For presentation at Infection Control in Healthcare Facilities
MASS Design and Harvard
Boston, 28 July 2015

Natural Ventilation for Infection Control in Health Care Settings

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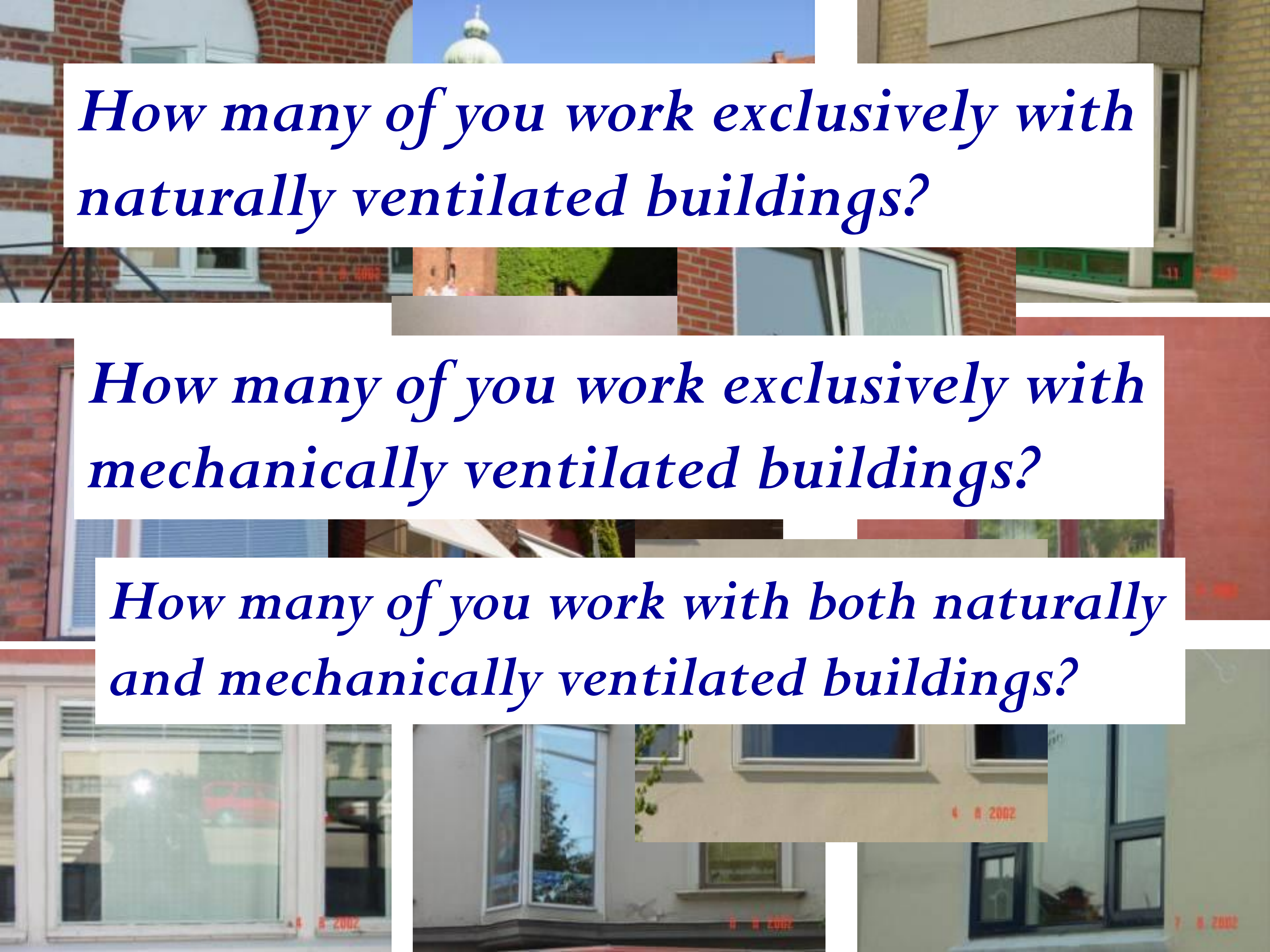


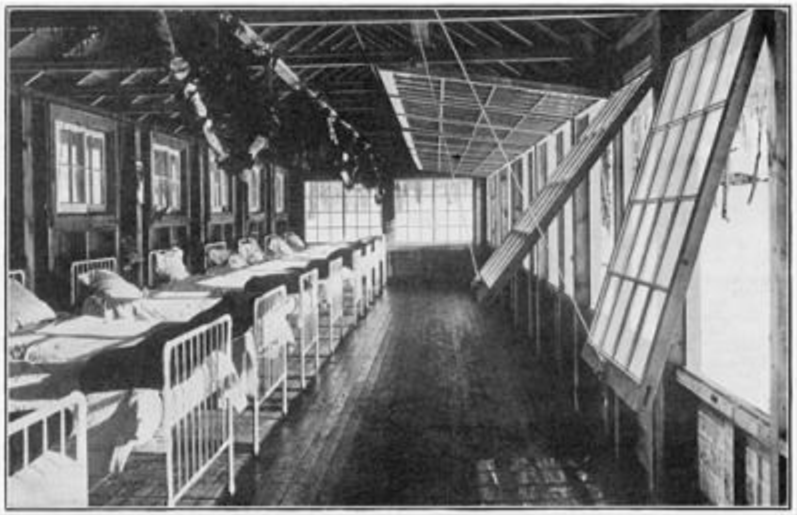
How many of you work exclusively with naturally ventilated buildings?

How many of you work exclusively with mechanically ventilated buildings?

How many of you work with both naturally and mechanically ventilated buildings?

Historical Natural Ventilation of Healthcare

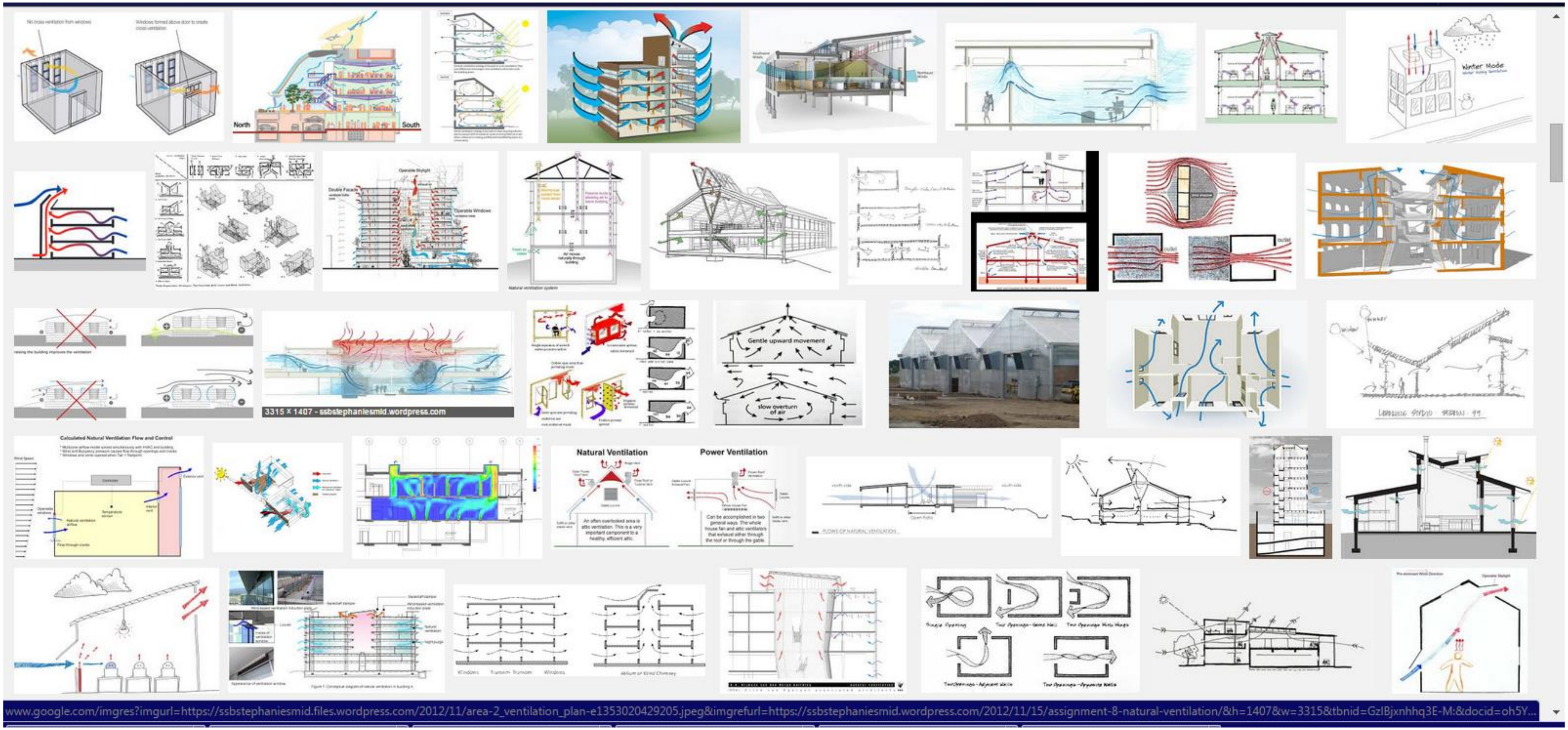
Natural Ventilation for Infection Control in Health Care Settings



What is your climate type?

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

Many designs, approaches
Google: Natural Ventilation images



Many more images available at that site

Natural Ventilation for infection control in healthcare settings: Overview

Definitions

Purpose of ventilation

- What is ventilation? Natural (aka “Passive”) or 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
- Convective cooling
- Physiological cooling

Issues: Focus of this presentation

- Weather-dependence: wind, temperature, humidity
- Outdoor air quality
- 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 either 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'.

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**
- **Thermal conditions controlled**
- **Management plan**

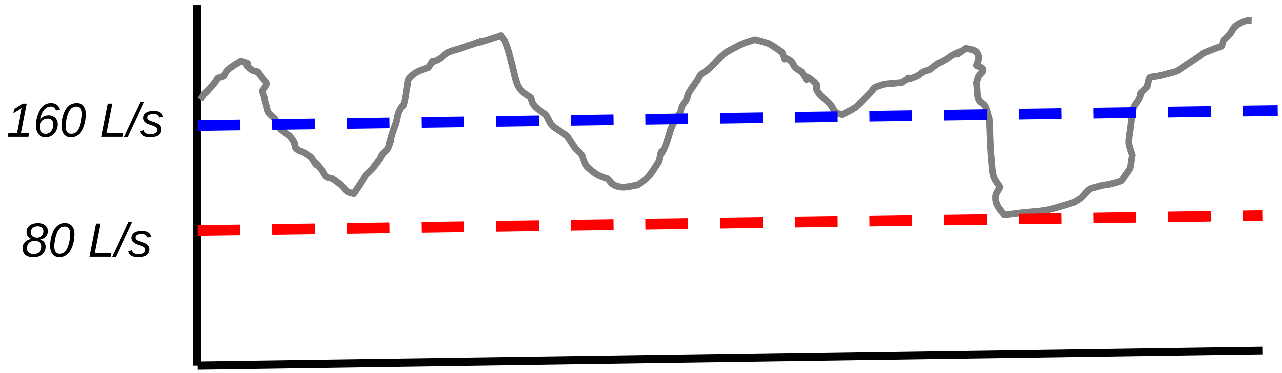
NatVent for healthcare

- 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 (or 80 L/s-p) ,
  - 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.**

Types of natural ventilation – driving forces
It's all about pressure differences

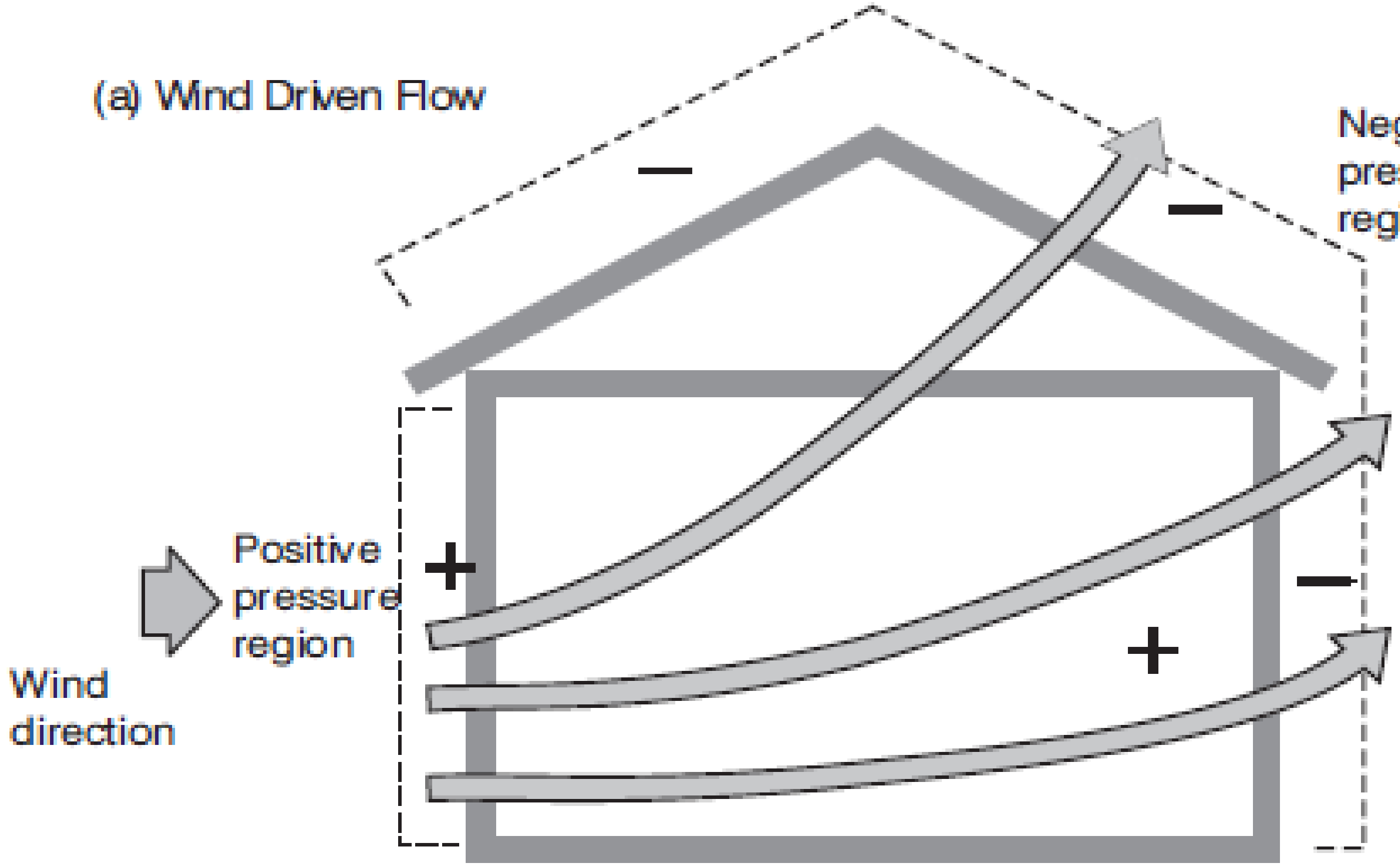
Stack effect (buoyancy)

- 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)

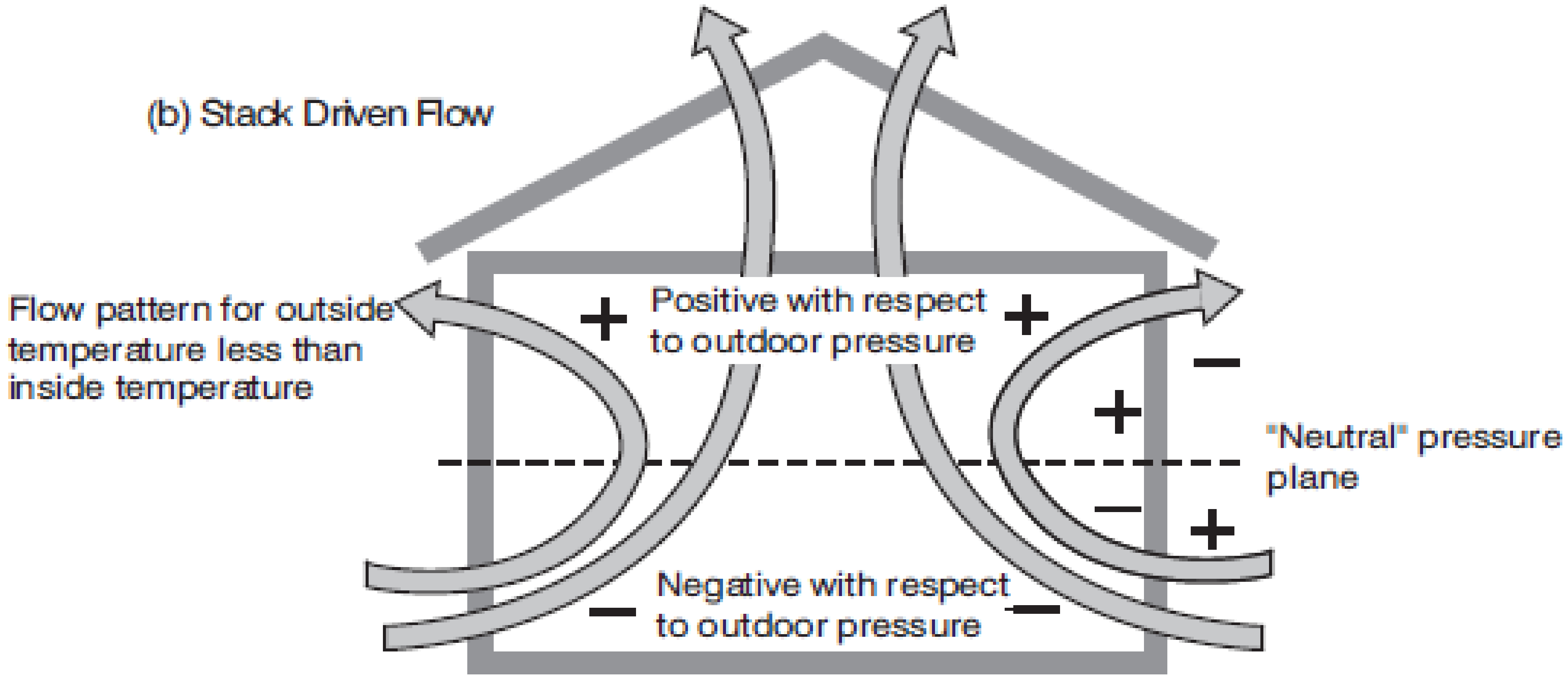
- Pressure differences result in air mass movement
- "Packets" of air flow from higher to lower air pressure regimes

Natural Driving Mechanisms – Pressure: Wind-driven air flow

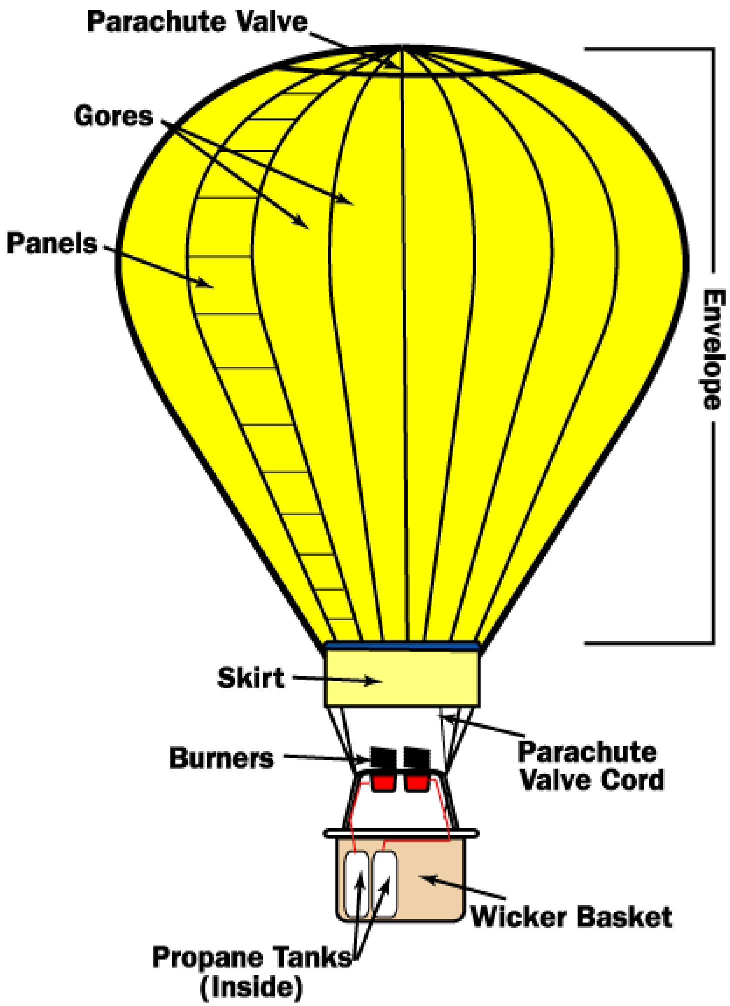


Natural Driving Mechanisms – Pressure: Wind-driven air flow

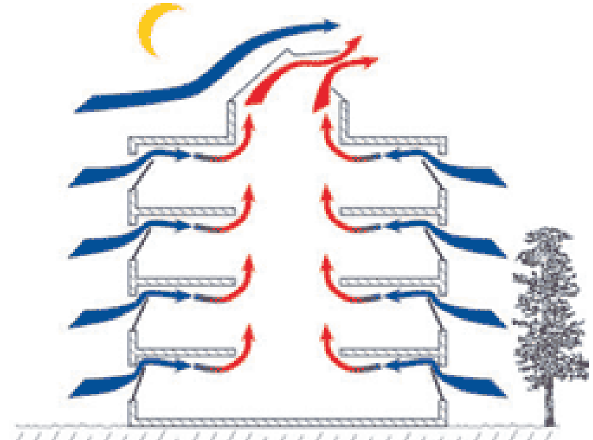
Natural driving mechanisms -- Buoyancy
Stack effect

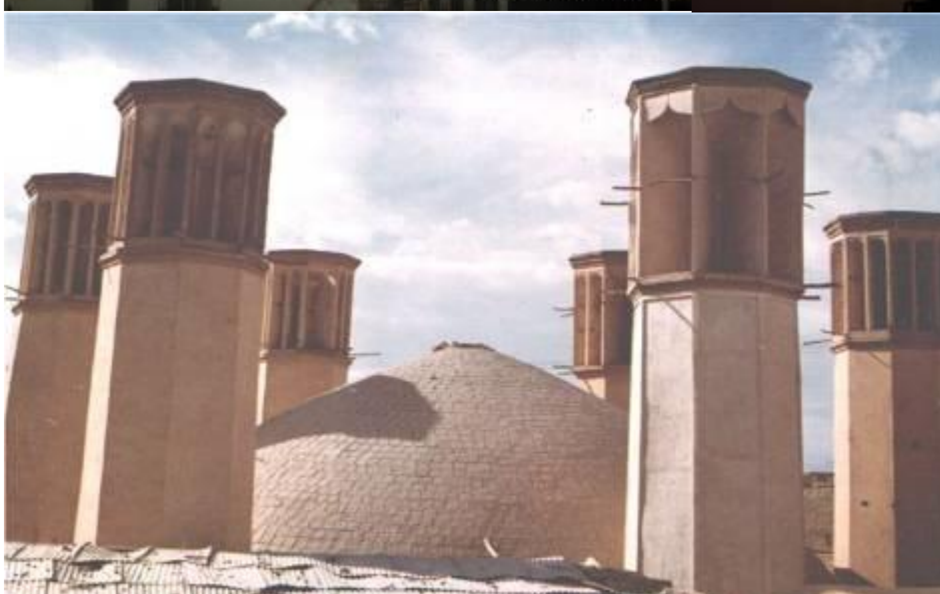


Hot air = buoyancy



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

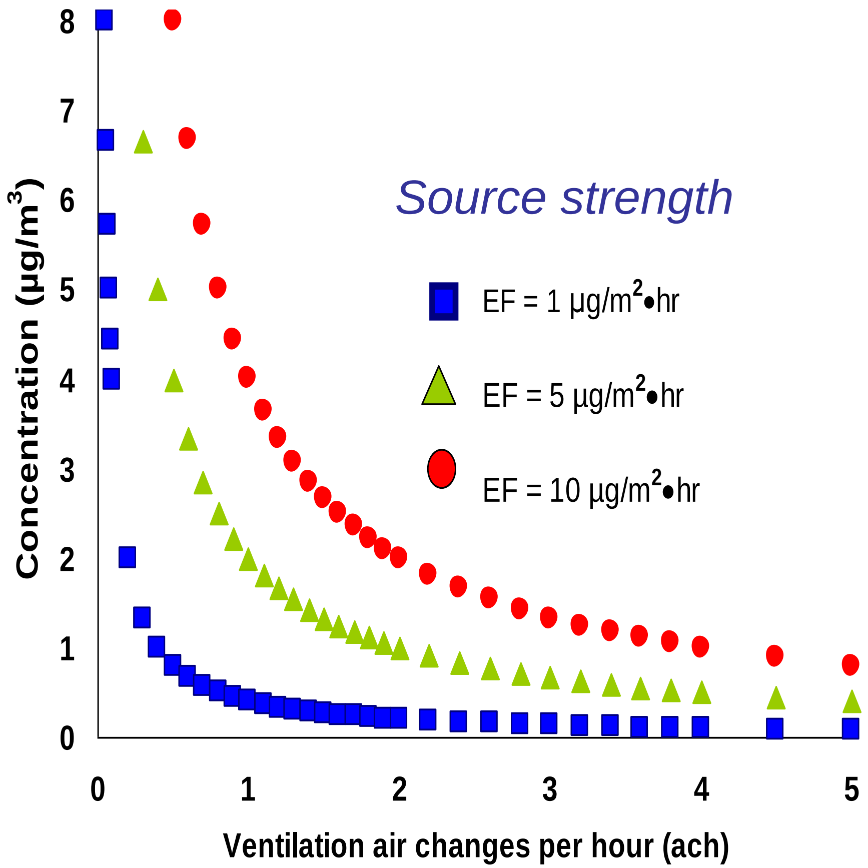


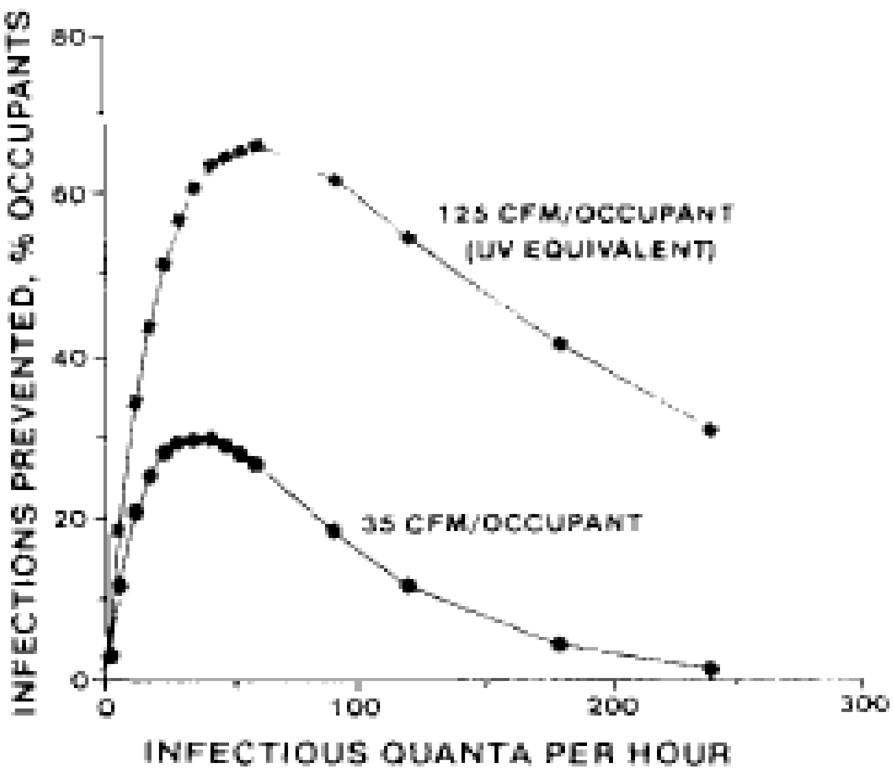


Applications: Supply of outdoor air

- 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": $gcm^{-1}s^{-1}$)

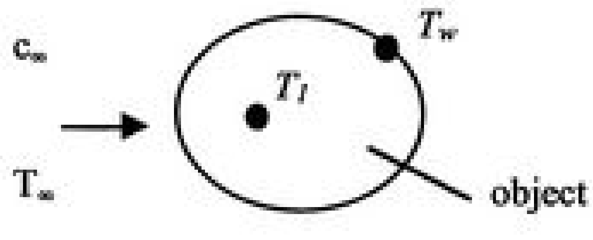
Pollutant concentration as a function of outdoor air exchange rate and source strength





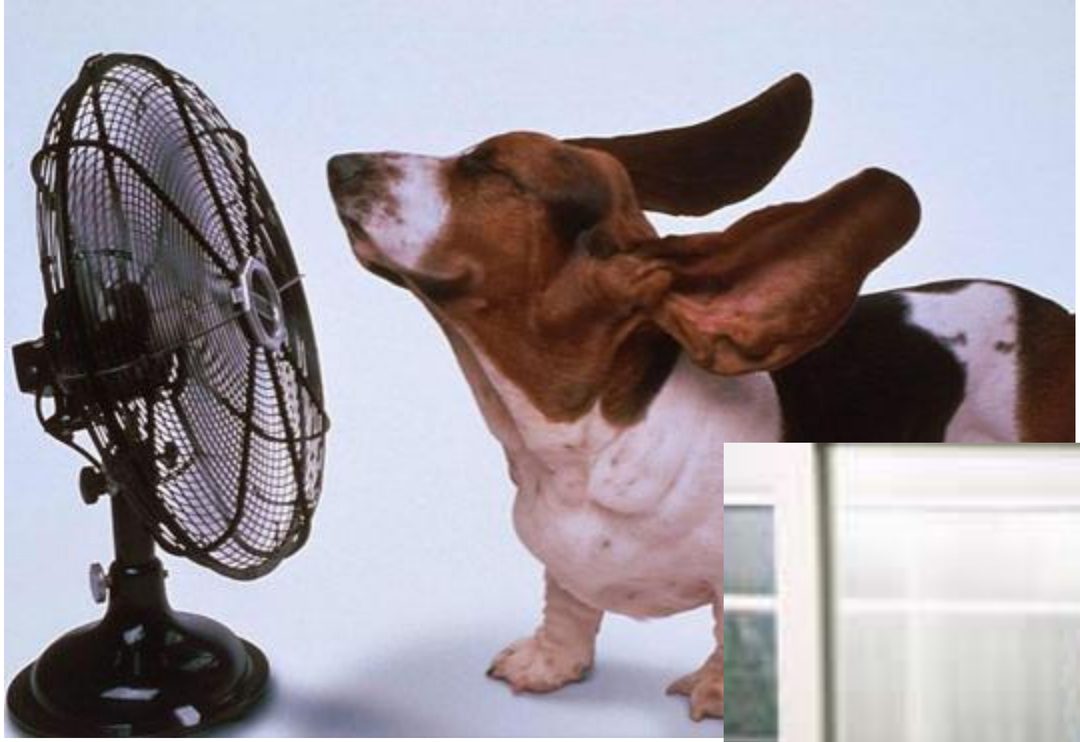
Applications: Convective cooling

- **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 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

What's wrong with this picture?

Eating ice cream has net warming effect.

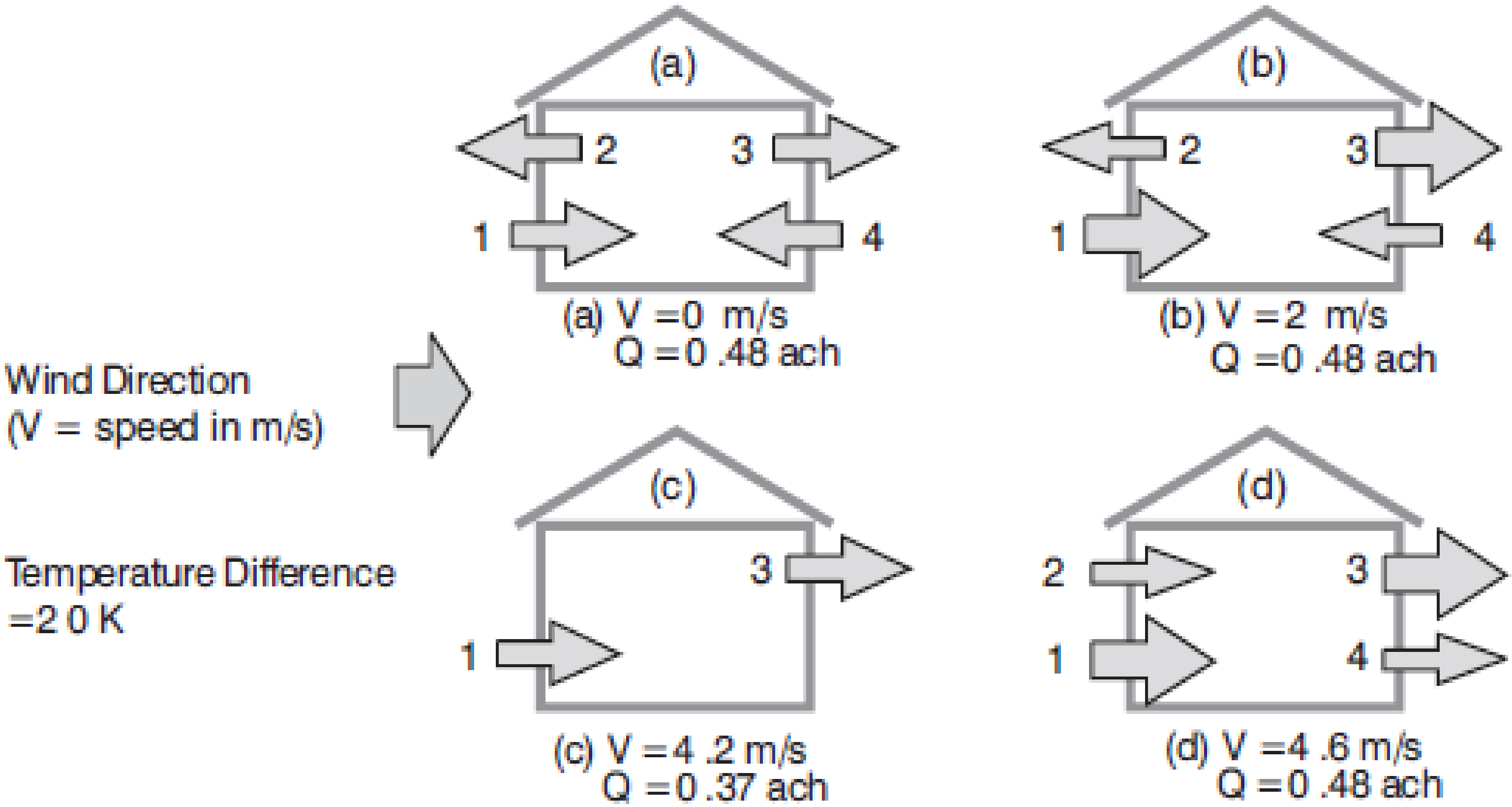
Applications: Physiological cooling

“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

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

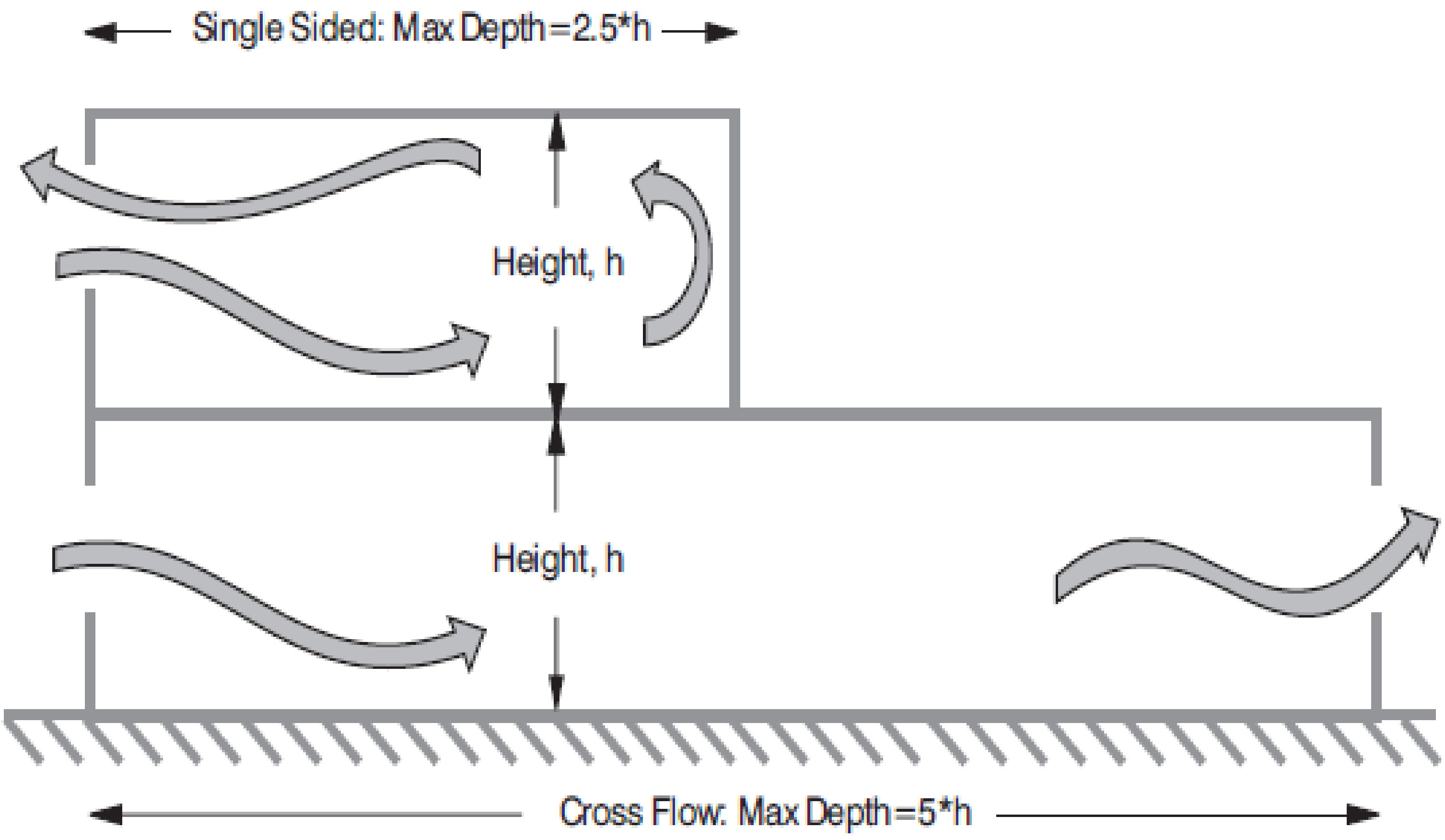


Influence of wind and temperature (stack effect) on ventilation rate and air flow pattern

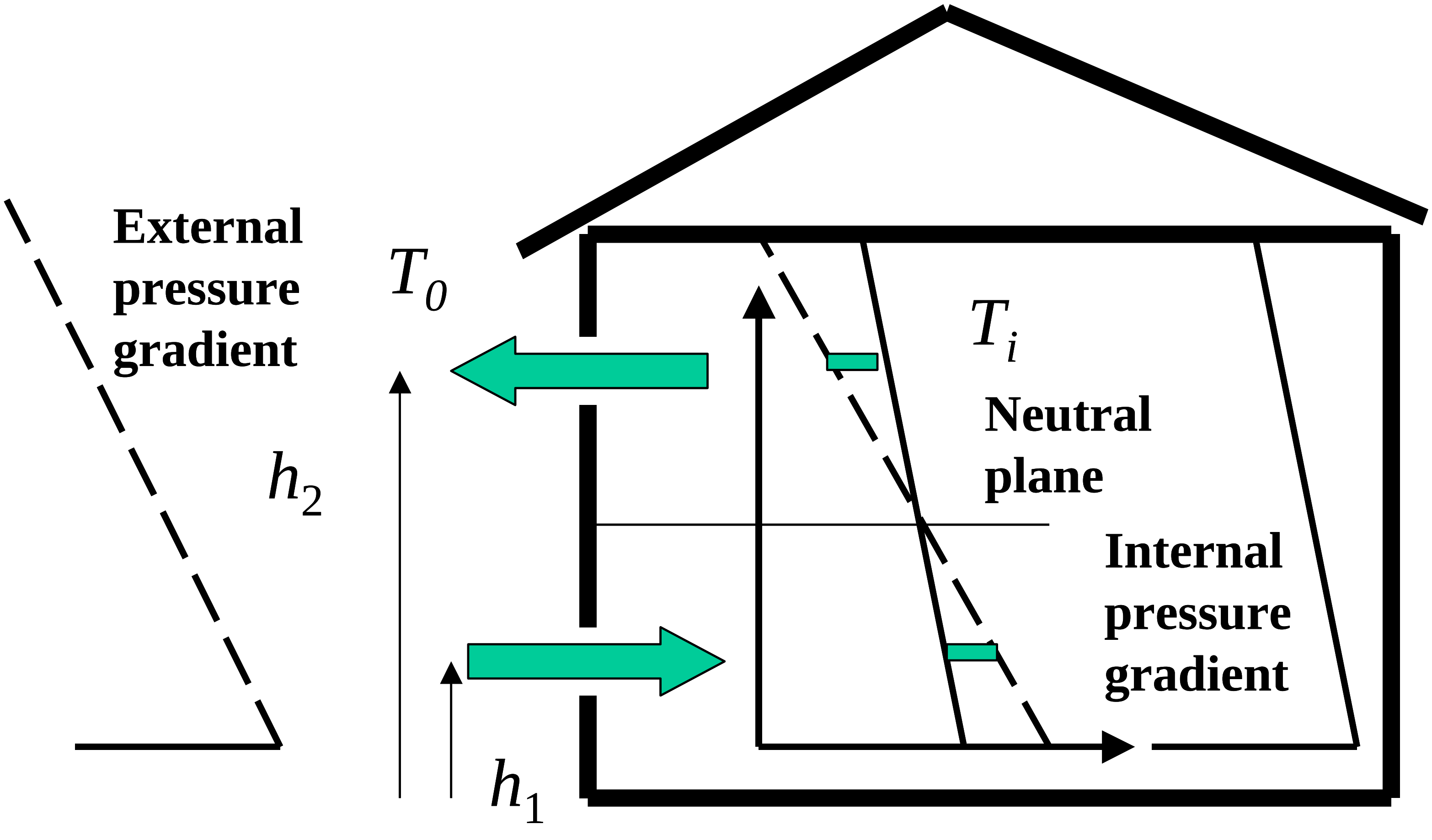
(source: AIVC, 2009)

Single-sided vs. Cross flow ventilation

(source: AIVC, 2009)



Concept of the neutral level



Natural ventilation in buildings

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

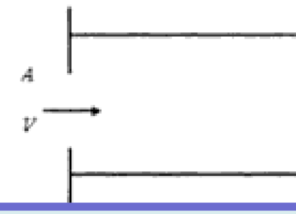
Directorate-General for Energy, ALTENER Program

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.



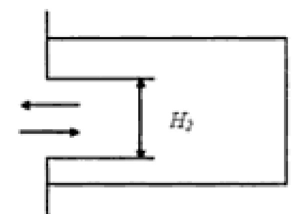
Lots of detailed calculations are possible but most critical factor, wind direction and velocity, fluctuates throughout the day and year.

where C_d is the discharge coefficient

Cross Section

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

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



Cross Section

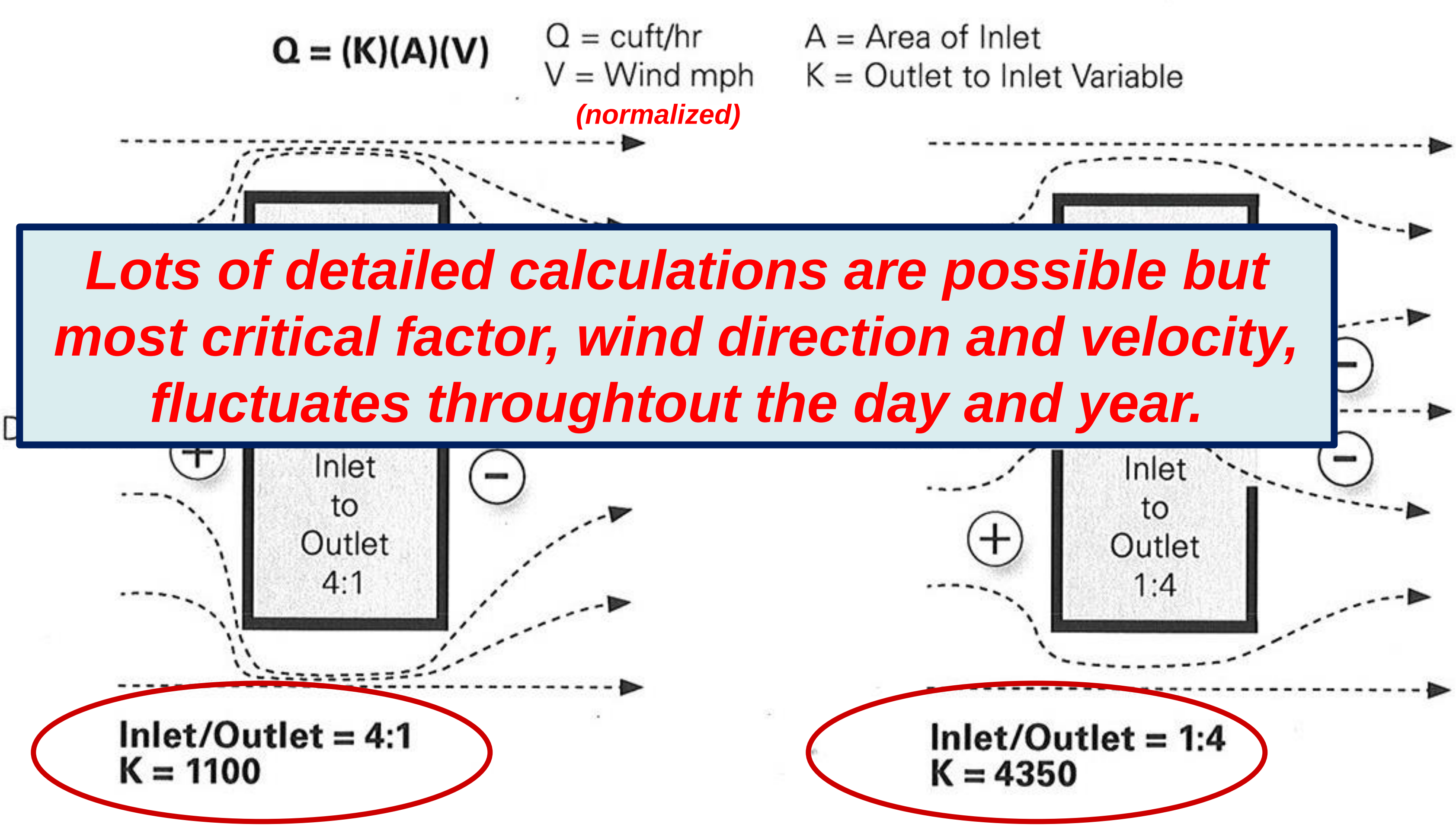
http://books.google.com/books?hl=en&lr=&id=1tdQMyhPA2gC&oi=fnd&pg=PR9&dq=Natural+ventilation+theory&ots=mFzmfd4mct&sig=XA3zksH_OBkkS8tILbxmwJqbWyo

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
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

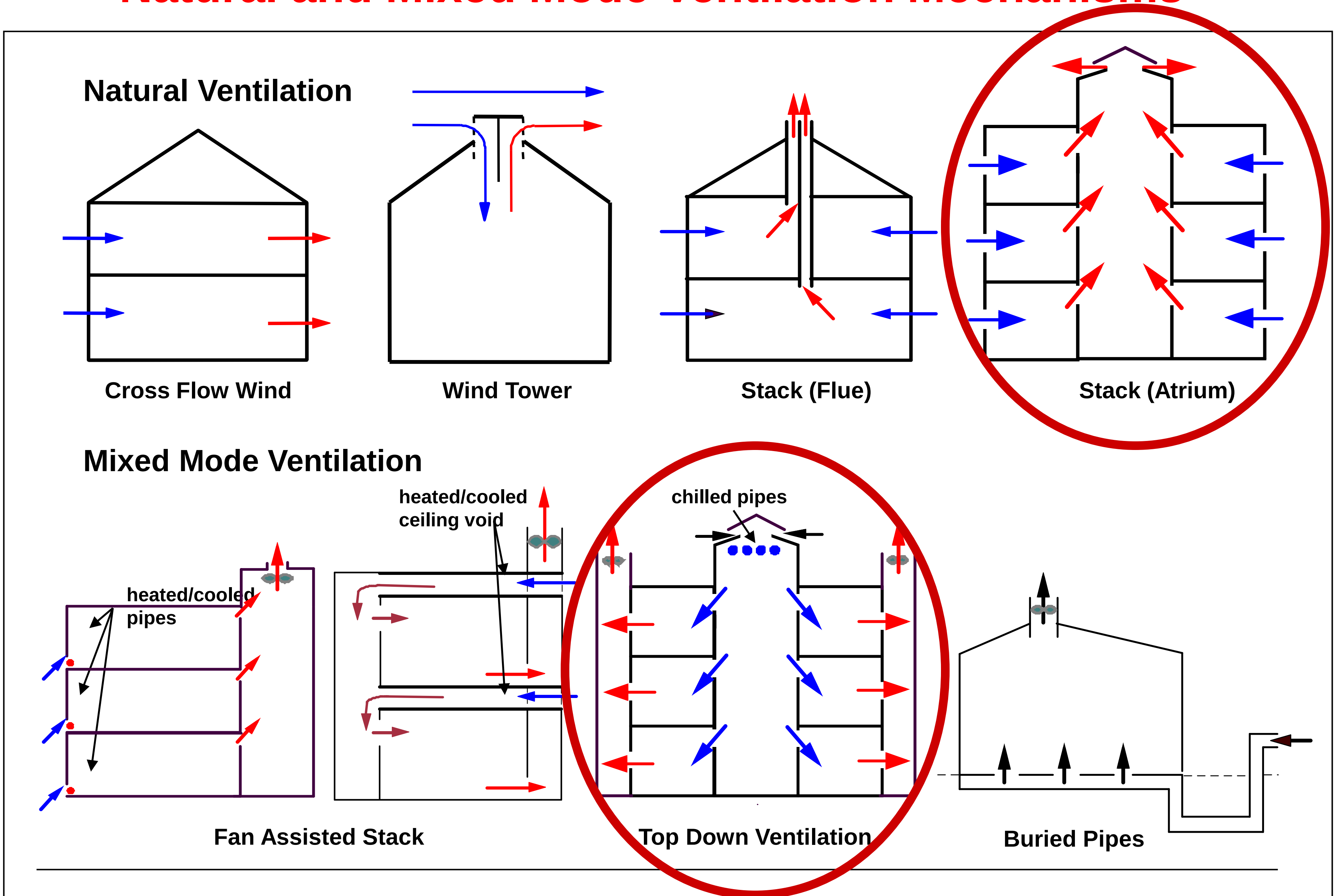
Lots of detailed calculations are possible but most critical factor, wind direction and velocity, fluctuates throughout the day and year.

Simple formulation for Vent Calculation



Lots of detailed calculations are possible but most critical factor, wind direction and velocity, fluctuates throughtout the day and year.

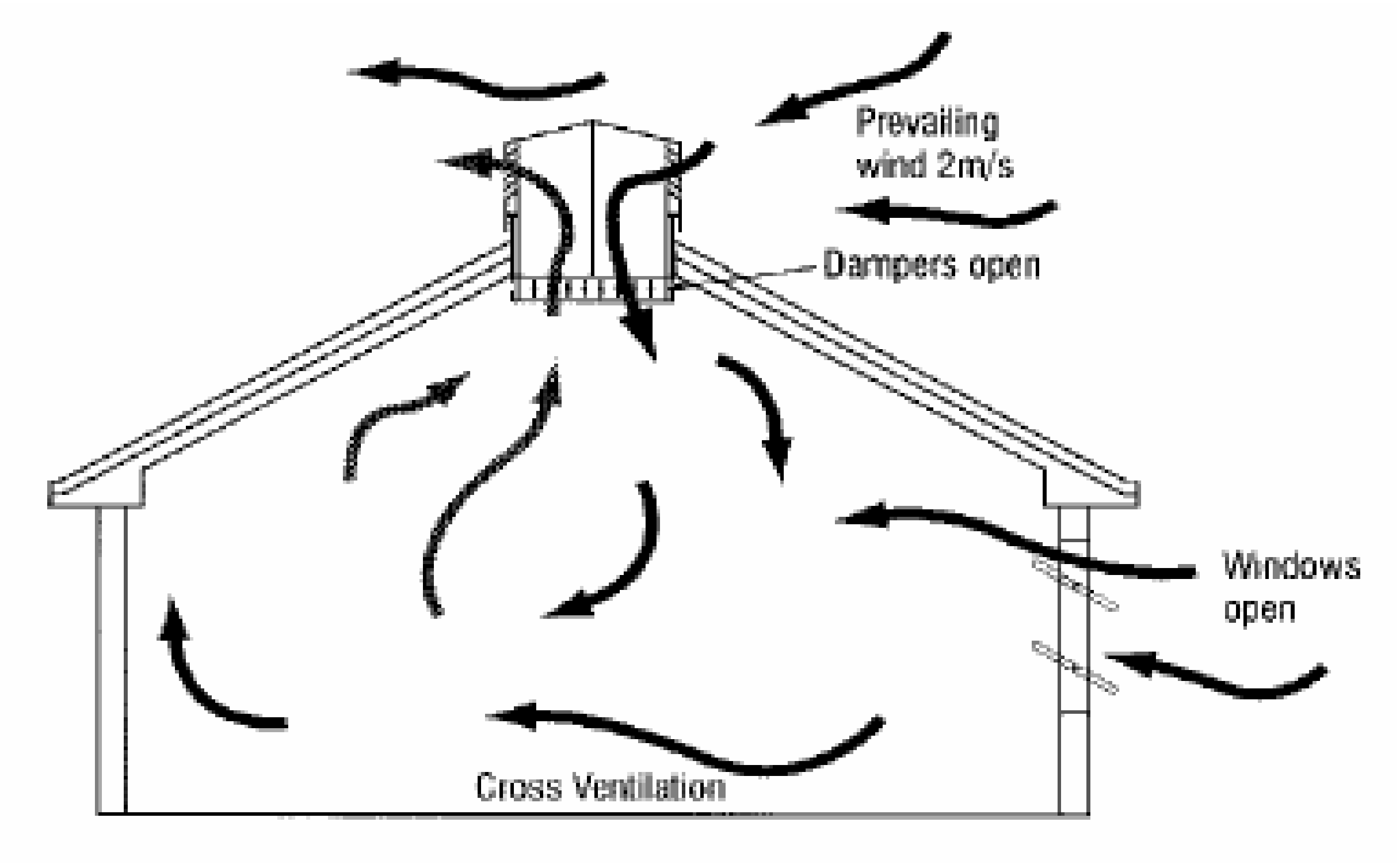
Natural and Mixed Mode Ventilation Mechanisms



Courtesy of Martin Liddament via Yuguo Li

33

Windcatcher ventilation



Wind Tower Ventilation

Not in handout materials (copyright limitation)

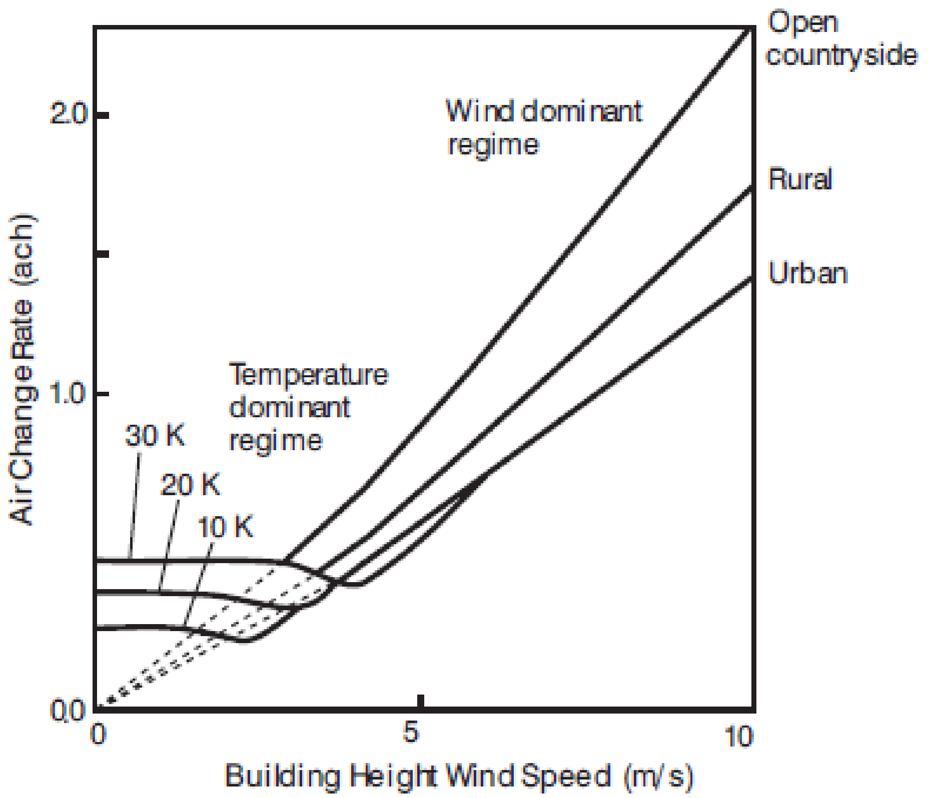
BRE's Environmental Office Building

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

Natural Ventilation Issues

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

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

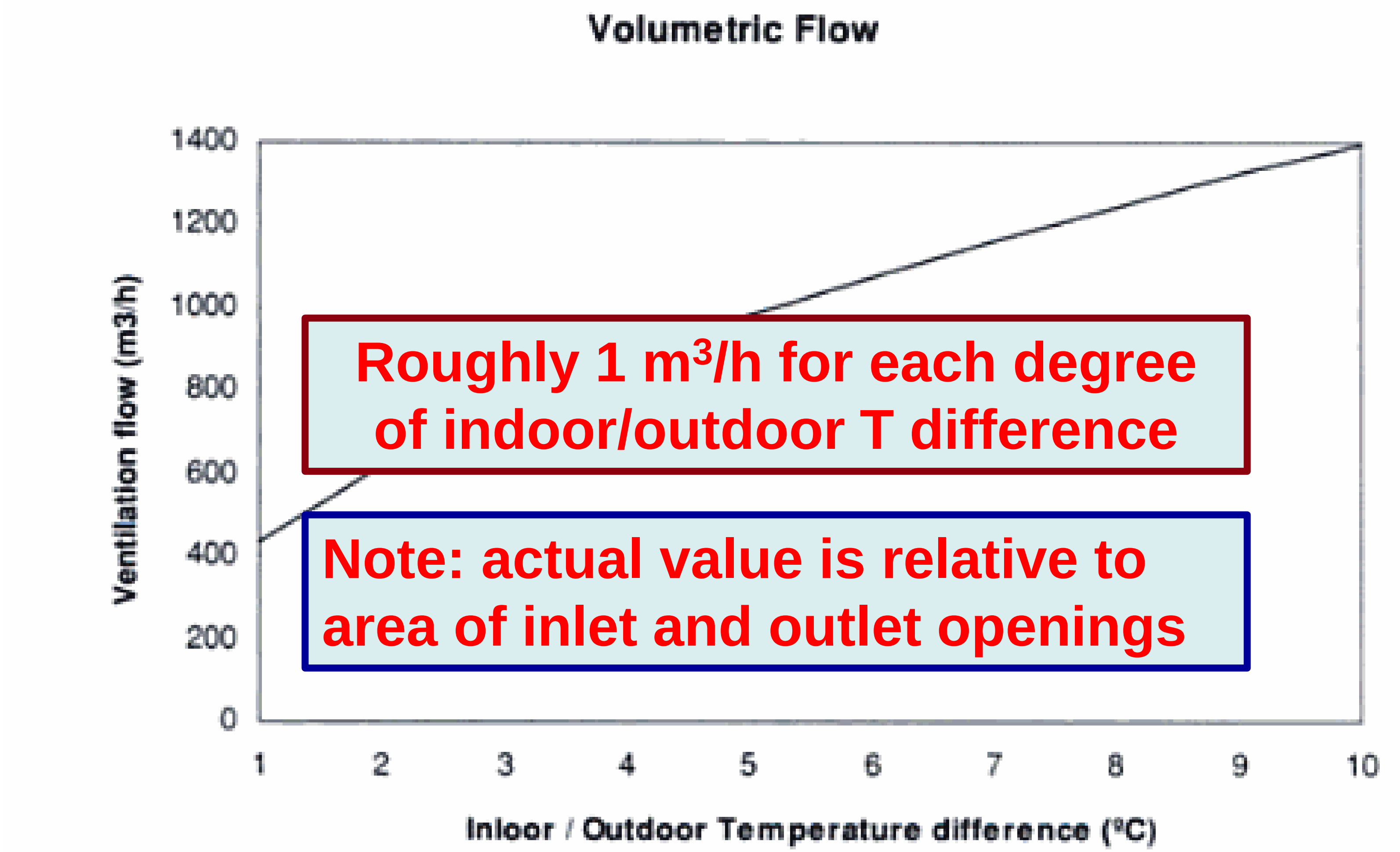
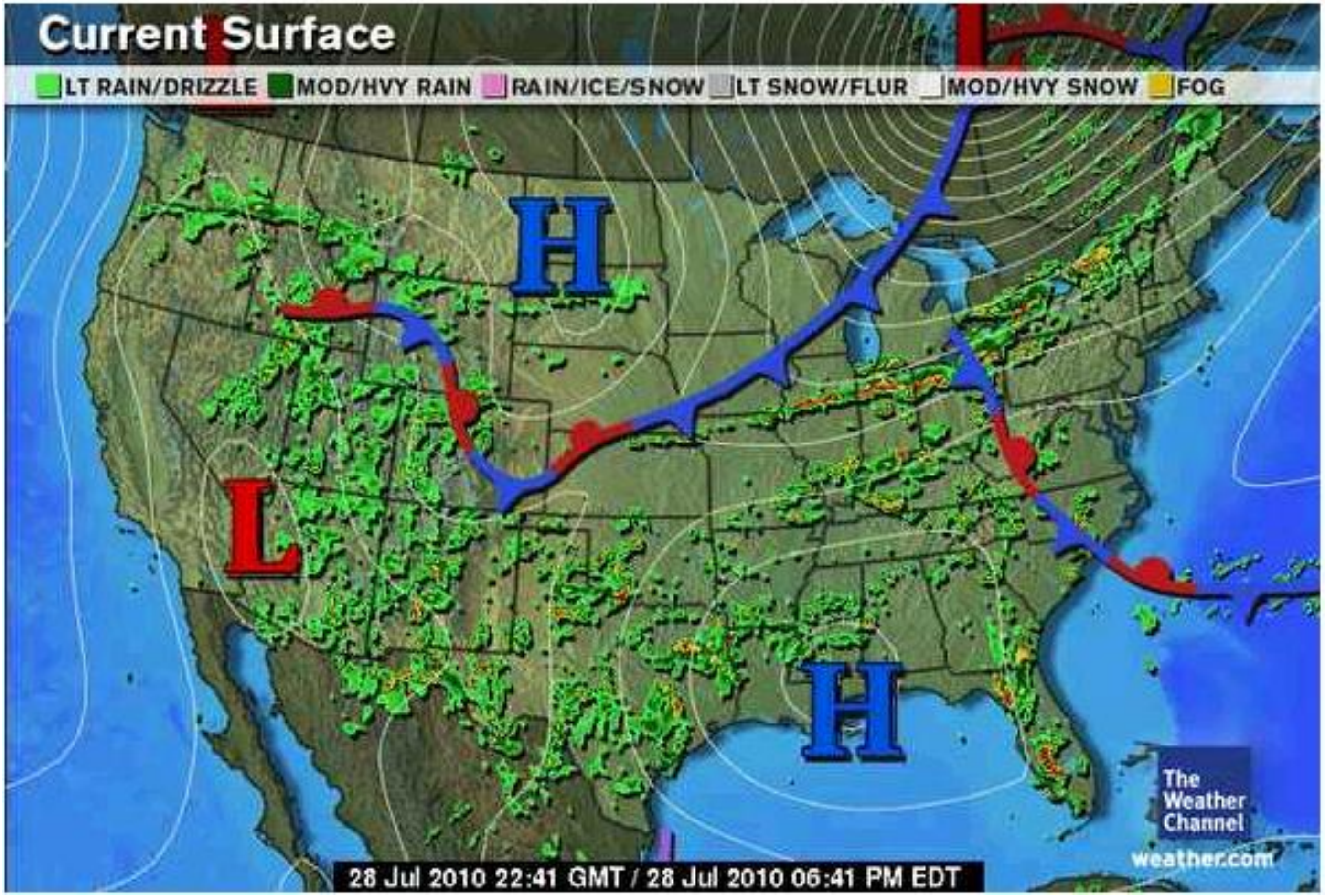


Figure 2.33. Airflow as a function of the temperature difference

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

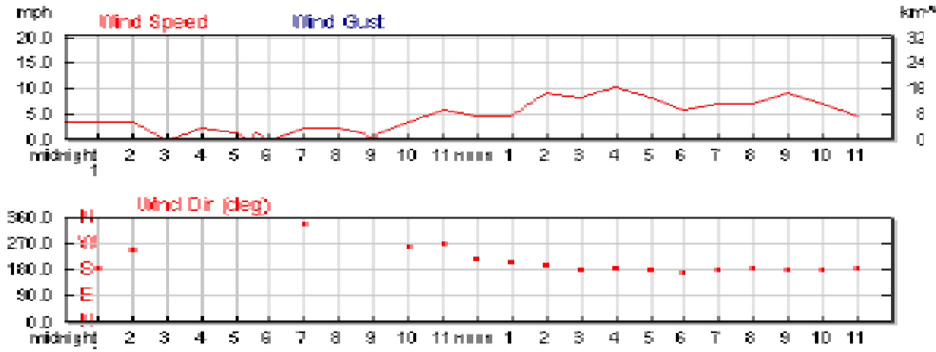
- Selected data from almost any city will show daily cycles and variations in wind direction and velocity
- Seasonal variations are more reliable, but daily variations are still the rule rather than the exception
- Even with many predictable situations, wind direction will change over the diurnal cycle – 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”

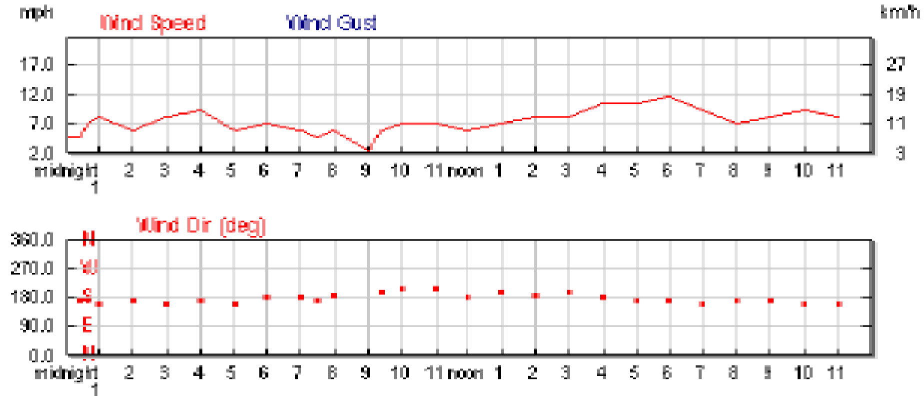


Lima, Peru: wind speed and direction

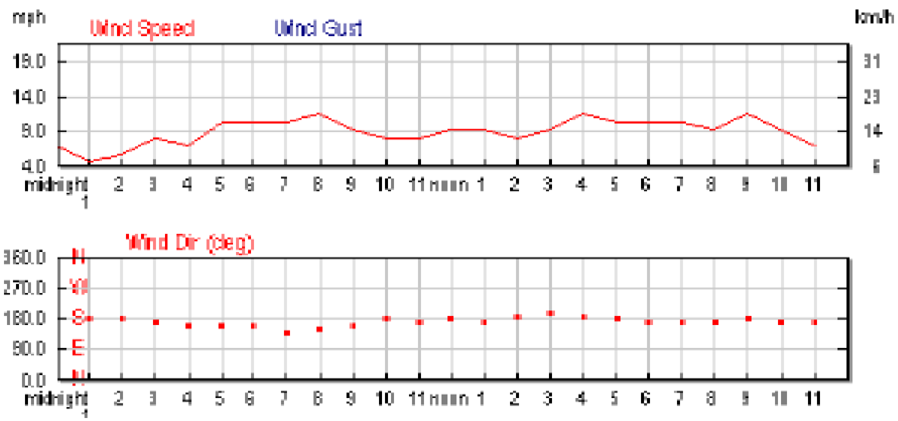
May 1, 2008



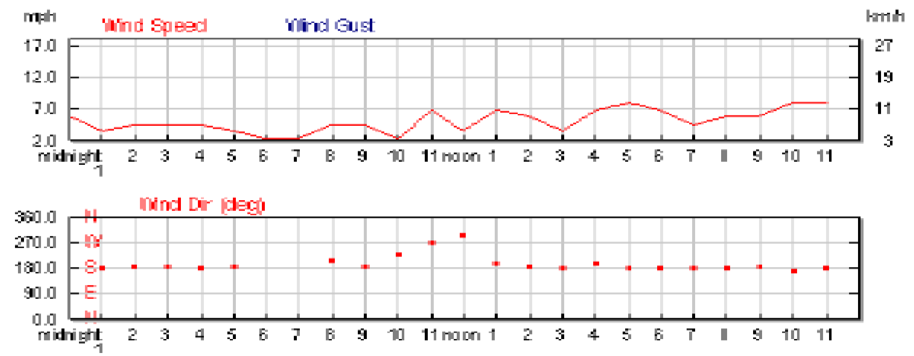
January 1, 2009



September 1, 2008

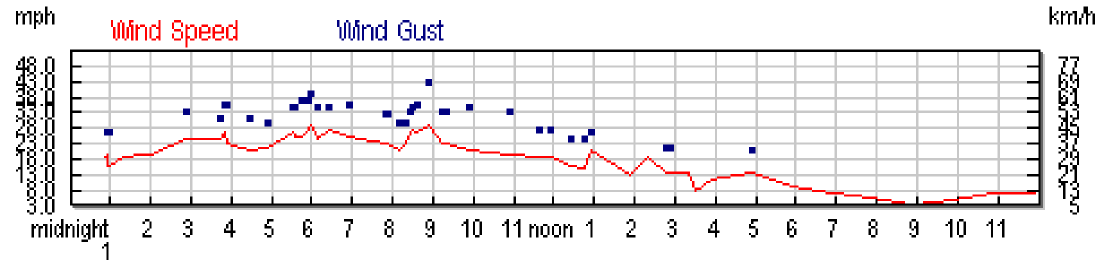


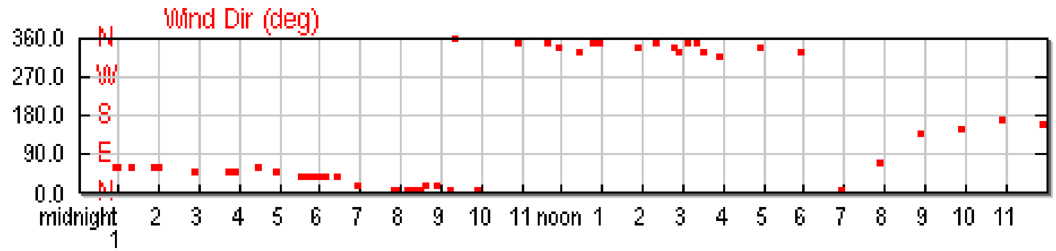
March 1, 2009



Boston, MA

July 24, 2009





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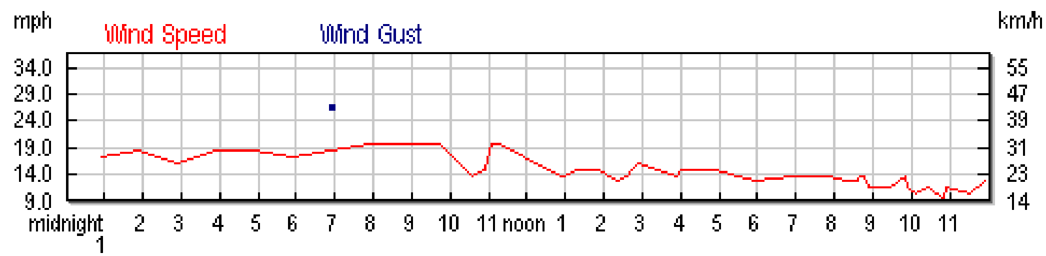
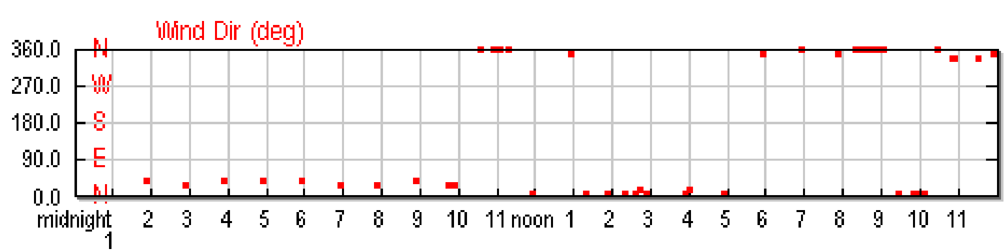
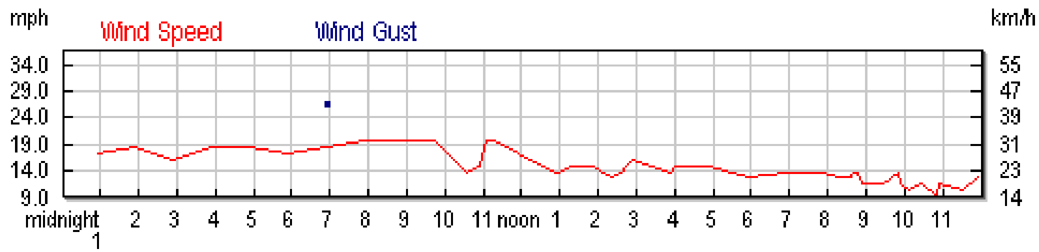
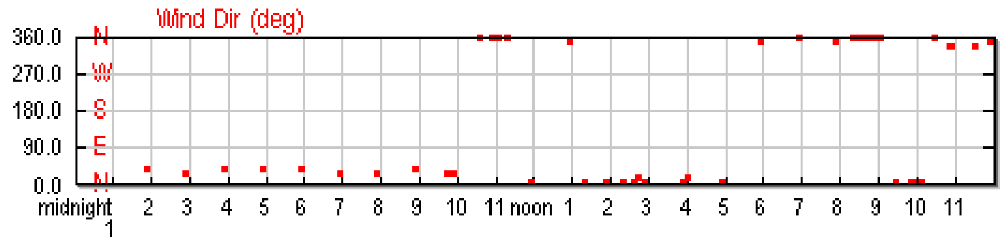




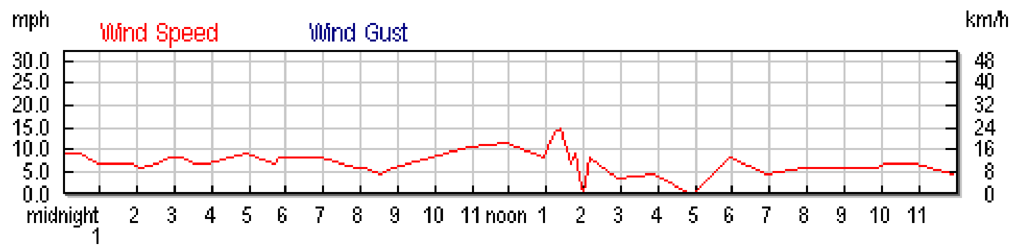
Boston, MA

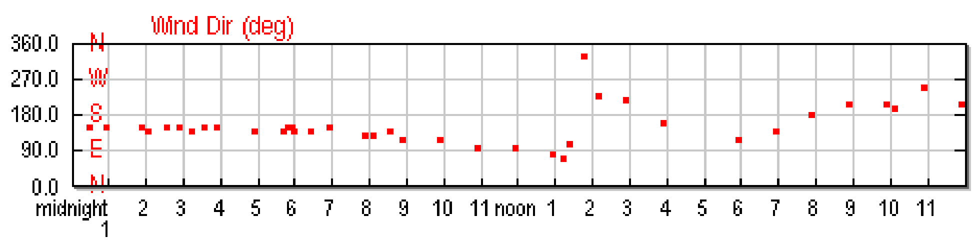
January 1, 2009





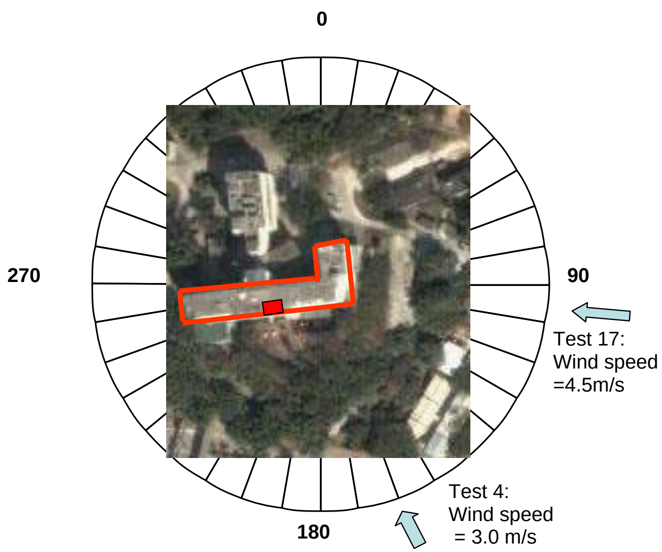
October 1, 2008

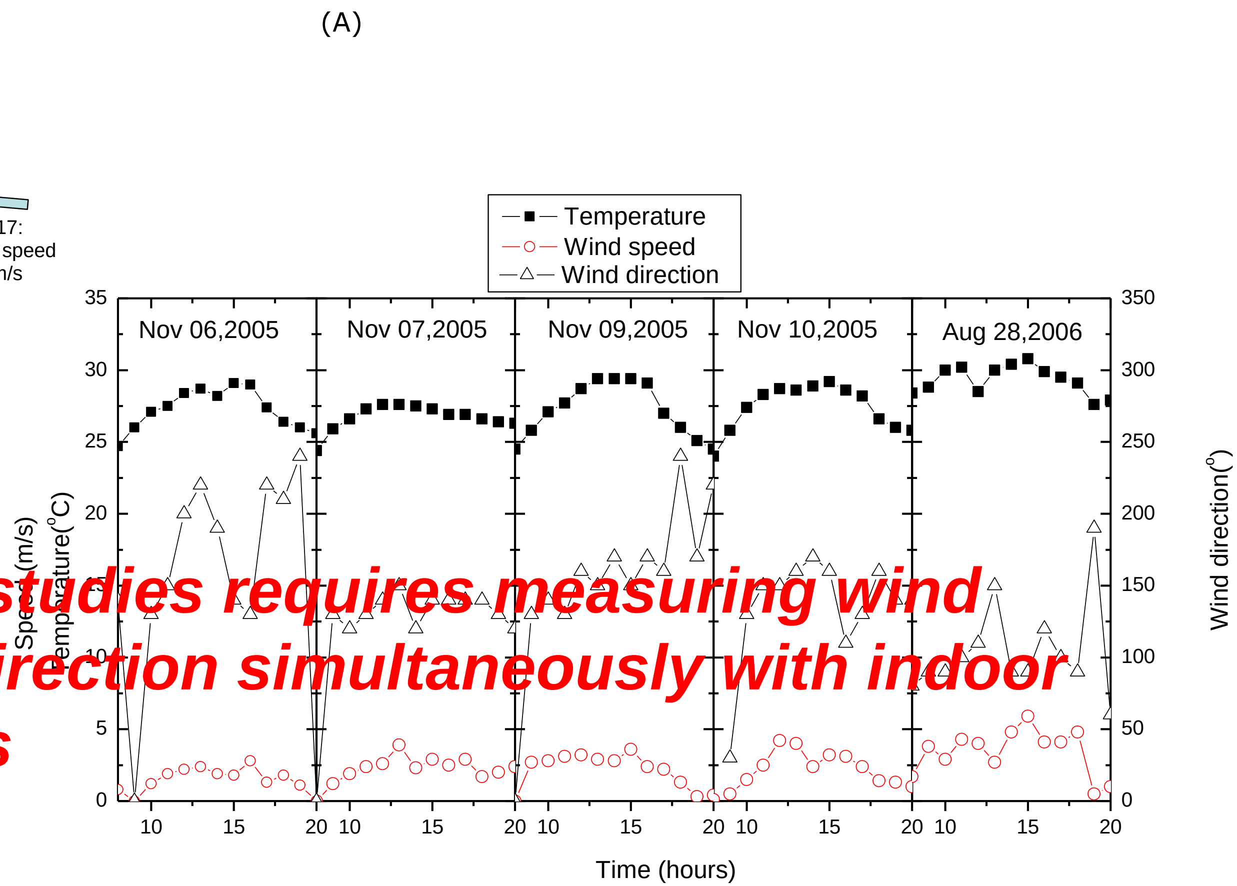




Grantham Hospital Study, Hong Kong

Yuguo Li, WHO 2009





Doing proper studies requires measuring wind velocity and direction simultaneously with indoor measurements

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 un-cleaned outdoor air.
- With highly susceptible health care facility occupant populations, consideration must be given to the effects of outdoor pollutants on the occupants' health.

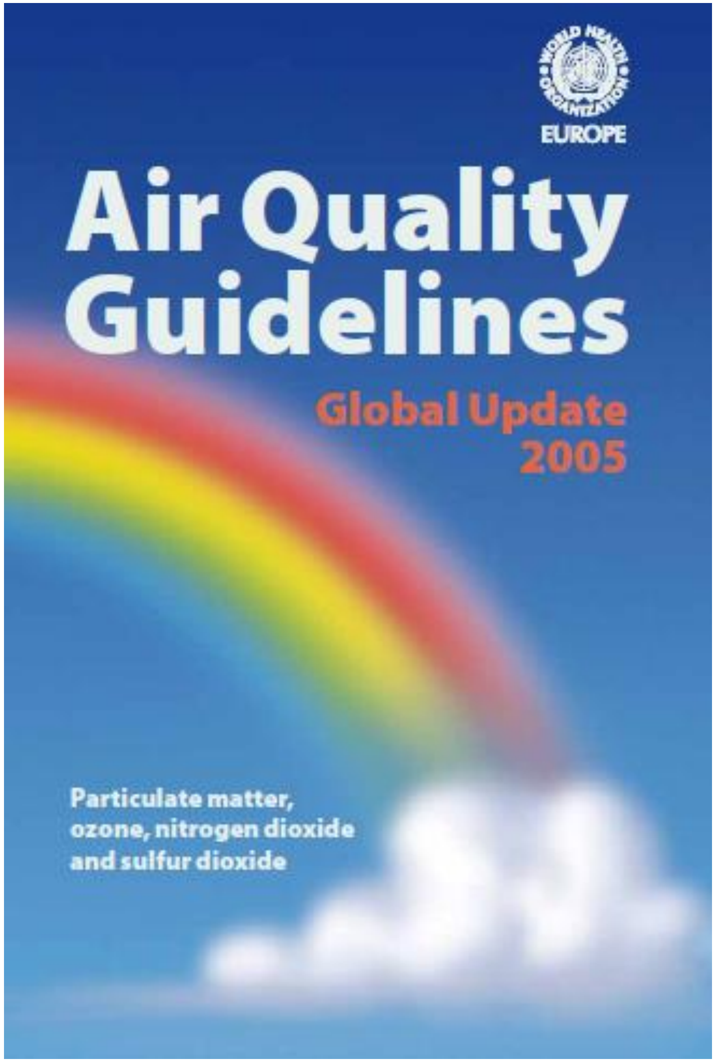
Air Quality Guidelines: Global Update

WHO, 2005

Chapter 2.

Global ambient air pollution concentrations and trends

Bjarne Sivertsen



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

WHO air quality update – 2012

Burden of disease from ambient and household air pollution

http://www.who.int/phe/health_topics/outdoorair/databases/en/

Burden of disease from ambient and household air pollution

In new estimates released, WHO reports that in 2012 around 7 million people died - one in eight of total global deaths – as a result of air pollution exposure. This finding more than doubles previous estimates and confirms that air pollution is now the world's largest single environmental health risk. Reducing air pollution could save millions of lives.

Read the news release on air pollution attributable deaths

Read the feature story on air pollution

- FAQs on air pollution and health
  pdf, 169kb
- Air pollution estimates
  pdf, 1.16Mb
  Summary of results and method descriptions

3.7 million deaths

attributable to ambient air pollution

Mortality from ambient air pollution for 2012 - summary of results
pdf, 293kb

4.3 million deaths

attributable to household air pollution

Mortality from household air pollution 2012 - summary of results.
pdf, 558kb

1600 cities

worldwide are reporting air pollution levels

Air quality in cities database – summary of results
pdf, 304kb

United States Environmental Protection Agency
National Ambient Air Quality Standards (NAAQS) Criteria

(SOURCE: HTTP://WWW.EPA.GOV/AIR/CRITERIA.HTML)

NAAQS Criteria	PM	Nitrogen [illegible]	Sulfur dioxide	Ozone
average annual	[illegible]	[illegible]	[illegible] ppm 85 $\mu g/m^3$)	
24-hour average	150 μg[illegible]	[illegible]	0.14 ppm (D) (395 $\mu g/m^3$)	
1-hour maximum		100 ppb (C) (203 $\mu g/m^3$)	75 ppb (F) (212 $\mu g/m^3$)	120 ppb (E) (254$\mu g/m^3$)

Going down soon! – 70 or 75 ppb?

NOTES TO TABLE:

(A) Not to be exceeded more than once per year on average over 3 years.

(B) The official level of the annual NO_2 standard is 0.053 ppm, equal to 53 ppb, which is shown here for the purpose of clearer comparison to the 1-hour standard.

(C) To attain this standard, the 3-year average of the 98th percentile of the daily maximum 1-hour average at each monitor within an area must not exceed 0.100 ppm (effective January 22, 2010).

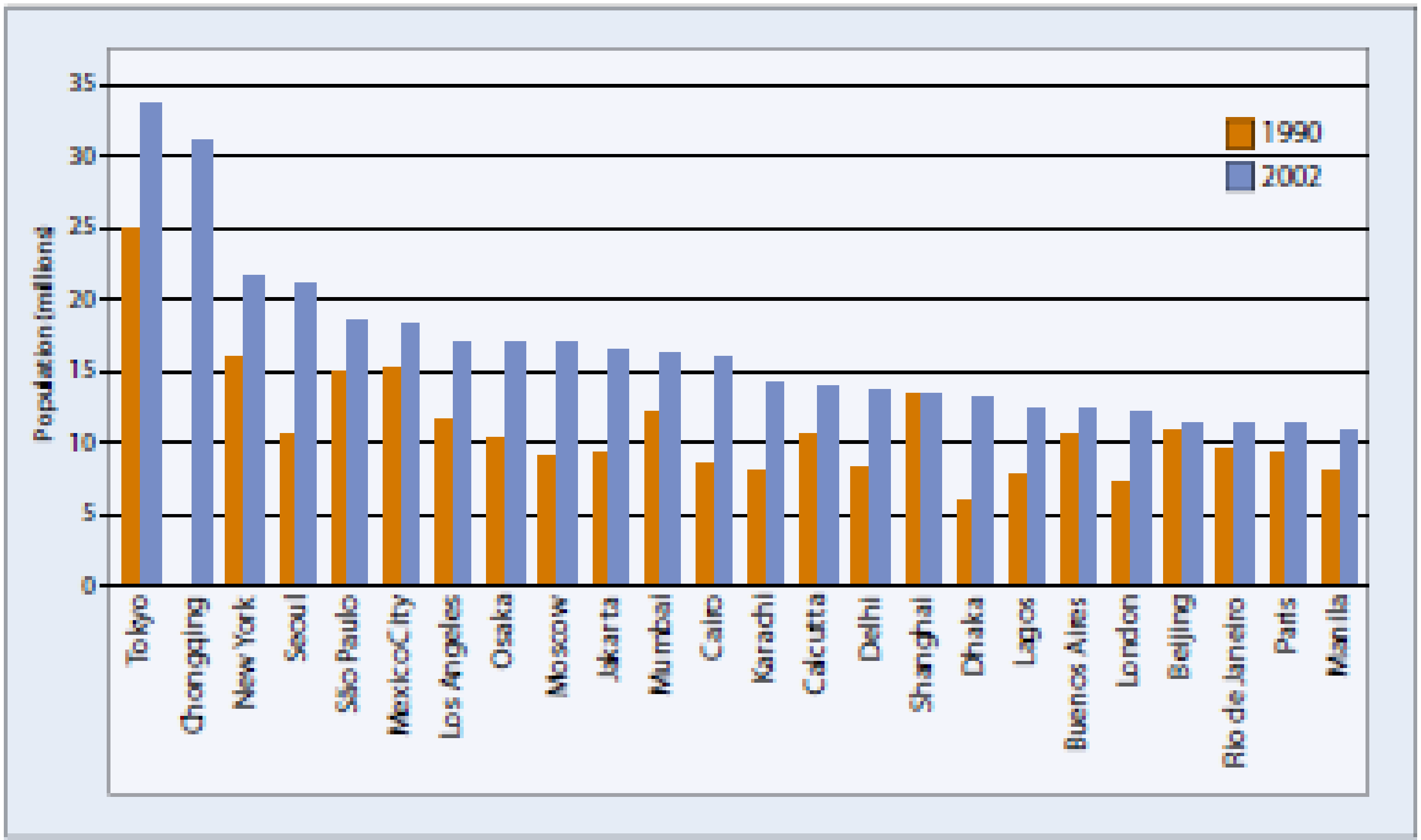
(D) Not to be exceeded more than once per year.

(E) The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 120 ppb is < 1.

(F) Announced June 3, 2010

Where are the people who will arrive in naturally-ventilated health care facilities?
(source: WHO, 2005)

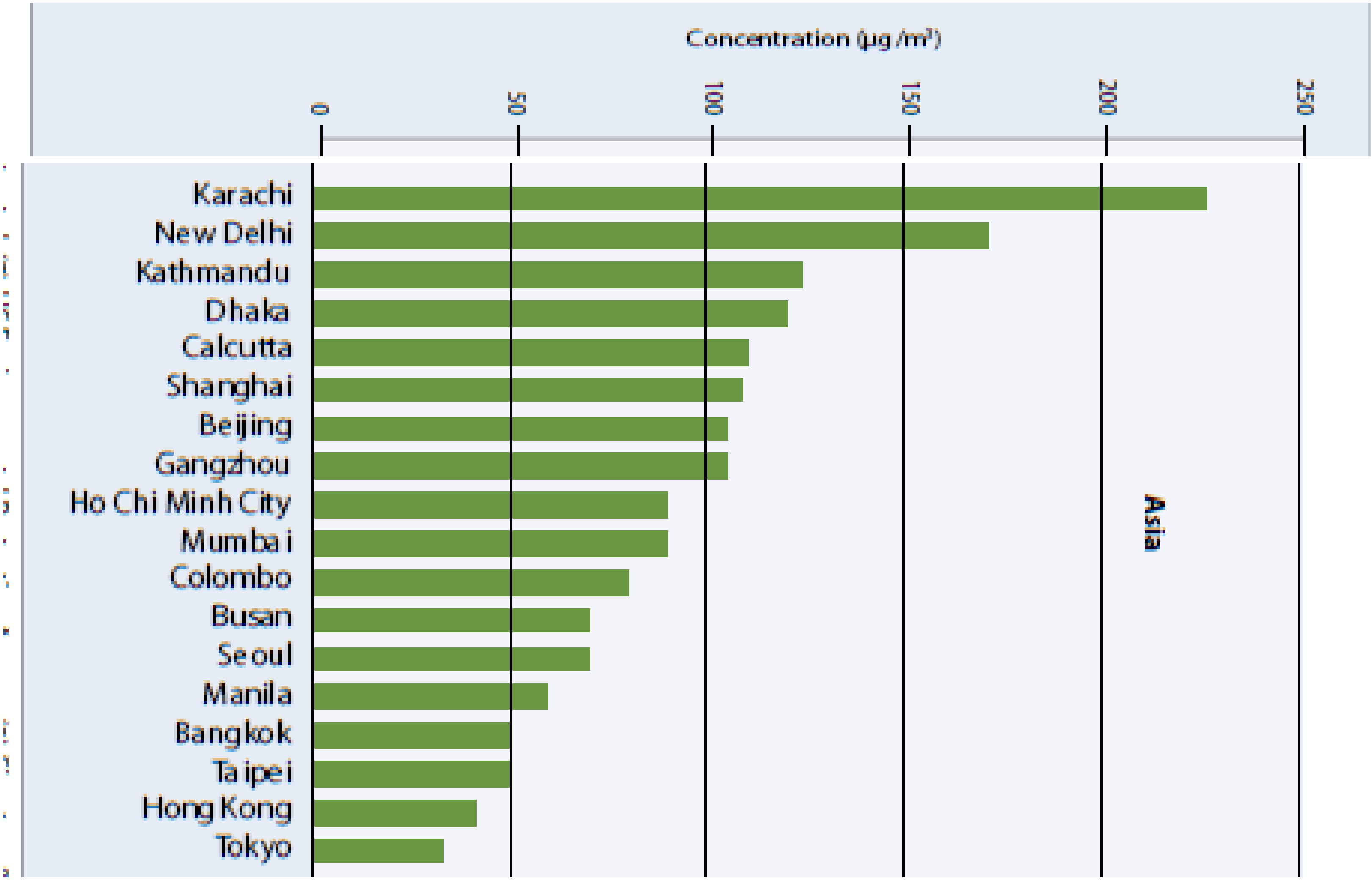
Fig. 2. The 24 megacities in the world with populations (including suburbs) exceeding 10 million in 2002



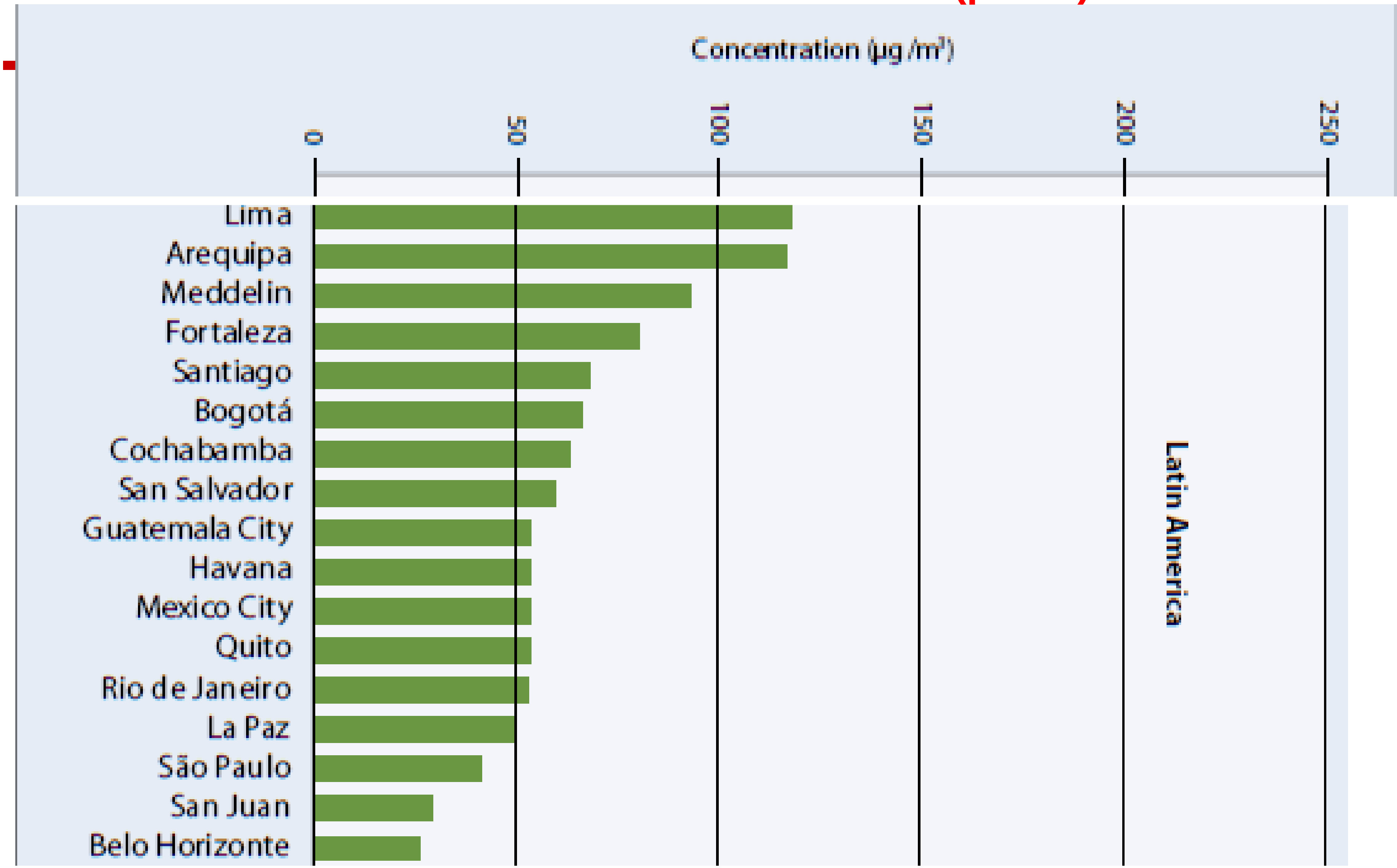
Source: United Nations (4).

(source: World Health Organization, 2005)

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

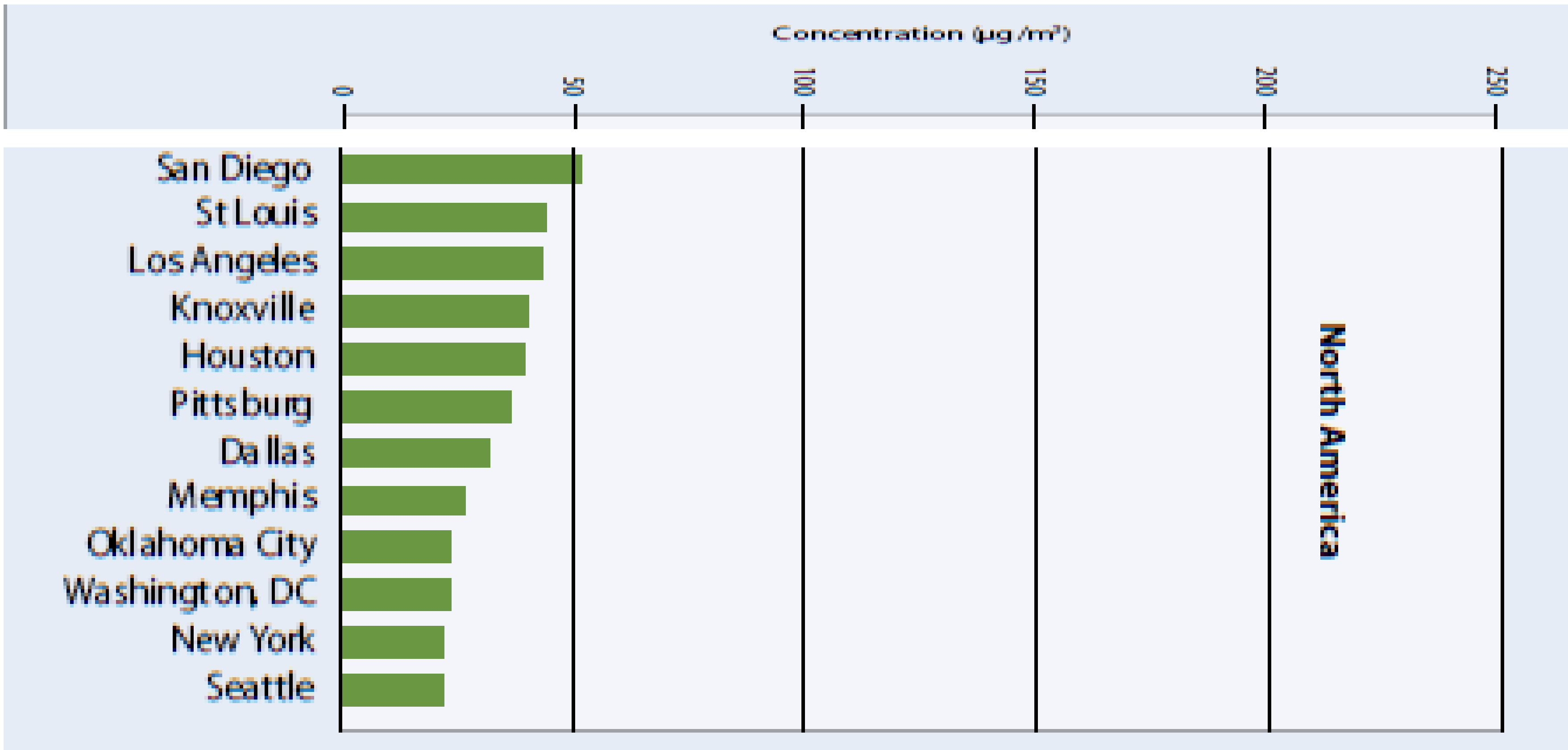


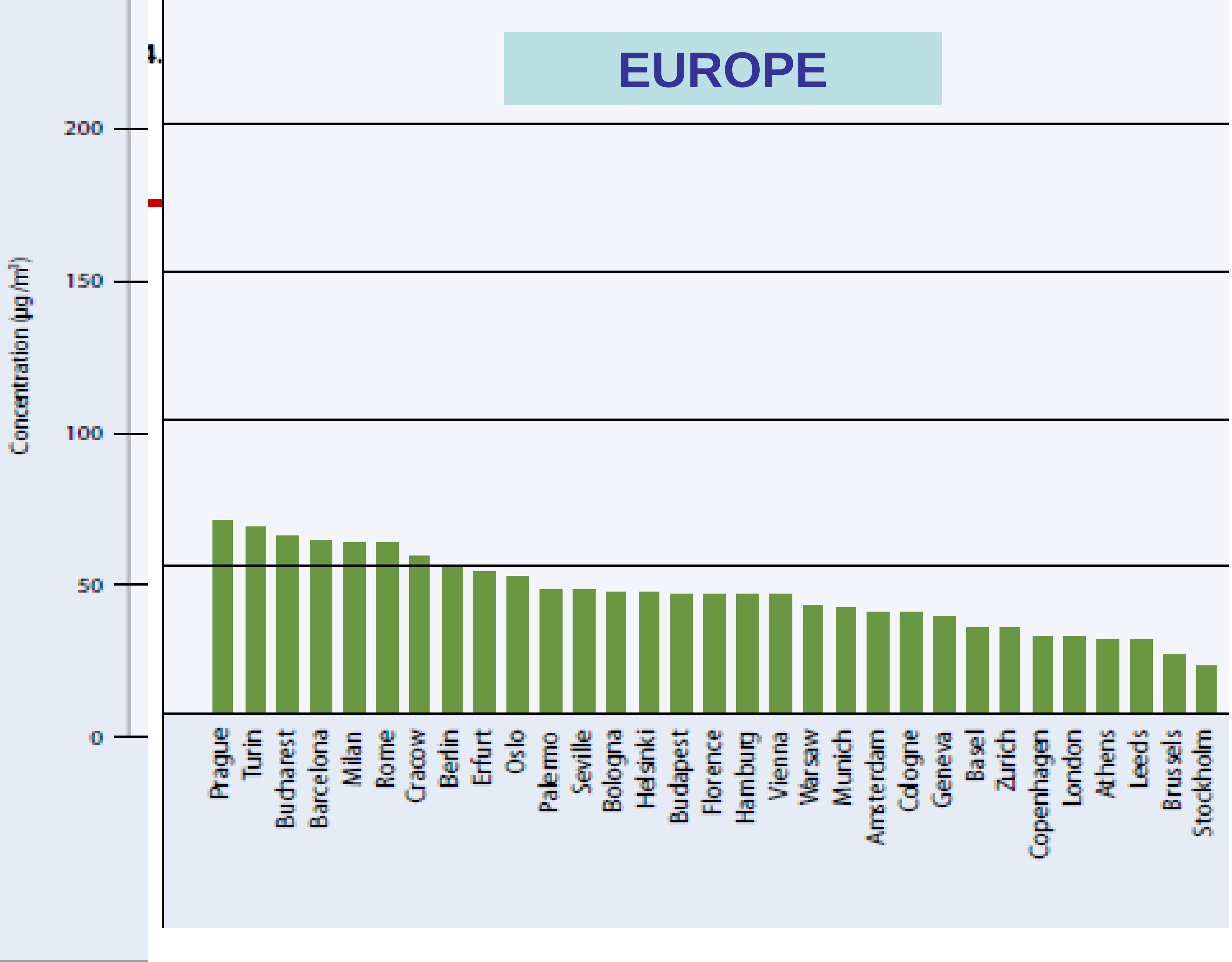
Average annual PM_{10} concentrations in selected cities world wide (part 3)



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

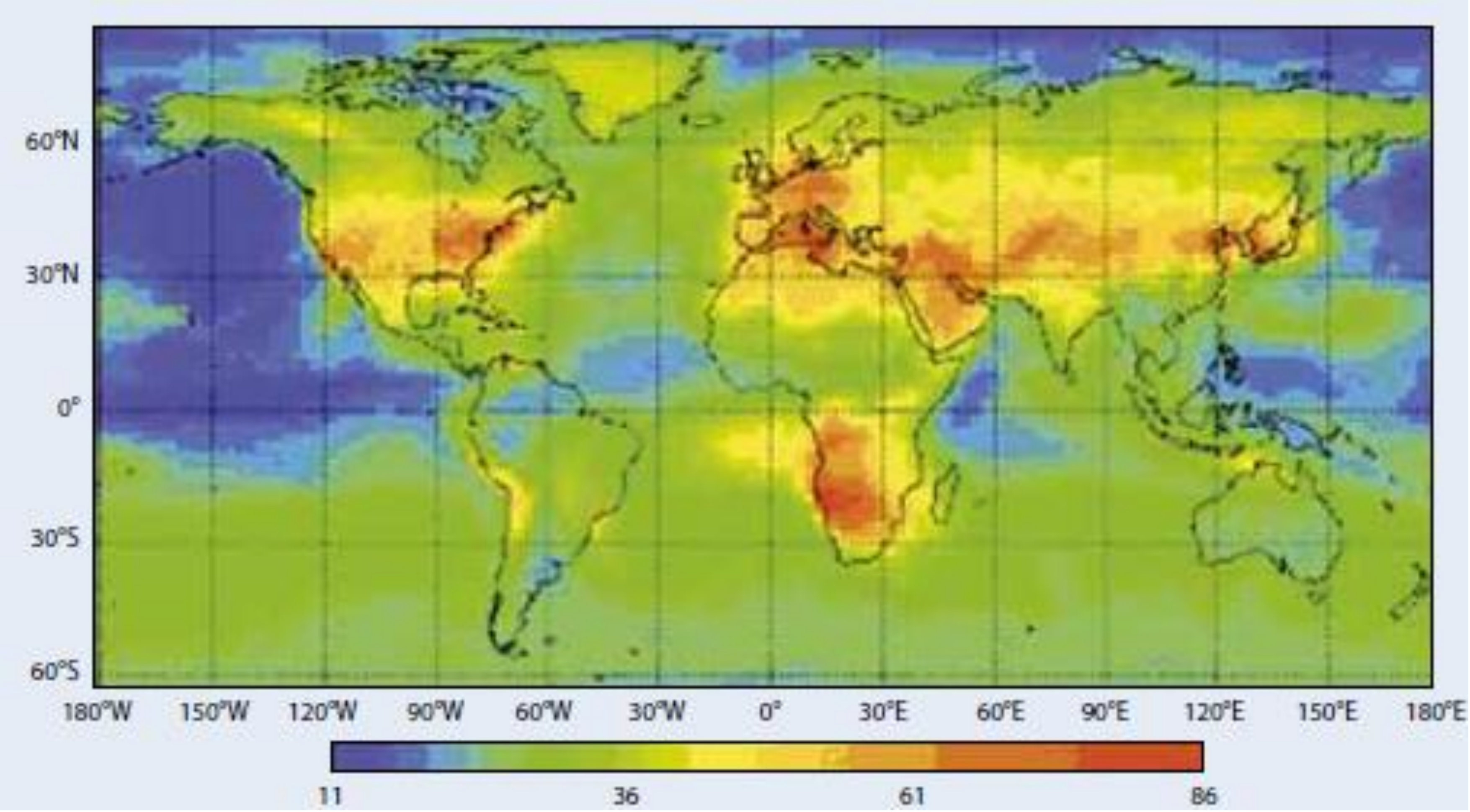
NORTH AMERICA



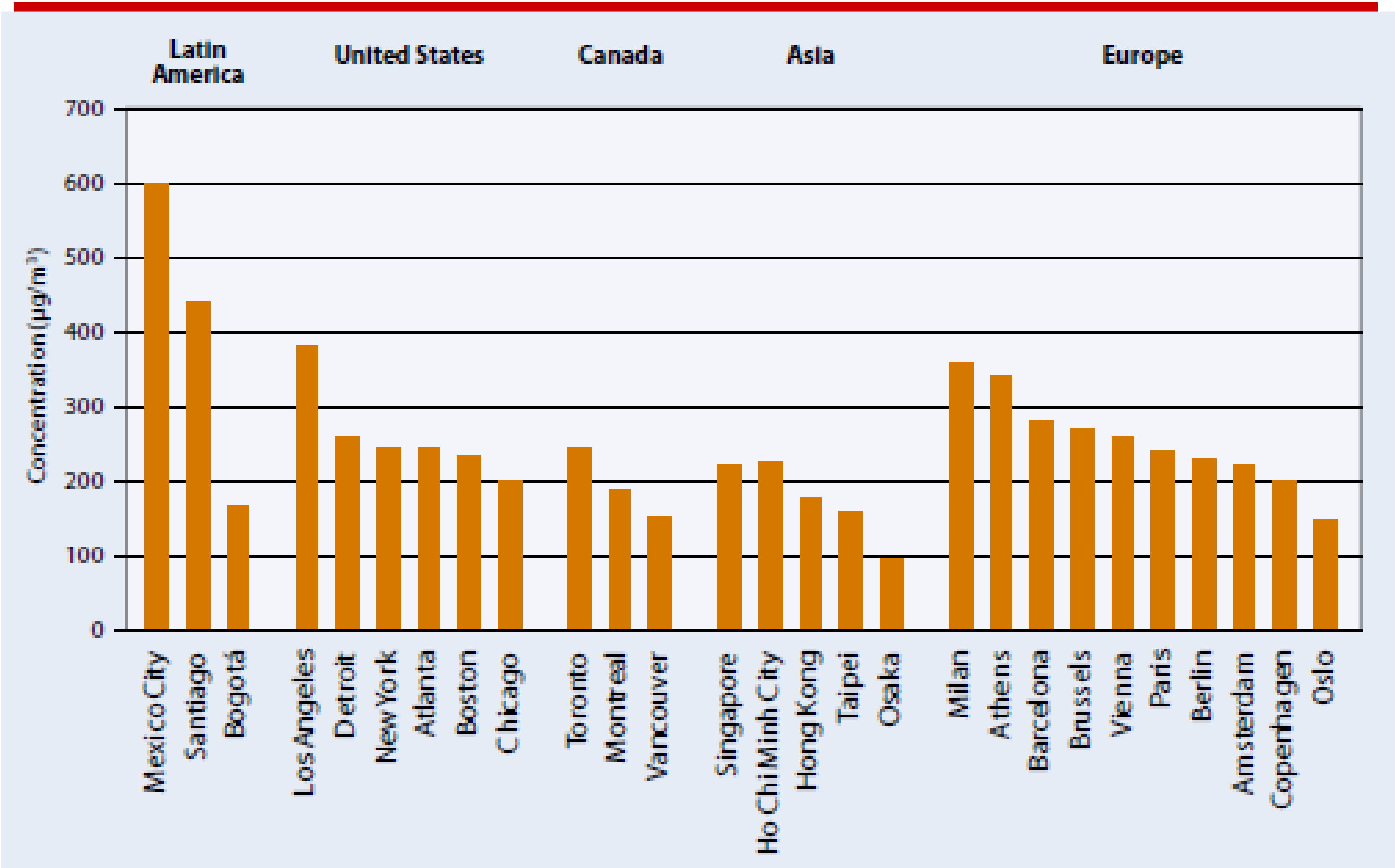


EUROPE
Concentration (µg/m³)
200
150
100
50
0
Prague
Turin
Bucharest
Barcelona
Milan
Rome
Cracow
Berlin
Erfurt
Oslo
Palermo
Seville
Bologna
Helsinki
Budapest
Florence
Hamburg
Vienna
Warsaw
Munich
Amsterdam
Cologne
Geneva
Basel
Zurich
Copenhagen
London
Athens
Leeds
Brussels
Stockholm

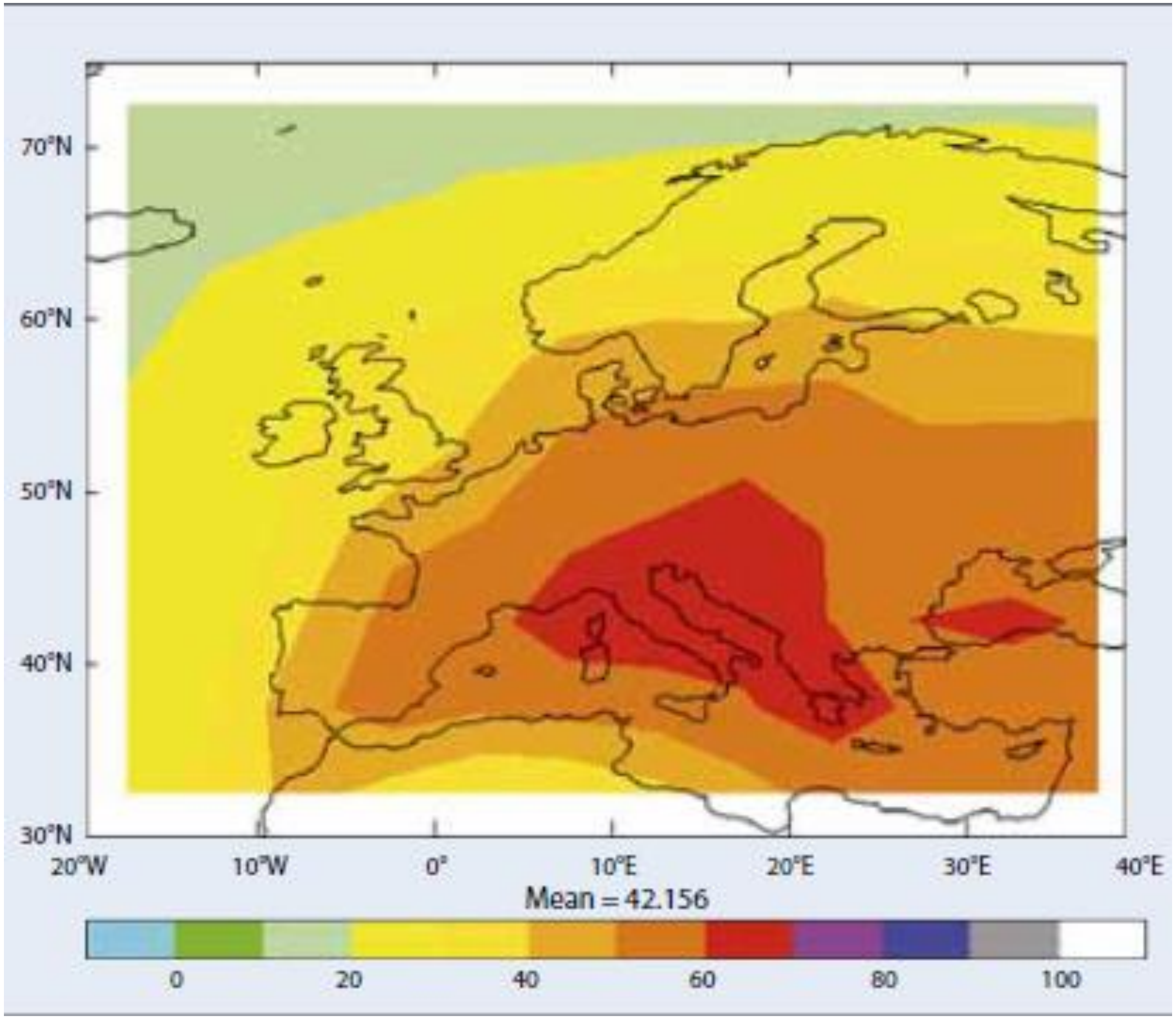
Mean afternoon (13:00 to 16:00) surface ozone concentrations calculated for the month of July (comment: where are people living?)



Highest (1 h average) ground-level O_2 concentrations measured in selected cities (µg/m³)



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 (ppbv)									
AER (h^{-1})	**20**	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**
1	5	11	16	21	26	32	37	42	47	53
2	8	17	25	33	42	50	58	67	75	83
4	12	24	35	47	59	71	82	94	106	118
6	14	27	41	55	68	82	95	109	123	136
12	16	32	49	65	81	97	114	130	146	162
20	18	35	53	70	88	105	123	140	158	175

Percentage increase in daily nonaccidental mortality per 10-ppb increase in lag —01 O_3

*Diamonds denote the point estimates, and vertical lines represent the 95% posterior intervals. Each estimate is obtained by including in the analysis only days with 24-hr average lag —01 O_3 levels below the s value specified on the x-axis. Not all communities had sufficient data for analysis at all s values: *25 communities; **74 communities; ***92 communities. All other estimates used 98 communities. The estimate at the far right marked by a square uses all data.*

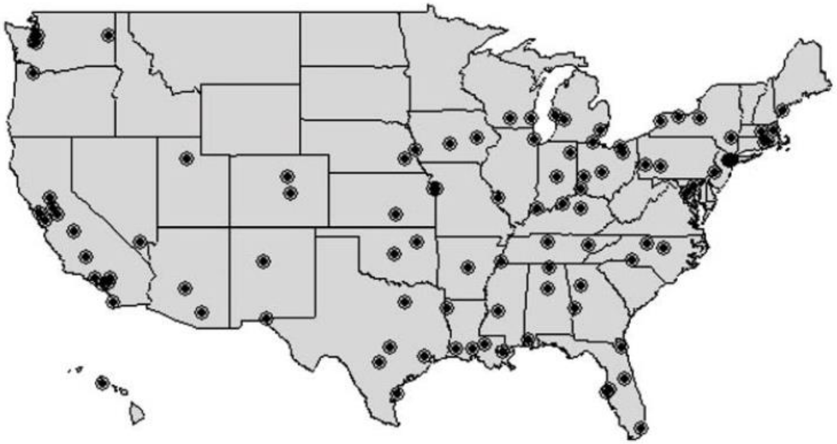
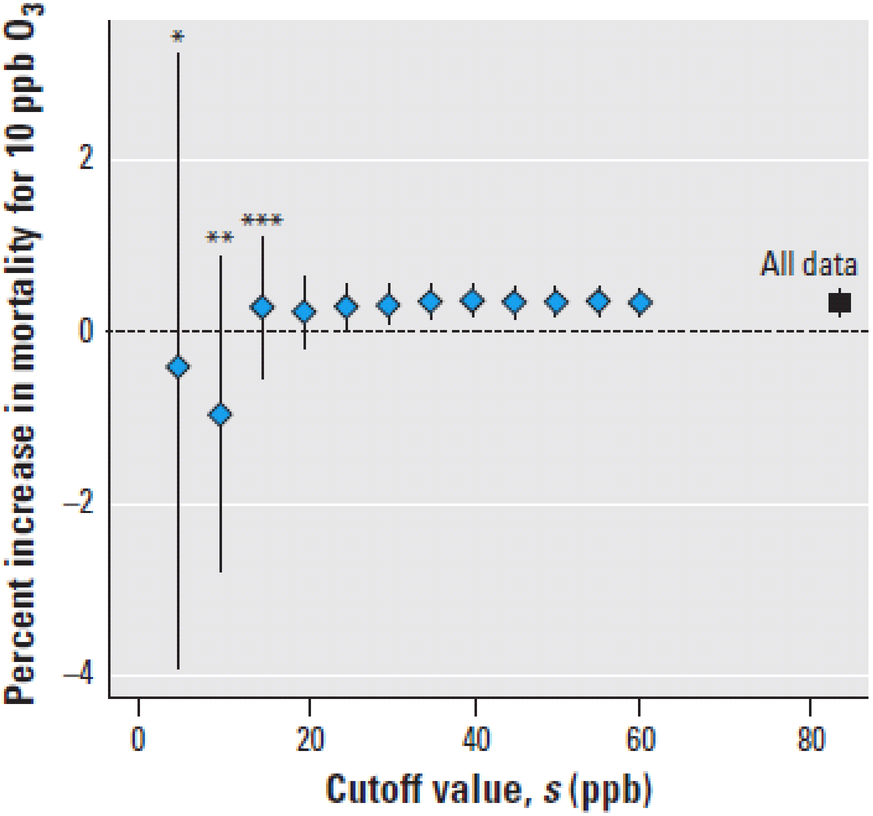


Figure 1. Locations of the 98 U.S. urban communities examined in this study.



"…any anthropogenic contribution to ambient O_3, however slight, …presents an increased risk for premature mortality."

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

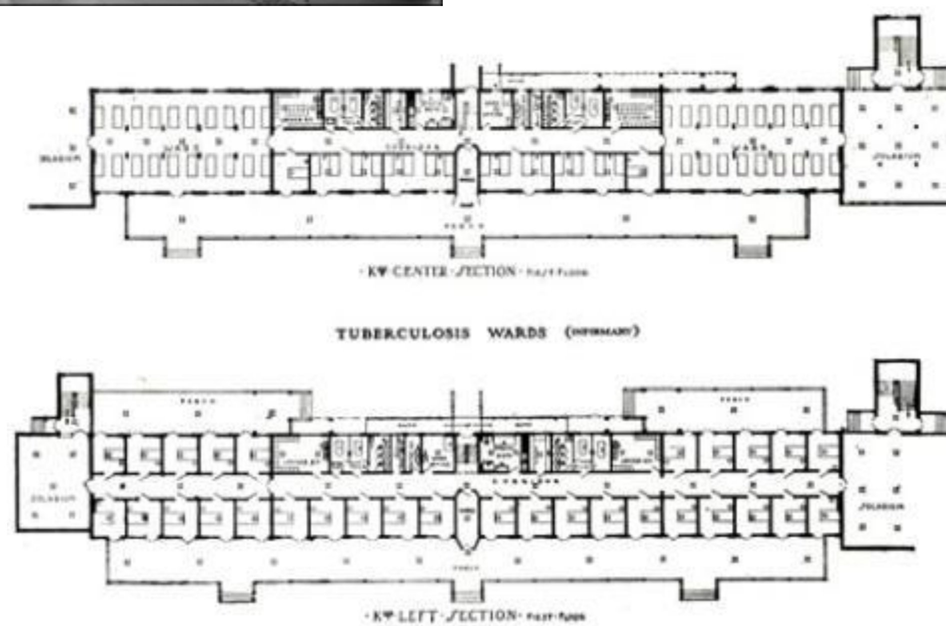
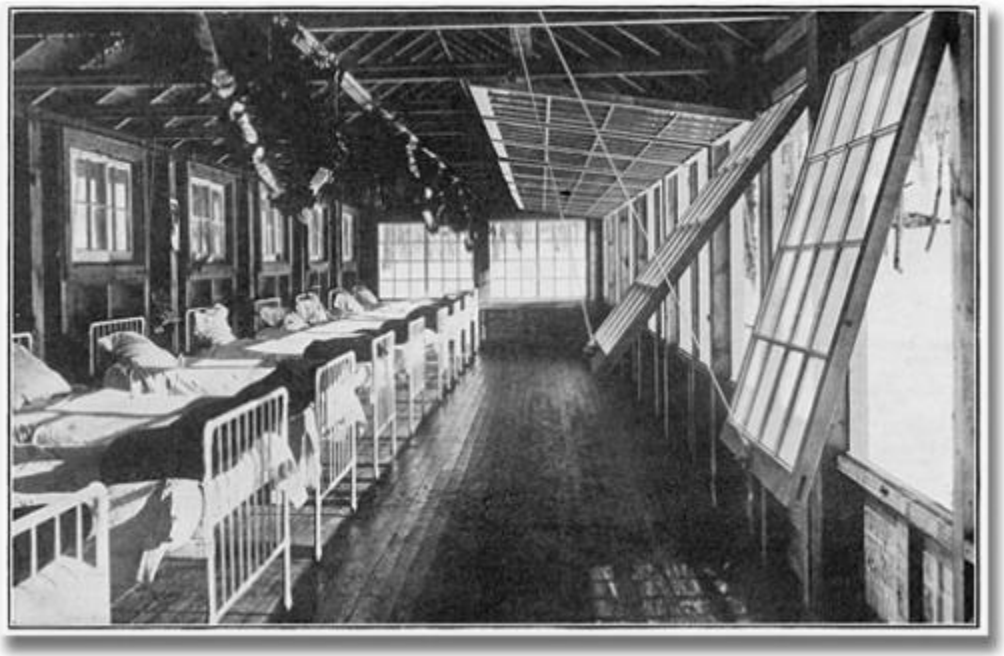


FIG. 27.

Management of openings

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



Ventilation measurement issues

- How do you confirm adequate outdoor air ventilation in a naturally-ventilated healthcare facility?
- Methods for approximation available, precise and reliable numbers are not practically feasible …. (Nor necessary?)
- Occupant CO_2 simply not technically valid for high air change rates – 6 to 12 ach (or higher)
- 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: 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

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: References

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