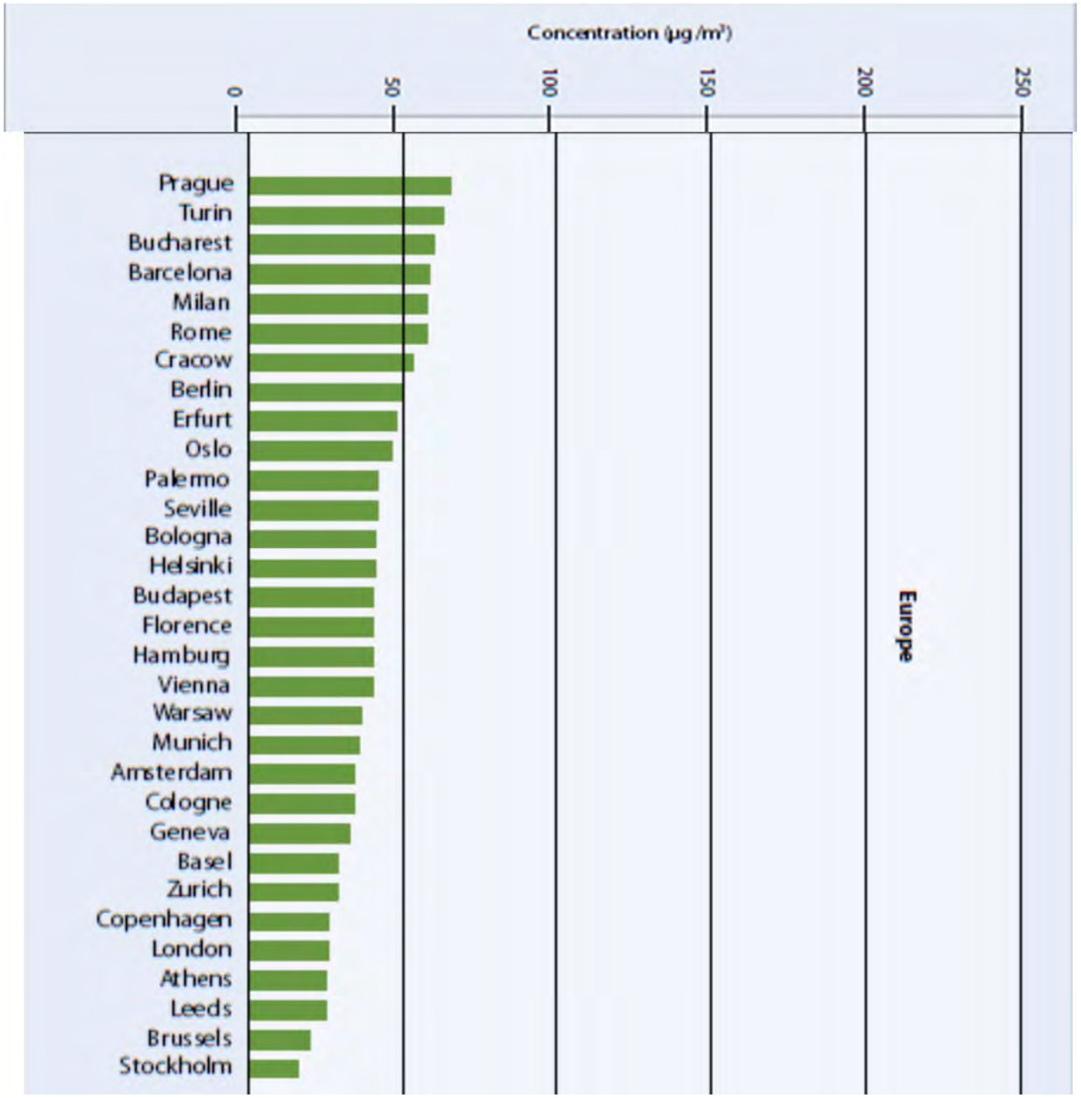


Average annual PM_{10} concentrations in selected cities world wide (part 5)

NORTH AMERICA

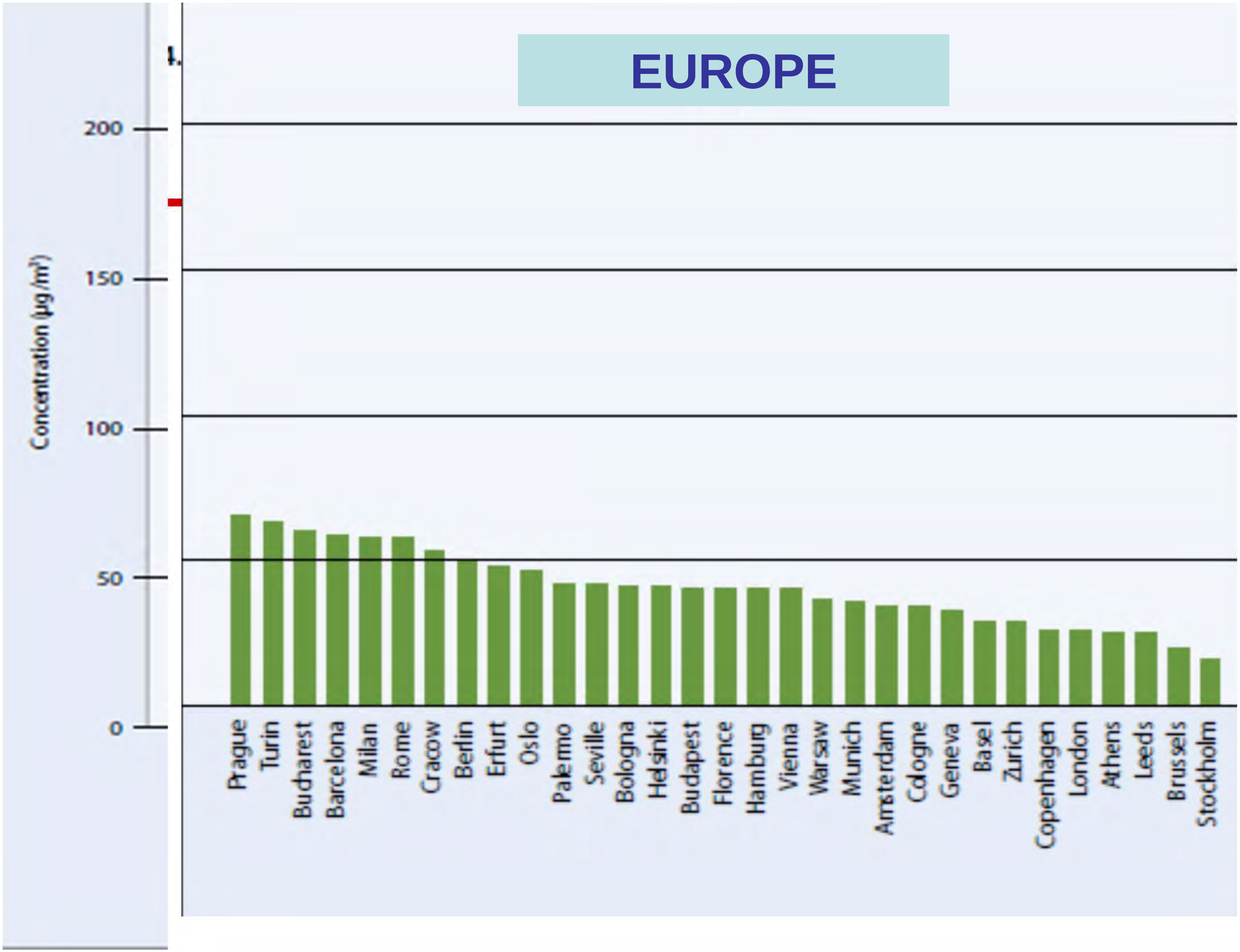


Average annual PM_{10} concentrations in selected cities world wide (part 6)



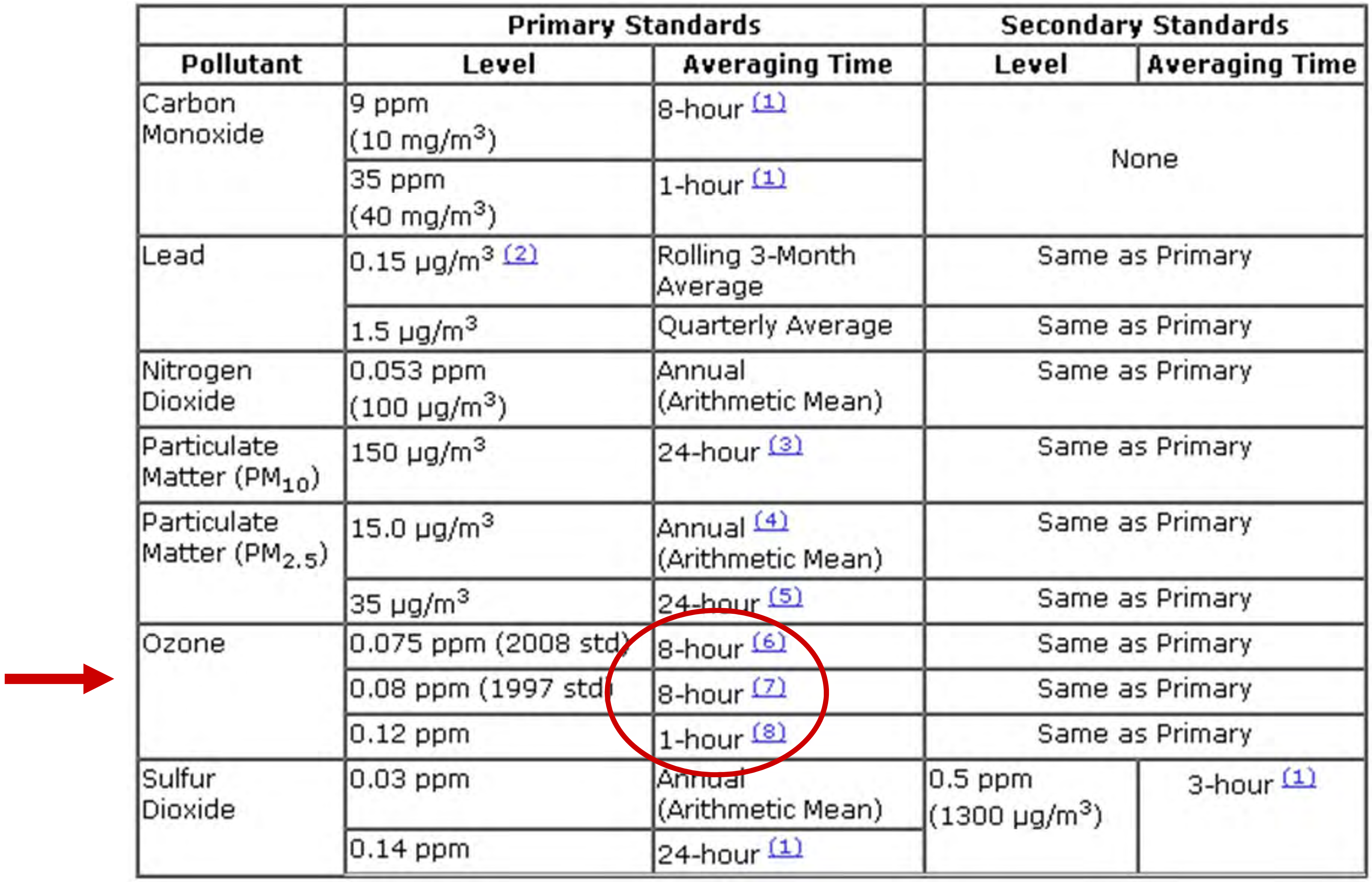
Europe

EUROPE


Concentration (μg/m³)
200
150
100
50
0
Prague
Turin
Bucharest
Barcelona
Milan
Rome
Cracow
Berlin
Erfurt
Oslo
Palermo
Seville
Bologna
Helsinki
Budapest
Florence
Hamburg
Vienna
Warsaw
Munich
Amsterdam
Cologne
Geneva
Basel
Zurich
Copenhagen
London
Athens
Leeds
Brussels
Stockholm

U.S. EPA National Ambient Air Quality Standards

(NAAQS) http://www.epa.gov/air/criteria.html



	Primary Standards		Secondary Standards	
Pollutant	Level	Averaging Time	Level	Averaging Time
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	35 ppm (40 mg/m^3)	1-hour (1)		
Lead	0.15 µg/m^3 (2)	Rolling 3-Month Average	Same as Primary	
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Nitrogen Dioxide	0.053 ppm (100 µg/m^3)	Annual (Arithmetic Mean)	Same as Primary	
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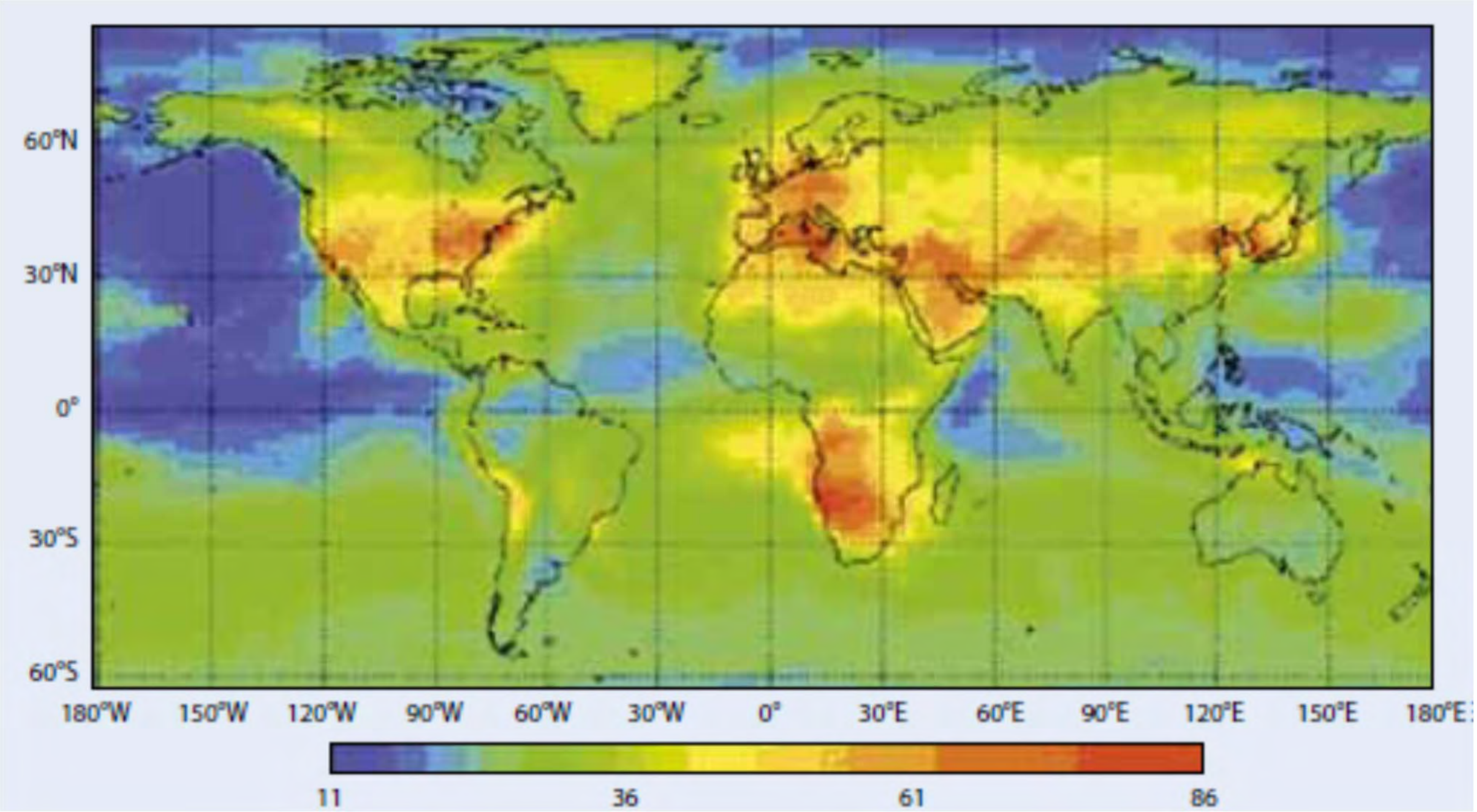
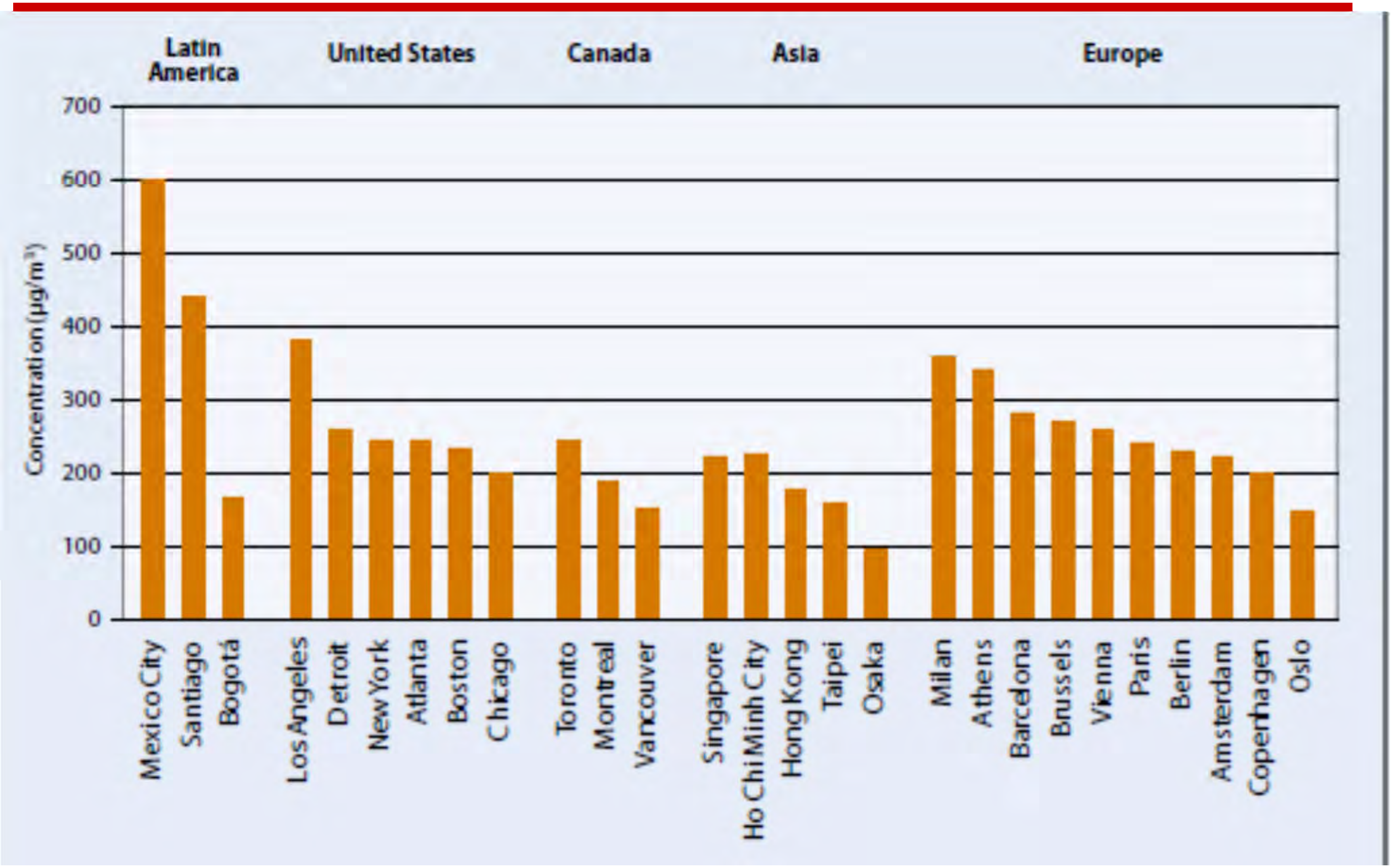
	0.12 ppm	1-hour (8)	Same as Primary	
Sulfur Dioxide	0.03 ppm	Annual (Arithmetic Mean)	0.5 ppm (1300 µg/m^3)	3-hour (1)
	0.14 ppm	24-hour (1)		

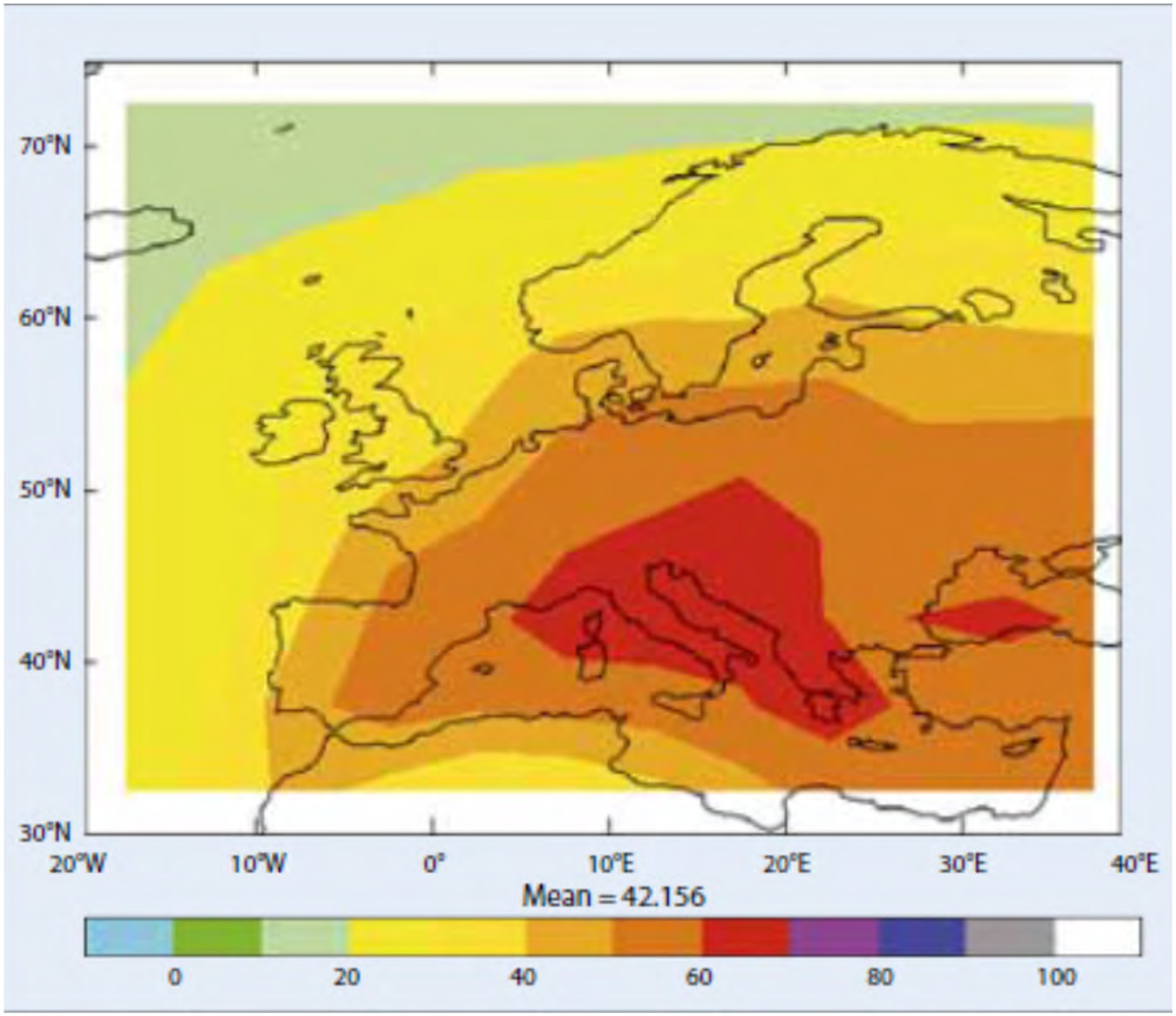
Mean afternoon (13:00 to 16:00) surface ozone concentrations calculated for the month of July (comment: where are people living?)



Highest (1-hour average) ground-level ozone concentrations measured in selected cities



Modeled surface ozone concentrations (ppb) over Europe during July for the years 2000– 2009



Indoor O_3 concentration as a function of outdoor concentration and ventilation rate

	Outdoor Air Ozone Concentration (parts per billion)									
AER (h^{-1})	20	40	60	80	100	120	140	160	180	200
1	5	10	15	20	25	30	35	40	45	50
2	7	15	22	30	37	45	52	60	67	75
4	11	22	33	44	55	66	77	88	99	110
6	13	26	40	53	66	79	92	106	119	132
12	16	32	48	64	80	96	112	128	144	160
20	18	36	54	72	90	108	126	144	162	180

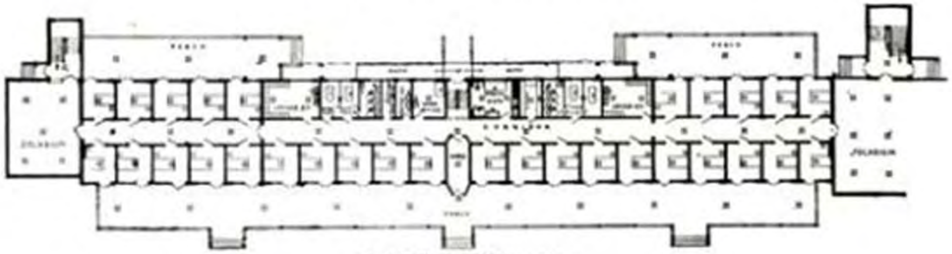
Immune compromised patients

- What is the trade-off between reducing the risk of infection by unfiltered outdoor air ventilation and decreasing the airborne concentration of infectious airborne agents?
- Does it depend on the kind and level of pollution?
- Does it depend on the kind of level of infectious agent?
- Does it depend on the health status of the patient?
- Does it depend on the age and life expectancy of the patient?
- Is there a simple answer to this dilemma?

Building configuration

· K♥ CENTER · SECTION · FIRST FLOOR

TUBERCULOSIS WARDS (INFIRMARY)

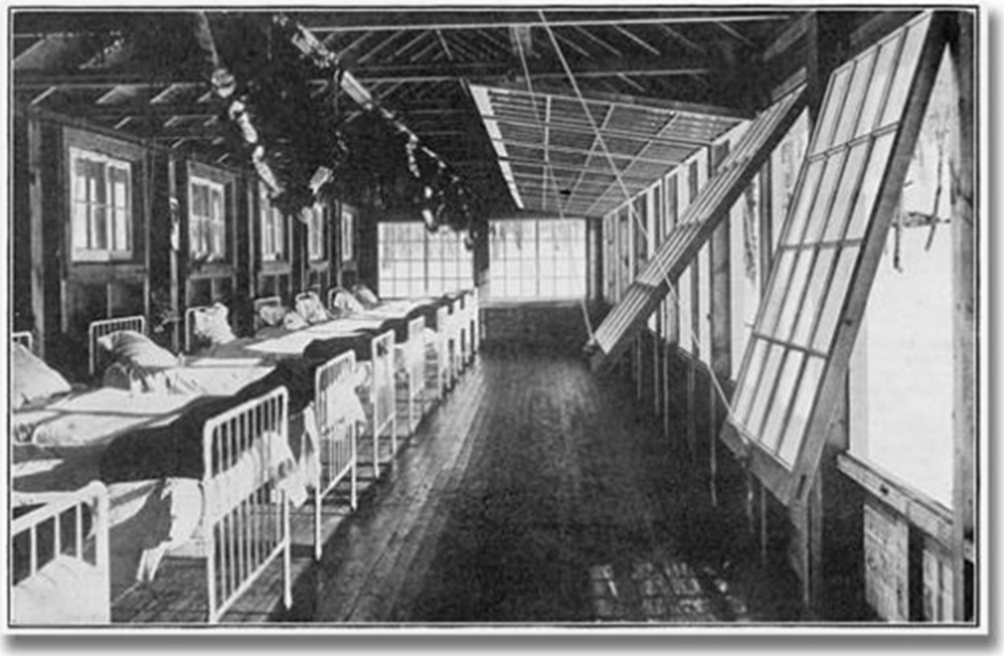


· K♥ LEFT · SECTION · FIRST FLOOR

FIG. 27.

Management of openings

- Who’s in charge here?
- What if the weather is bad?
- What if it’s smoky outside?
- Security?



Measurement issues

- How do you confirm adequate outdoor air ventilation in a naturally-ventilated healthcare facility?
- Methods for approximation available, precise numbers are not feasible …. Nor necessary.
- Carbon dioxide from occupants simply not technically valid for high air change rates – 6 to 12 ach.
- Only under special conditions can CO_2 be used in lower occupant density spaces – steady conditions, not usually present for natural ventilation.
- Air flow direction can be and should be confirmed.

Natural Ventilation: Theory Summary - Review

Purpose of ventilation What is ventilation?

Types of natural ventilation (Driving forces):

- Buoyancy (stack effect; thermal)
- Pressure driven (wind driven; differential pressure)

Applications

- Supply of outdoor air
- Convective cooling
- Physiological cooling

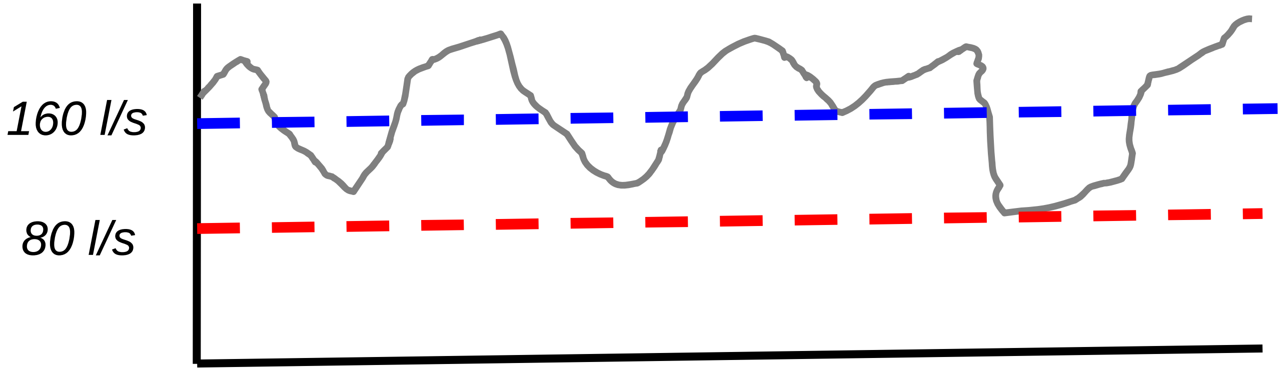
Issues

- Weather-dependence: wind, temperature, humidity
- Outdoor air quality
- Immune compromised patients
- Building configuration (plan, section)
- Management of openings
- Measurement and verification

WHO 2009 NatVent Guideline – key ideas

(source: Y. Li, HB2009, Syracuse.)

- **For natural ventilation, a minimum hourly averaged ventilation rate of 160 L/s/patient for airborne precaution rooms (with a minimum of 80 L/s/patient).**



- When natural ventilation alone cannot satisfy the requirements, mechanically assisted natural ventilation system should be used.

- **Overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.**

Keys to Natural Ventilation for Infection Control in Healthcare Settings

- Air change rate
  - Ensure adequate average flow and minimum flow specifications are met
  - Approximate measurements under all weather and building operational conditions
  - Measurements , Verification
- Air distribution:
  - Flow direction:
    - Away from infected - verify
    - Ensure and verify consistency under all ventilation regimes
  - Flow of infectious agents directly out of building
  - Avoid flow toward other patients, especially susceptibles
- Management plan

Natural Ventilation: Theory References

Allard, Francis, Mat Santamouris, Servando Alvarez, “Natural ventilation in buildings.” European Commission. Directorate-General for Energy, ALTENER Program. on-line: t *http://books.google.com/books?hl=en&lr=&id=1tdQMyhPA2gC&oi=fnd&pg=PR9&dq=Natural+ventilation+theory&ots=mFzmfd4mct&sig=XA3zksH_OBkkS8tILbxmwJqbWyo*

Andersen, Karl Terpager, 2003. Theory for natural ventilation by thermal buoyancy in one zone with uniform temperature. *Building and Environment* **38**: 1281–1289.

Heiselberg, P., Ed., 2002. *Principles of Hybrid Ventilation*. IEA-ECBS Annex 35 report. Downloadable from http://hybvent.civil.auc.dk/

Li ,Yuguo, 2000. Buoyancy-driven natural ventilation in a thermally stratified one-zone building.” *Building and Environment* **35**: 207-214.

Nielsen, P. V. 2009, Control of airborne infectious diseases in ventilated spaces, *J. R. Soc. Interface 2009 6,* S747-S755. available at http://rsif.royalsocietypublishing.org/*.*

WHO, 2005. *Air Quality Guidelines, 2005 Update*. Geneva: World Health Organization. http://www.who.int/phe/health_topics/outdoorair_aqg/en/

WHO, 2009. Natural Ventilation for Infection Control in Health-Care Settings. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/natural_ventilation.pdf

Natural Ventilation: Measurement Challenges

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Building Design and Engineering Approaches to Airborne Infection Control
Harvard School of Public Health – August 2, 2012

Steady State (*theoretical*) basis for fully mixed room

$$C(t) - Co = S\,(1 - e^{-at}) / aV$$

where

c(t) = indoor concentration (volumetric proportion) at time t,

Co = constant outdoor concentration (volumetric proportion),

S = generation rate of the source (volume per time unit),

a = air change rate (per time unit),

t = time, and

V = volume in the occupied space.

Requirements for satisfying quasi steady state conditions during build-up period

- Constant number of occupants
- Constant occupant metabolic rate
- Constant outdoor air CO_2 concentration
- Constant ventilation rate (mechanical, leakage, and entry from adjacent (connecting) spaces all at same conditions of occupancy and ventilation

- Are these conditions ever met in your experience?

CO_2 is easy to measure, right?

Not!

It is easy to calculate or assess ventilation based on CO_2 measurements, right?

- *C(t) - Co = S(1 - e-at)/aV*

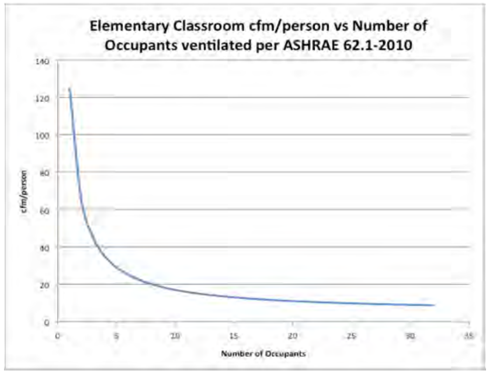
At=	Percent Steady State	Hours required at alternative ACH				
		ACH-0.25	ACH=0.5	ACH=.75	ACH=I.0	ACH=2.0
1	63.21%	4	[illegible]	1.33	1	0.5
2	86.47%	8	[illegible]	2.67	2	1
3	95.02%	12	[illegible]	4	3	[illegible]
4	98.17%	16	[illegible]	5.3[illegible]	4	[illegible]
5	99.33%	20	10[illegible]	6.[illegible]	5	2.5

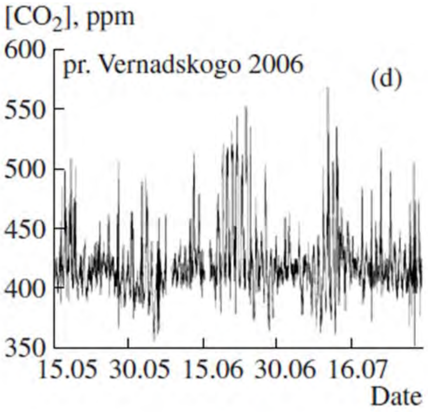
Steady State Ind-Out CO_2 (ppm)	Outdoor Air (cfm/p)	Outdoor air (L/s-p)
4700	2	1
22[illegible]0	5	2
[illegible]0	6	3
[illegible]	9	4
[illegible]00	15	7
[illegible]00	18	8
[illegible]500	21	10

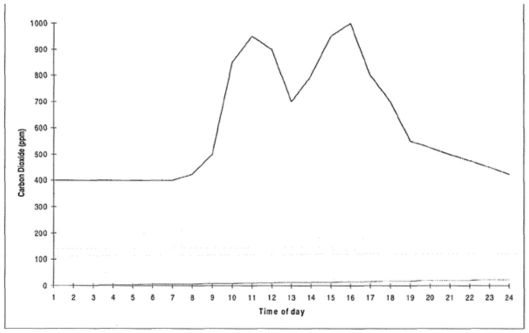
Not!

Css- Co = s/c

Css-Co = S/aV.



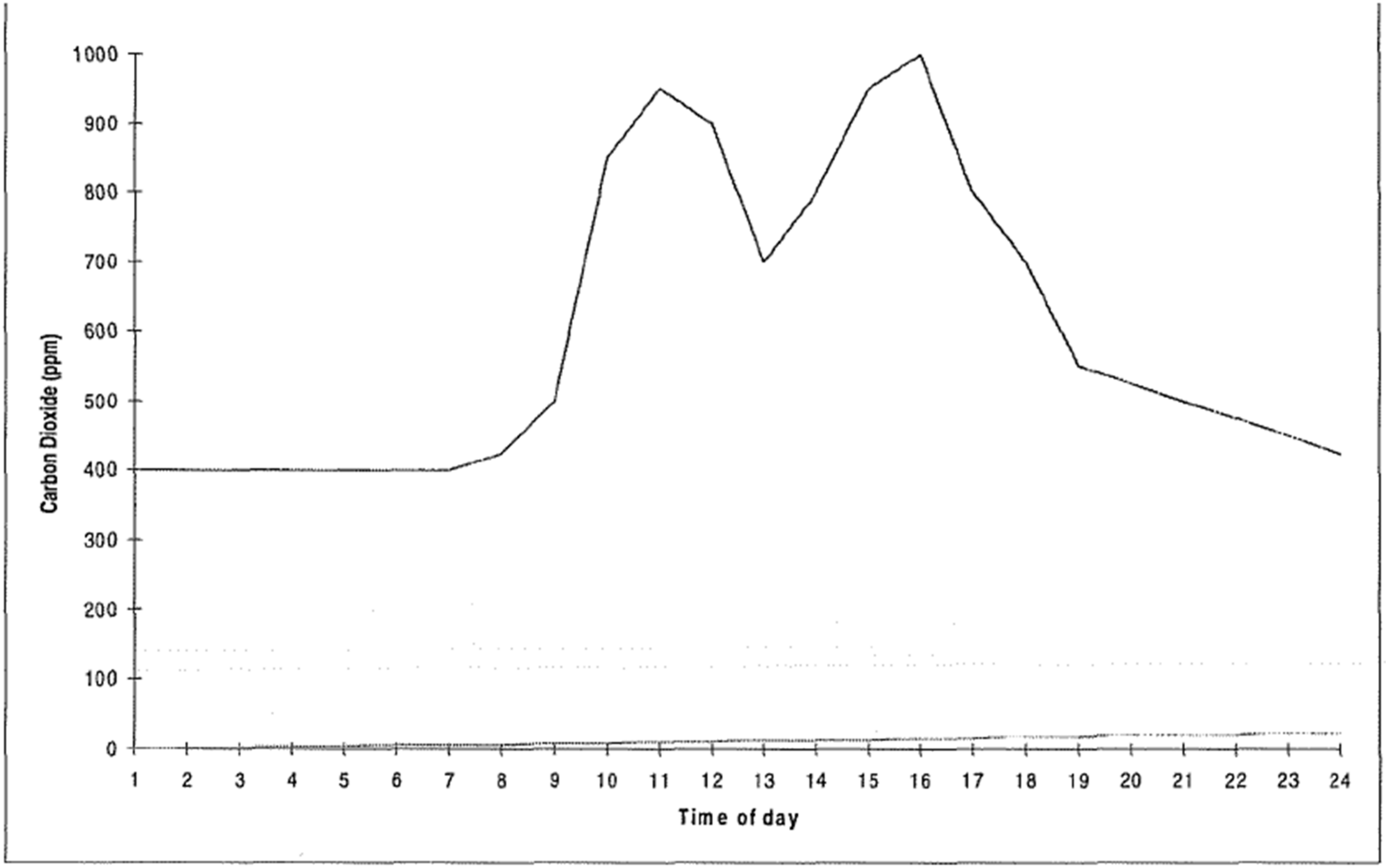




Basic theory of CO_2-ventilation relationships

- Typical CO_2 concentration in relation to occupancy
- Steady State theoretical basis
- Indoor and outdoor sources of CO_2
- Indoor – Outdoor (I-O) CO_2 relationships
- Variations in occupant generation rates- metabolism as a function of activity, gender, age, health status
- Steady state construct and reality in real world buildings
- Variable outdoor air concentrations

Lag time: Typical CO_2 concentration in relation to typical office building occupancy



Indoor and outdoor sources of CO_2

OUTDOOR CO_2

- CO_2 outdoor sources dominated by combustion processes
- CO_2 outdoors is removed by plants – concentrations in a forest can be 10s of ppm below global ave. concentrations
- Global average >390 ppm rising approximately 3 ppm/year
- Urban concentrations can be ~50 to 200 ppm higher than global average concentrations (425 – 600 ppm)

INDOOR CO_2

- People, animals exhale concentrations of 20 to 40 * 10^3 ppm

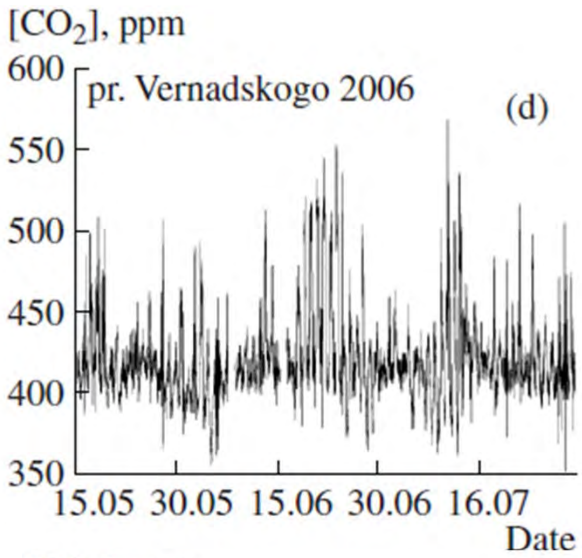
Variable outdoor air concentrations
390-600 ppmv today!

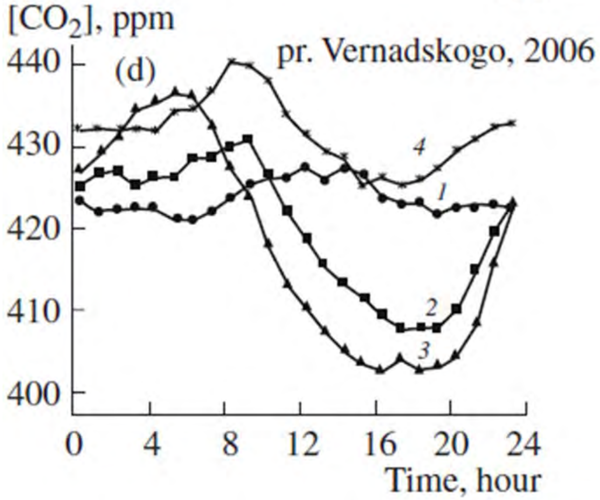
TIME DEPENDENCY

- Daily – traffic, power plants, process combustion
- Weekly – commuters, recreation
- Seasonal – plant growth, foliage; temperature, humidity, wind

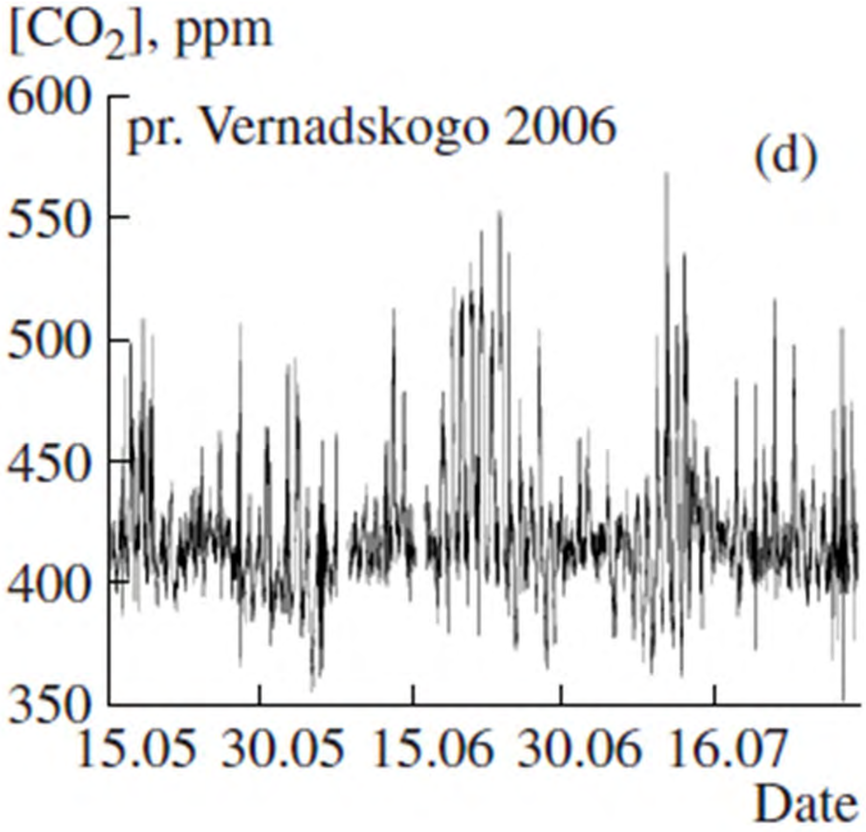
LOCATION DEPENDENCY

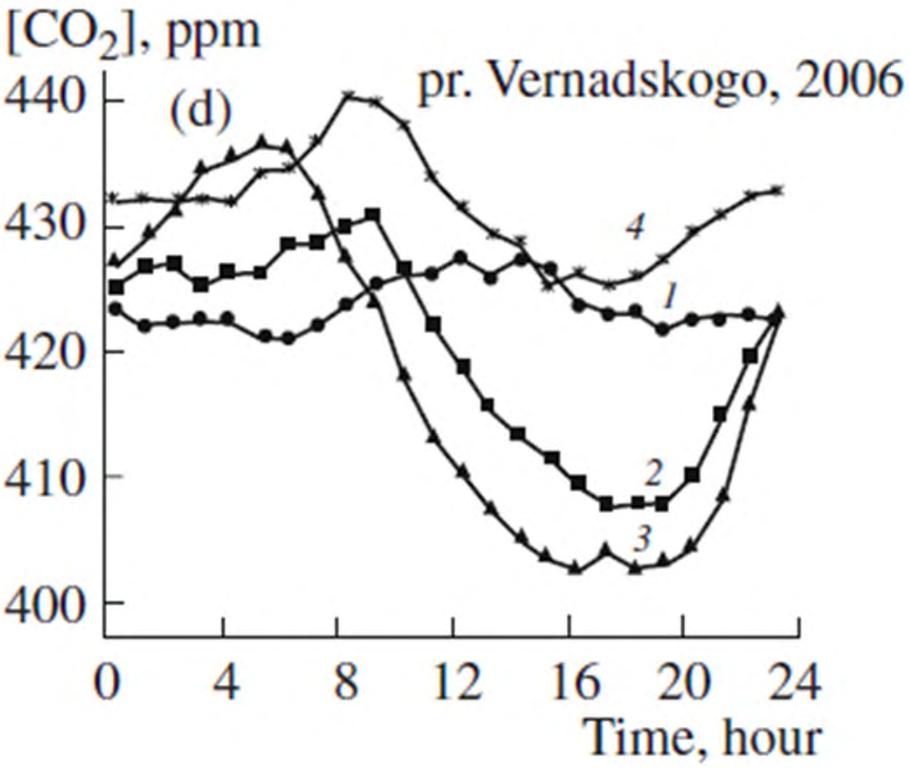
- Near power plants, other strong point sources
- Near roadways, parking lots
- Population density (urban-rural), building-roadway ratios
- Height above the ground
- Near dense forests (even urban)





Time-, day-, and Season-dependent variation in outdoor CO_2

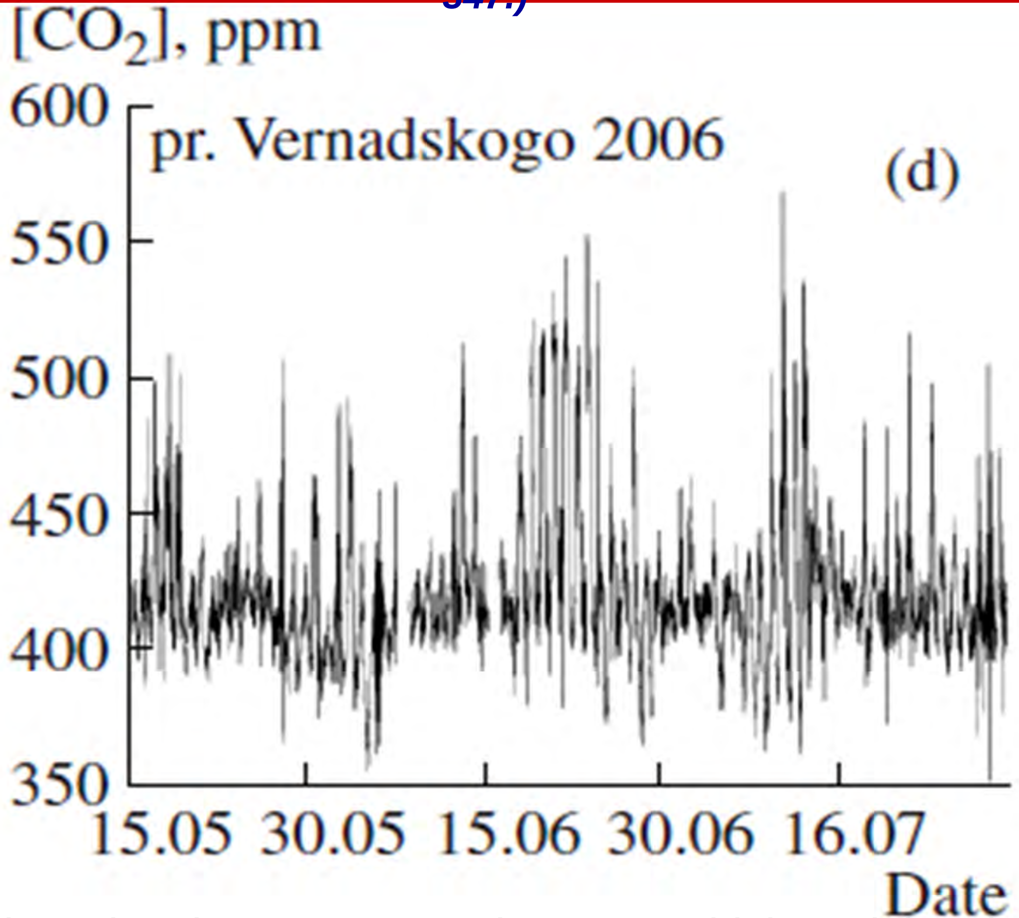




(1) winter, (2) spring, (3) summer, and (4) fall.

“Typical” CO_2 concentrations in urban air?

(Gorchakov et al, 2008. *Izvestiya AN. Fizika Atmosfery i Okeana, 2009, Vol. 45, No. 3, pp. 337–347.)*

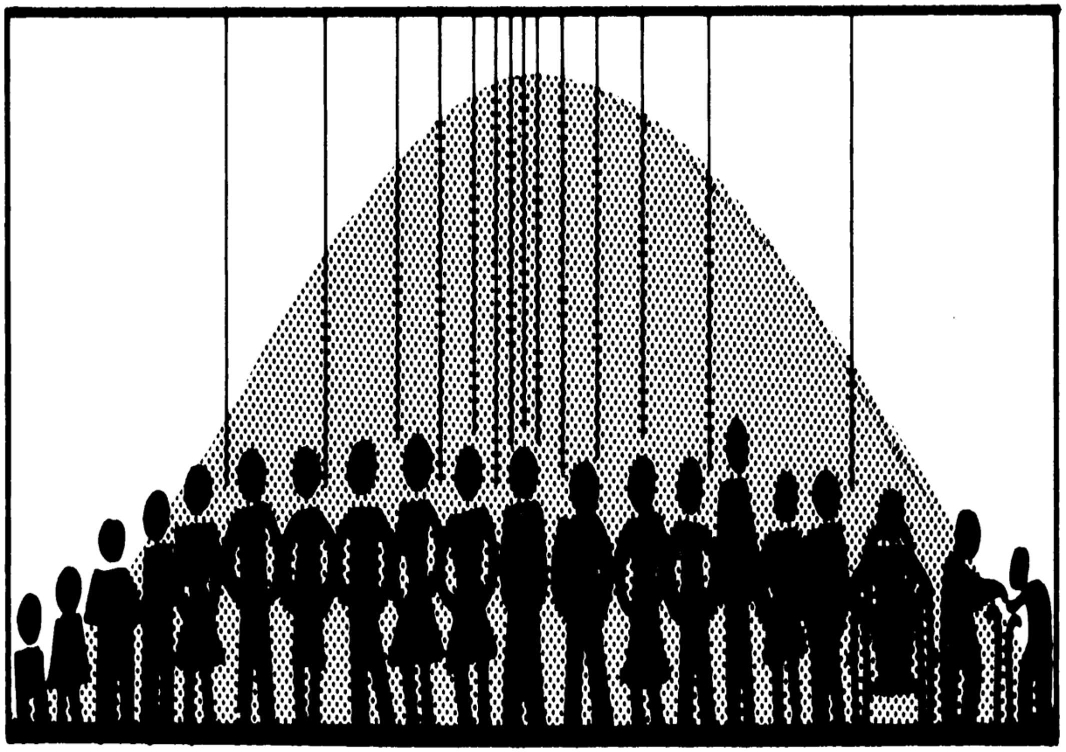


It is evident from Fig. 1 that these concentrations vary widely and that the diurnal cycle and intradiurnal variability of concentrations are important for all of the gaseous components considered here. In particular, the range of intradiurnal variations of carbon dioxide concentration reaches 150 ppm with a noise component near ±5 ppm.

Variations in occupant generation rates-

METABOLISM AS A FUNCTION OF…

- **Activity level (metabolic rate)**
- **Diet (metabolic rate)**
- **Gender (?)**
- **Age (size?)**
- **Health status**
- **Stress (Wang, 1971, *ASHRAE Transactions*)**



Steady state construct and real world buildings

In summary

"Everything changes"

- **Suzuki Roshi**
- **(contemporary Zen master)**

Issues: use of CO_2 measurement devices

- Requirements for satisfying quasi steady state conditions
- Accuracy and stability of sensors
- Calibration issues
- Portable vs. fixed monitors
- Multiple vs single sensor measurements
- Lag time, short time periods of activity, intermittent occupancy
- Special issue of high density occupancy
- Variability among measurement devices
- Use of CO_2 for Demand Controlled Ventilation (DCV)
- Approaches to correcting for problems

Accuracy of CO_2 Sensors in Commercial Buildings:
A Pilot Study

Fisk, Faulkner, and Sullivan, 2006. LBNL Report 61862

Many anecdotal reports of poor CO_2 sensor performance in actual commercial building applications.

Evaluated the accuracy of 44 CO_2 sensors located in nine commercial buildings to determine if CO_2 sensor performance, in practice, is generally acceptable or problematic.

CO_2 measurement errors varied widely, sometimes hundreds of ppm.

Despite its small size, study indicates accuracy of CO_2 sensors used in commercial buildings frequently less than needed to measure peak indoor-outdoor CO_2 concentration differences with less than a 20% error.

Conclusion: there is a need for more accurate CO_2 sensors and/or better sensor maintenance or calibration

Accuracy and stability of sensors

Shrestha et al, 2009. An Experimental Evaluation of HVAC Grade Carbon-Dioxide Sensors: Part 2, Performance Test Results

- Fifteen models of NDIR HVAC-grade CO_2 sensors were tested and evaluated to determine the accuracy, linearity, repeatability, and hysteresis of each sensor.
- The sensors were tested at 40% relative humidity, 73^oF (22.8^oC) temperature, 14.70 psia (101.35 kPa) pressure, and at five different CO_2 concentrations (400 ppm, 750 ppm, 1100 ppm, 1450 ppm, and 1800 ppm).
- The test results showed a wide variation in sensor performance among the various manufacturers and in some cases a wide variation among sensors of the same model.

Accuracy and stability of sensors

Shrestha, *ASHRAE Transactions, Pt.1,* 2010

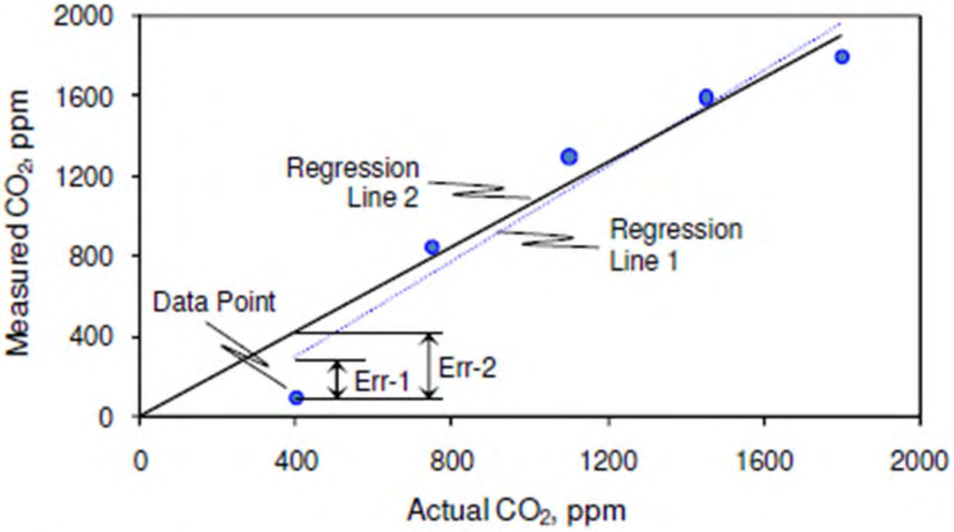
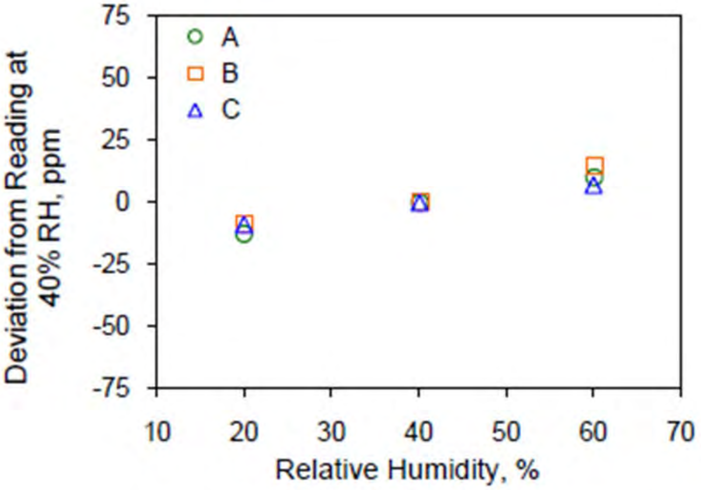
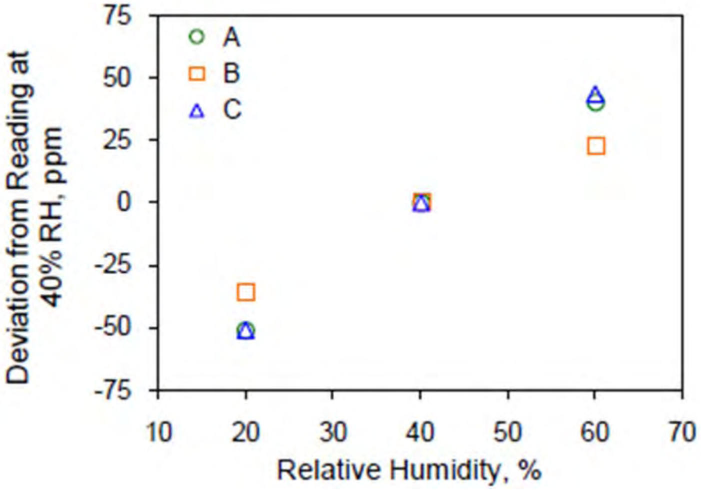


Figure 11. Illustration of linearity error of a CO_2 transmitter.

<u>None</u> of the tested transmitter manufacturers reported humidity sensitivity



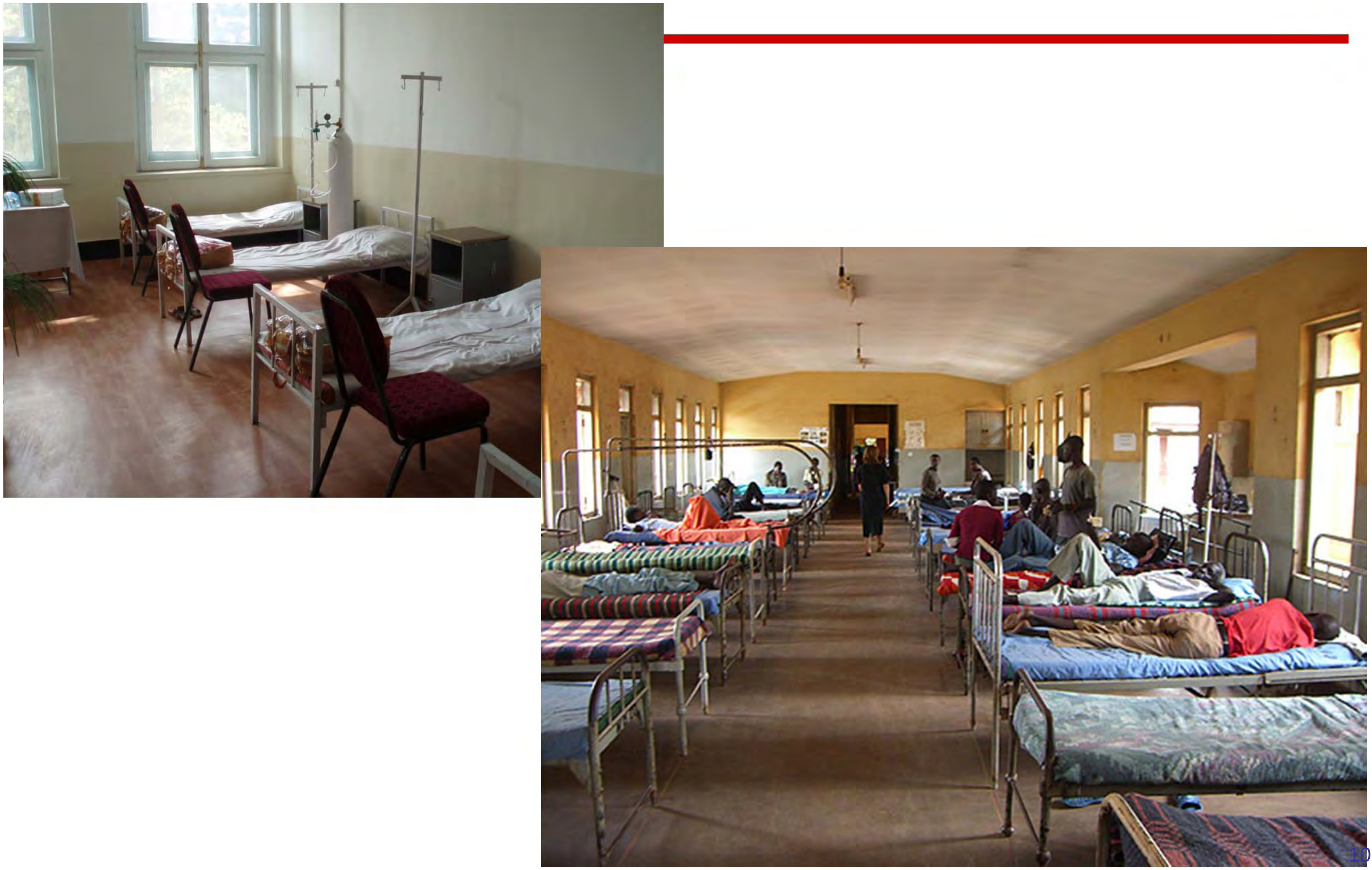


Calibration issues

- Portable handheld monitors are known to lose calibration Easily and must be re-calibrated frequently, perhaps daily, perhaps after any significant move or time has elapsed.

- The need for calibration makes the use of the portable, handheld devices as well as sensors used for DCV far less convenient and useful.

Where to measure ventilation or air flow?

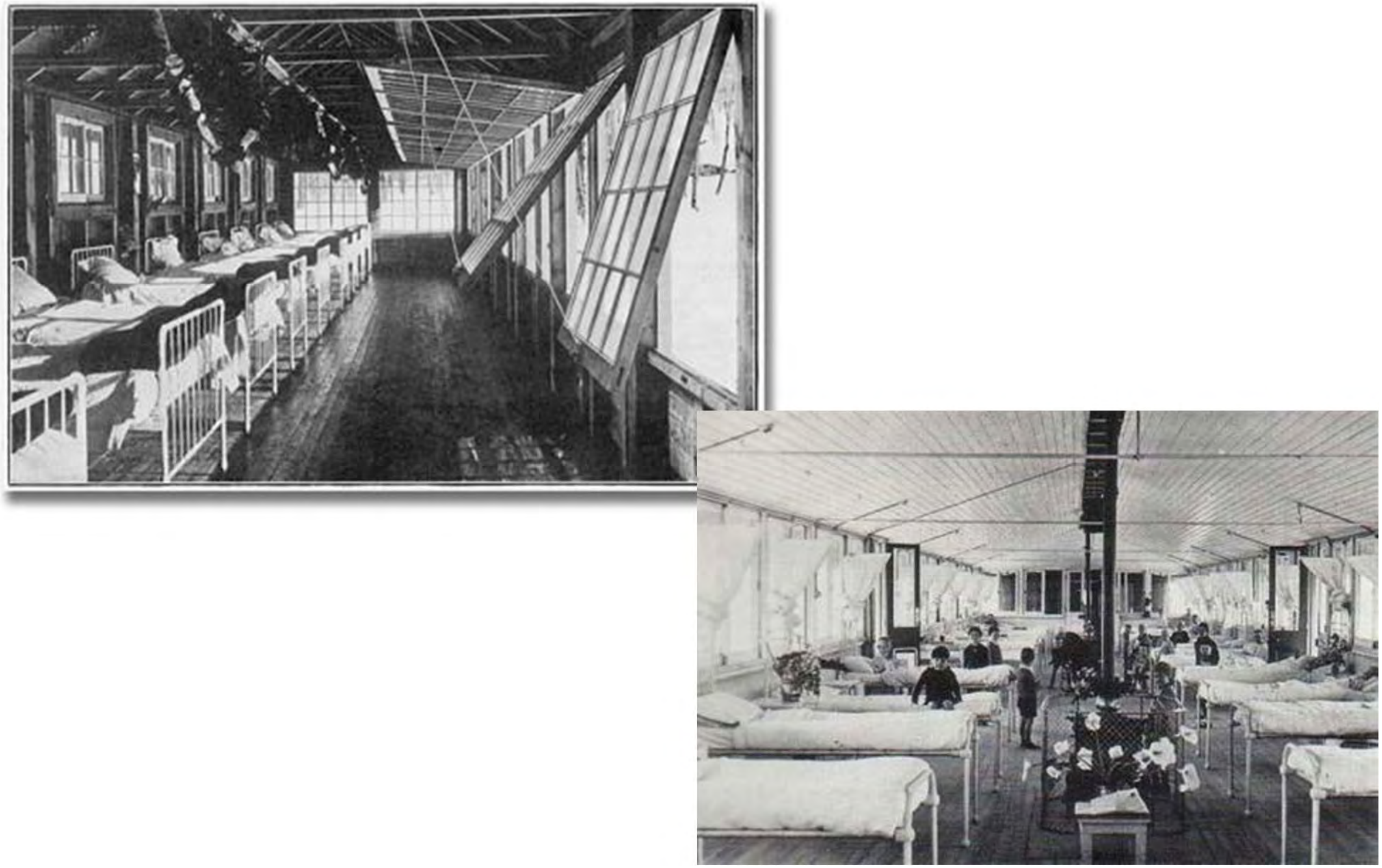


Ventilation- air flow measurement

Air capture hood for air flow measurement

Where to measure air flow?

Where to measure air flow?



What to measure?

CO_2

Air flow rate

ventilation rate

air flow direction

Interpretation of “Results”

- How do we interpret results?
- What does 215 ACH really mean? How do we know the range.
- Is it good to have a lot of ACH part of the day and little the another part?
- Should we simply say poor, OK, and great (or a lot)?