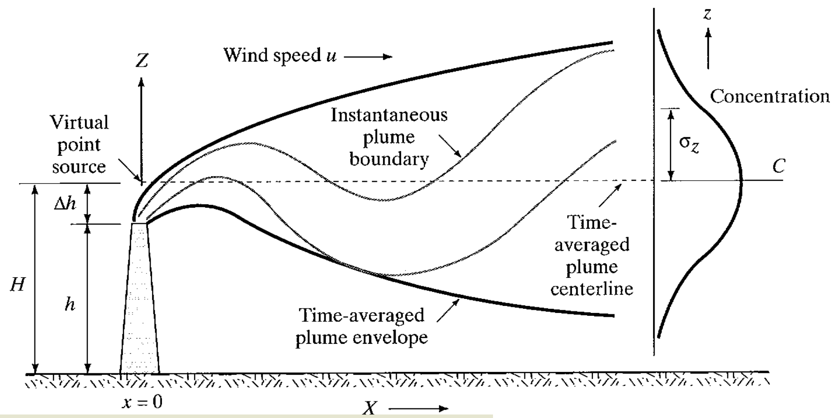


$$C(x,y,0)=\left[\frac{Q}{\pi\sigma_y\sigma_z u_H}\right]\left[\exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right]\right]\left[\exp\left[-\frac{1}{2}\left(\frac{H}{s_z}\right)^2\right]\right]$$

Lecture 5

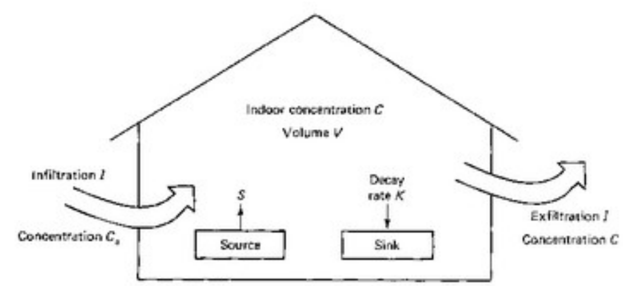
Air Quality:

Air Pollution Modeling

Harish C. Phuleria

CESE, IIT Bombay

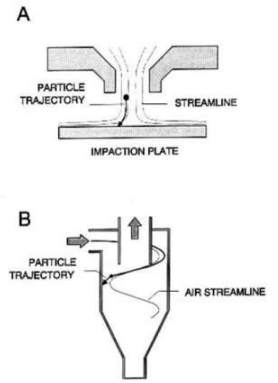
Email: phuleria@iitb.ac.in



accumulation rate = input rate +sources – output rate – decay

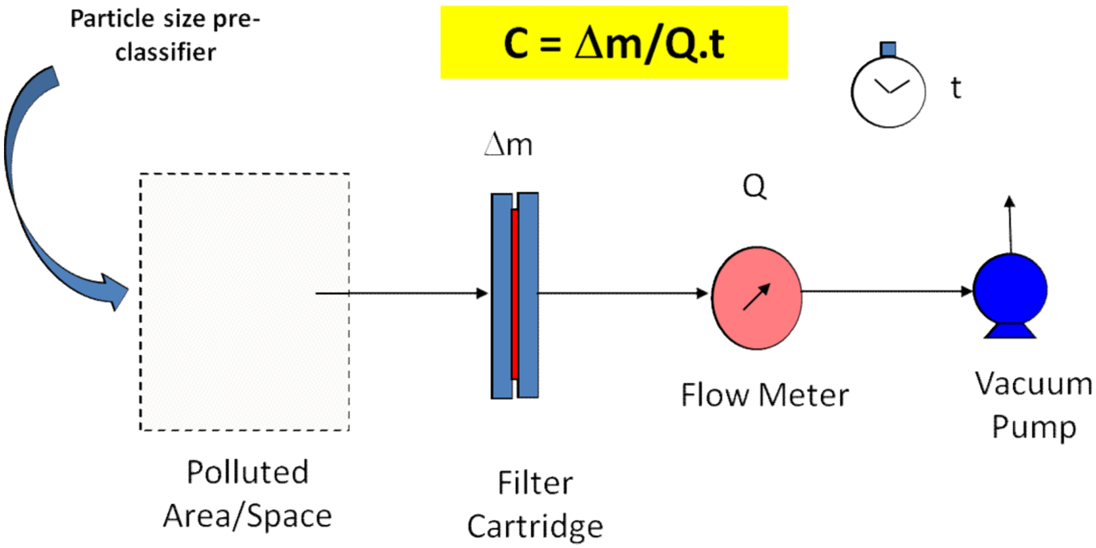
$$\boxed{V\frac{dC}{dt}=S+C_aIV-CIV-KCV}$$

Recap 1



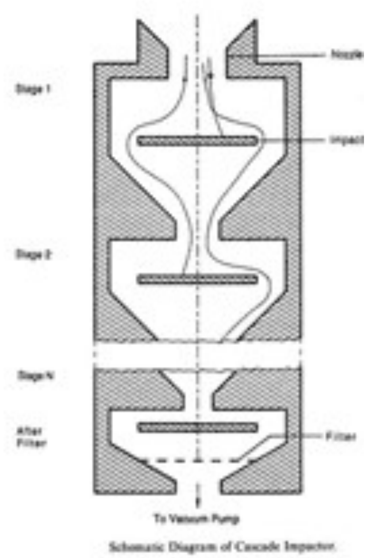
Inertial Collection. (a) Impactor, (b) Cyclone.

$C = \Delta m/Q.t$

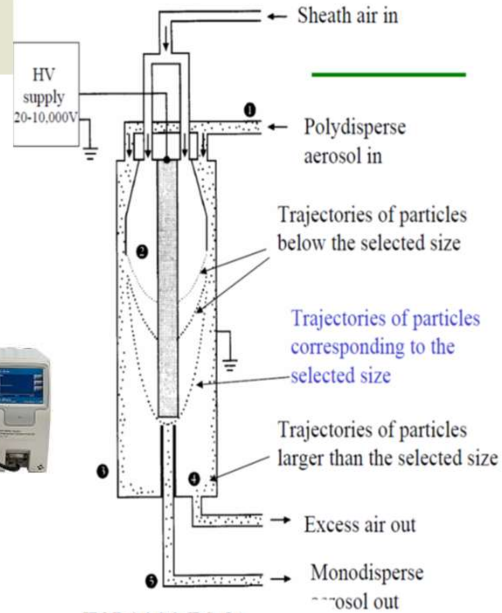


Choice of instruments is a function of its cost, intended analysis, time resolution, portability, ease of use

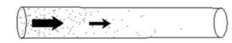
Recap 2

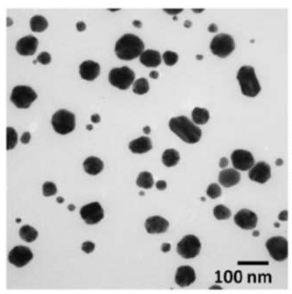


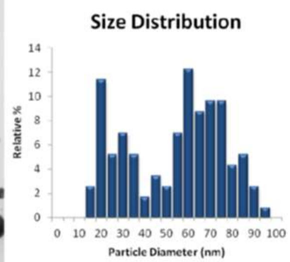
Anderson six-stage viable impactor

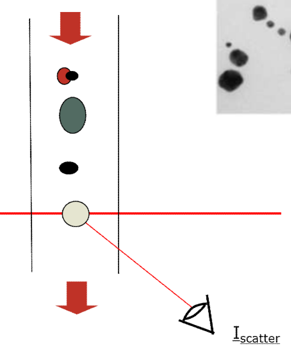


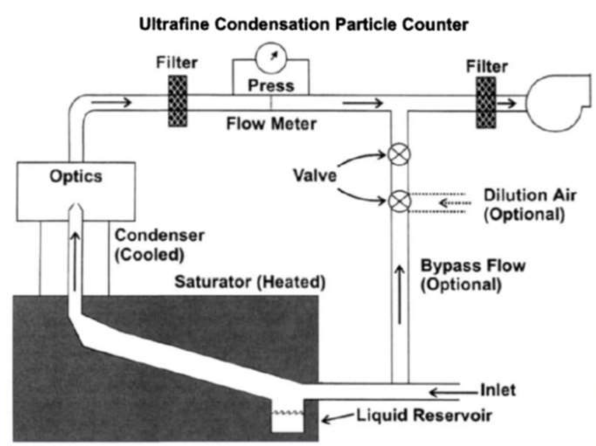
TSI 3080 DMA







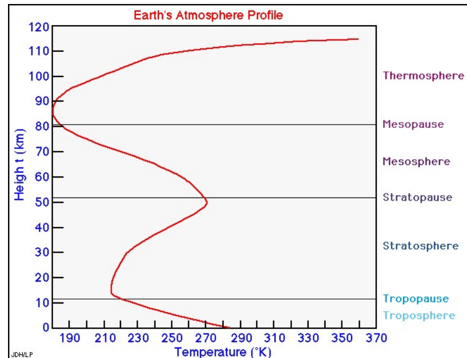


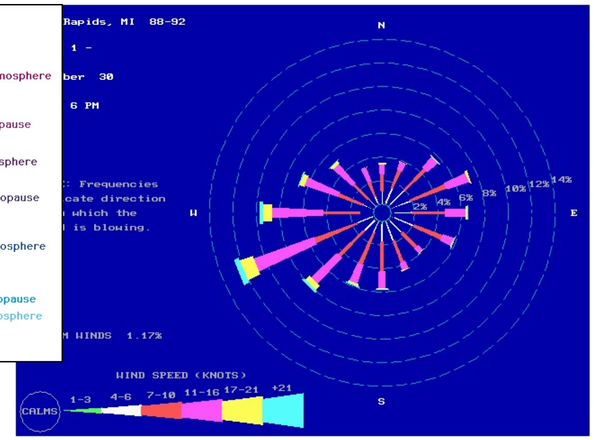


Recap 3



- Three type of sources: point, line, & area
- Atmospheric mixing and dispersion is governed by meteorology
  - Horizontal
    - Wind speed and direction
  - Vertical
    - Temperature

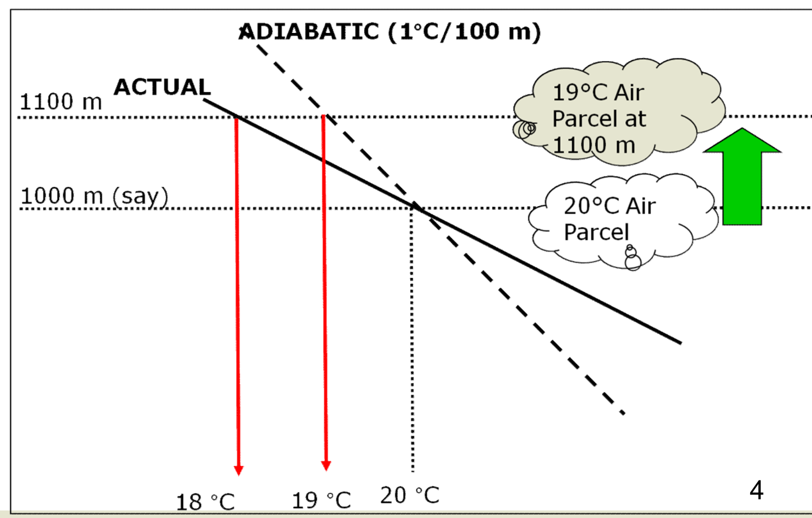




- Atmosphere cools with height
  - Dry (adiabatic) lapse rate

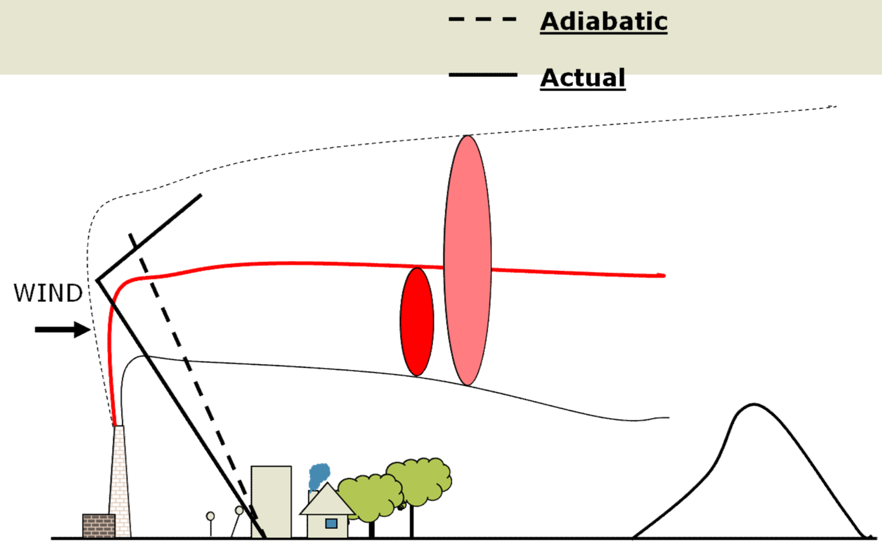
$$\Gamma = -\frac{dT}{dz} = -1.00\,^{\circ}\mathrm{C}/100\ \mathrm{m}$$

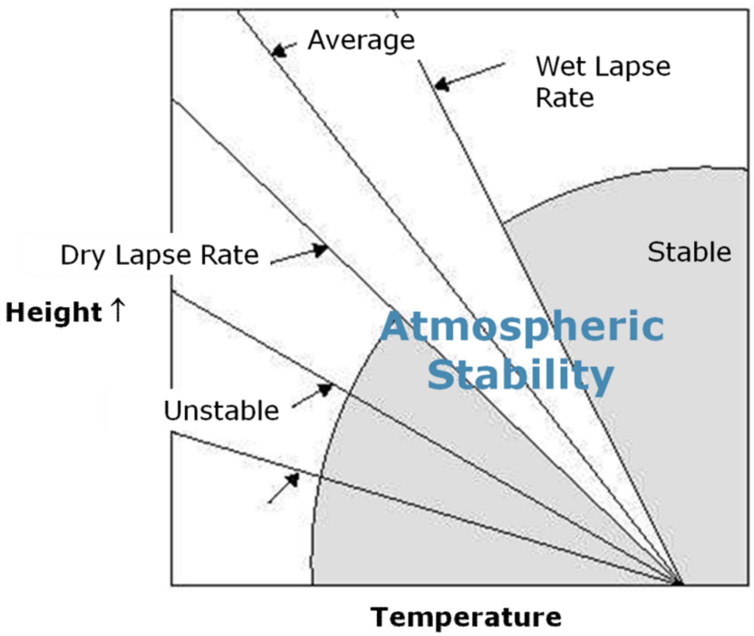
- Effect of actual lapse rate on vertical mixing

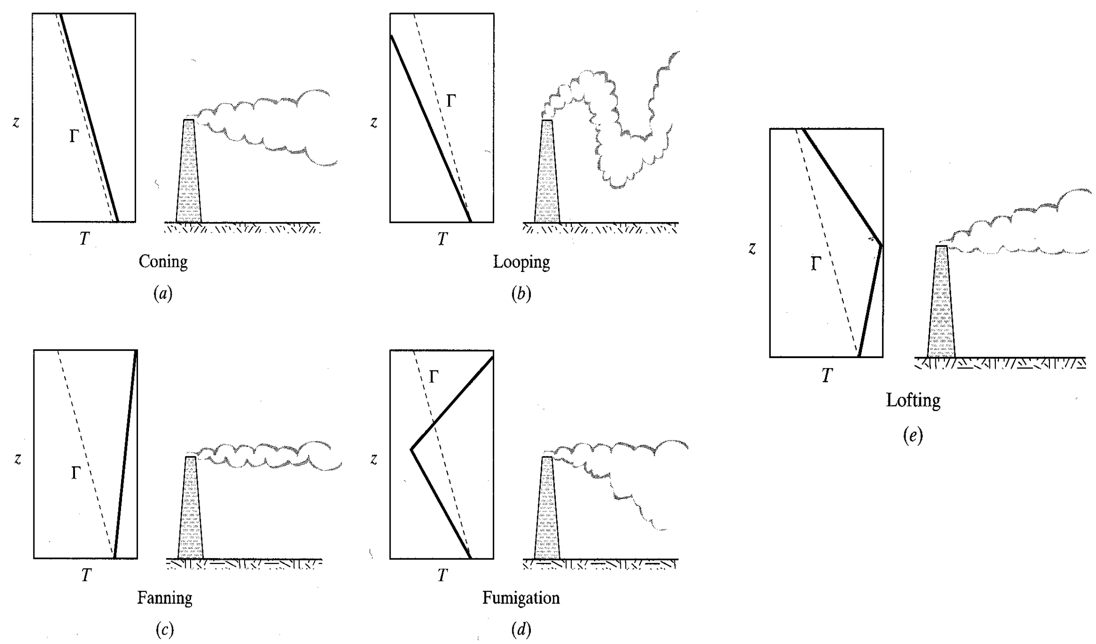


Recap 4

- Extreme case of stability when lapse rate is actually <u>positive</u>, leads to temperature inversion prevents nearly all upward mixing







Today's Learning Objectives !

- To learn about air quality modeling methods

Why are we doing all of this ?

- If we want to set up a new industry, it implies adding a new source of pollutant(s)
- This source is PERMITTED to emit after it has applied the Best Available Control Technology (BACT) on their processes
- AFTER leaving the chimney, the concentrations on ground is determined by the meteorology

Why are we doing all of this ?

Therefore,

- If we want to know WHERE to put the new industry

- If we want to know the pollution levels under the worst case scenario of STABLE conditions and low wind speeds

- If we want to know what height does the chimney need to be

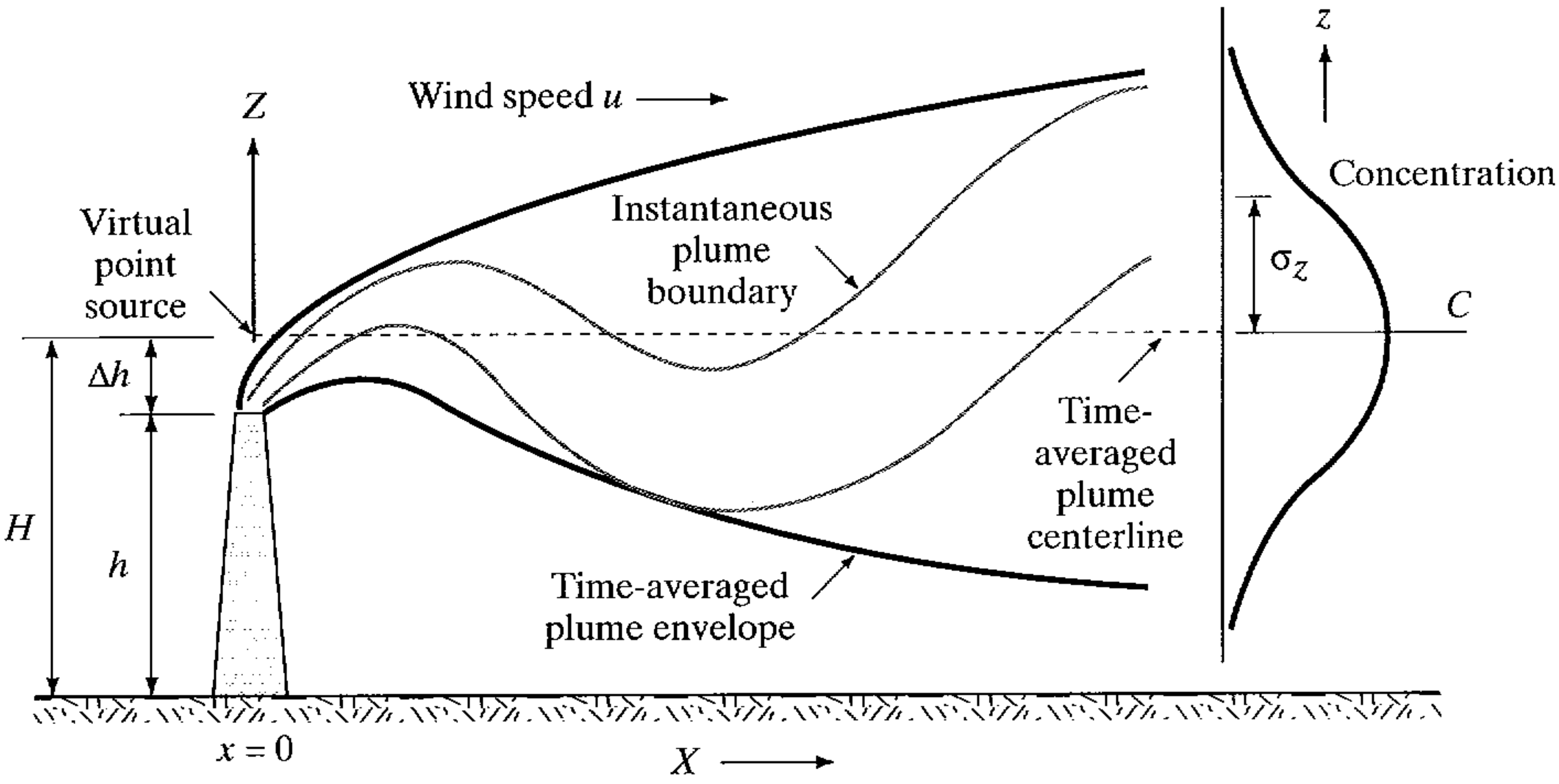
⇒ QUANTIFICATION of horizontal movement and vertical mixing becomes essential

Modeling air quality

- Gaussian Plume (Dispersion) Model (GPM) is used to estimate the ground level concentrations for pollutants coming from a chimney

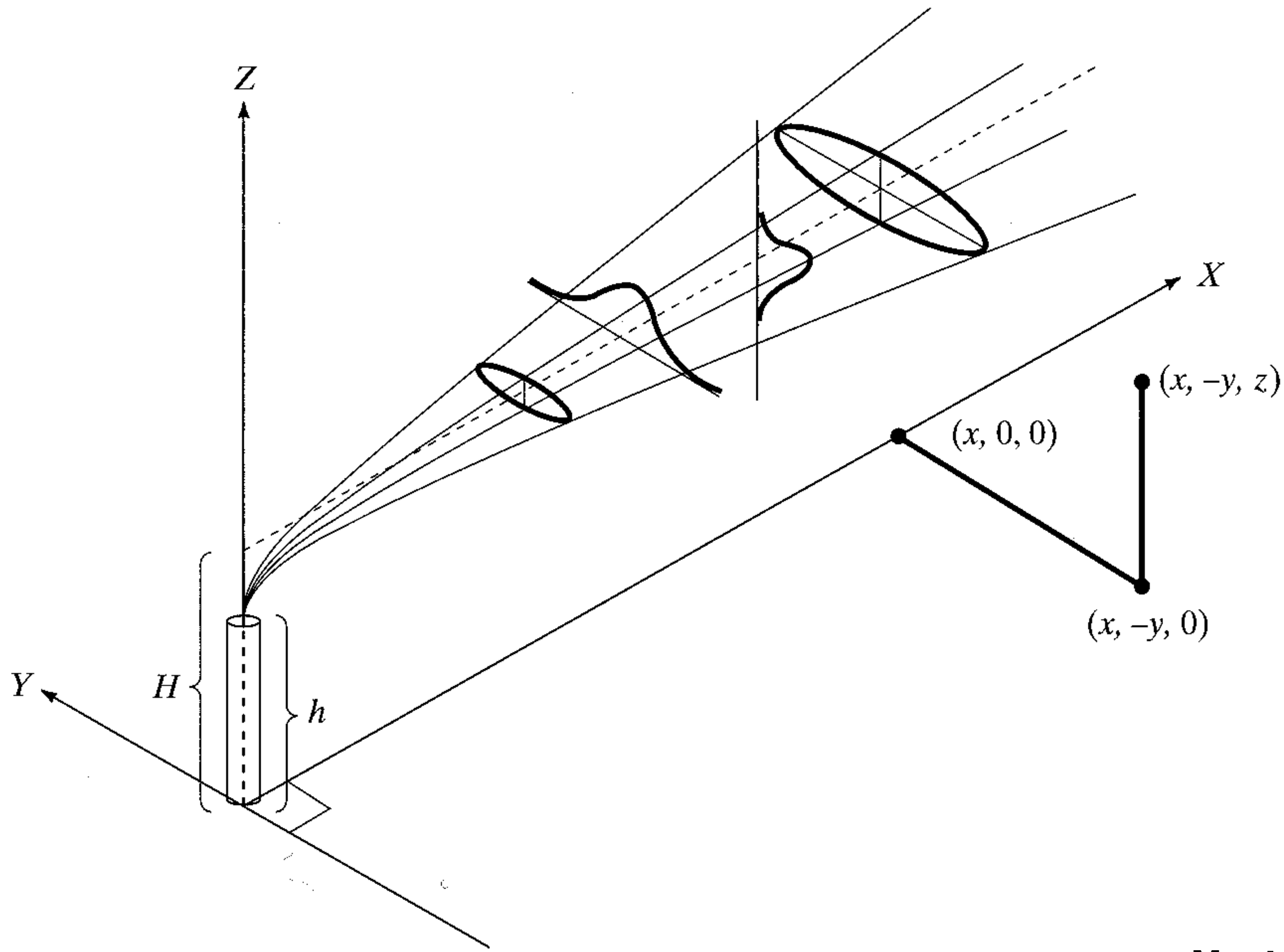
- Inputs to GPM
  - Height of chimney and Source strength
  - Wind rose data
  - Atmospheric stability of the region

Point Source Gaussian Plume Model



Masters & Ela, 2008

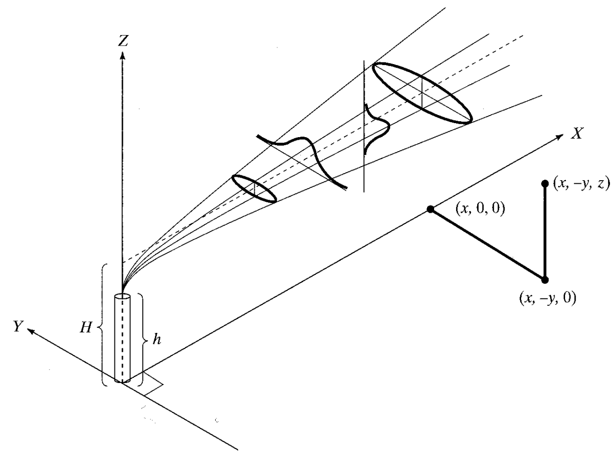
Point Source Gaussian Plume Model



Masters & Ela, 2008

GPM: Model Structure & Assumptions

- pollutants released from a “virtual point source”
- advective transport by wind
- dispersive transport (spreading) follows normal (Gaussian) distribution away from trajectory
- constant emission rate
- wind speed constant with time and elevation
- pollutant is conservative (no reaction)
- terrain is flat and unobstructed
- uniform atmospheric stability



Point Source GPM: Mathematical expression

$$C(x,y,0)=\left[\frac{Q}{\pi s_y s_z u_H}\right]\left[\exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right]\right]\left[\exp\left[-\frac{1}{2}\left(\frac{H}{s_z}\right)^2\right]\right]$$

Where,

- C = downwind concentration at ground level ($\mu g/m^3$)
- *Q* = emission rate of pollutant ($\mu g/s$)
- s_y, s_z = plume standard deviations (m)
- *u* = wind speed (m/s)
- *x, y, z* = distances (m)
- H = Effective Stack Height (m)

Point Source GPM: Effective Stack Height

$$H = h + \Delta H$$

where, H = Effective stack height (m)

h = height of physical stack (m)

ΔH = plume rise (m)

- Holland's formula

$$\Delta H = \frac{v_s d}{u}\left[1.5 + \left(2.68 \times 10^{-3} (P) \left(\frac{T_s - T_a}{T_s}\right) d\right)\right]$$

where, v_s = stack velocity (m/s)

d = stack diameter (m)

u = wind speed (m)

P = atmospheric Pressure, millibars

T_s = stack gas temperature (ºK)

T_a = air temperature (ºK)

Holland's formula, however, does not take into account the meteorology of the atmosphere, and good for certain atmospheric conditions only

Point Source GPM: Stability Categories

TABLE 11–6 Key to Stability Categories

Surface Wind Speed (at 10 m) ($m \cdot s^{-1}$)	Day[a] Incoming Solar Radiation			Night[a]	
	Strong	Moderate	Slight	Thinly Overcast or $\geq \frac{4}{8}$ Low Cloud	$\leq \frac{3}{8}$ Cloud
<2	A	A–B	B		
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

A Extremely Unstable

B Moderately Unstable

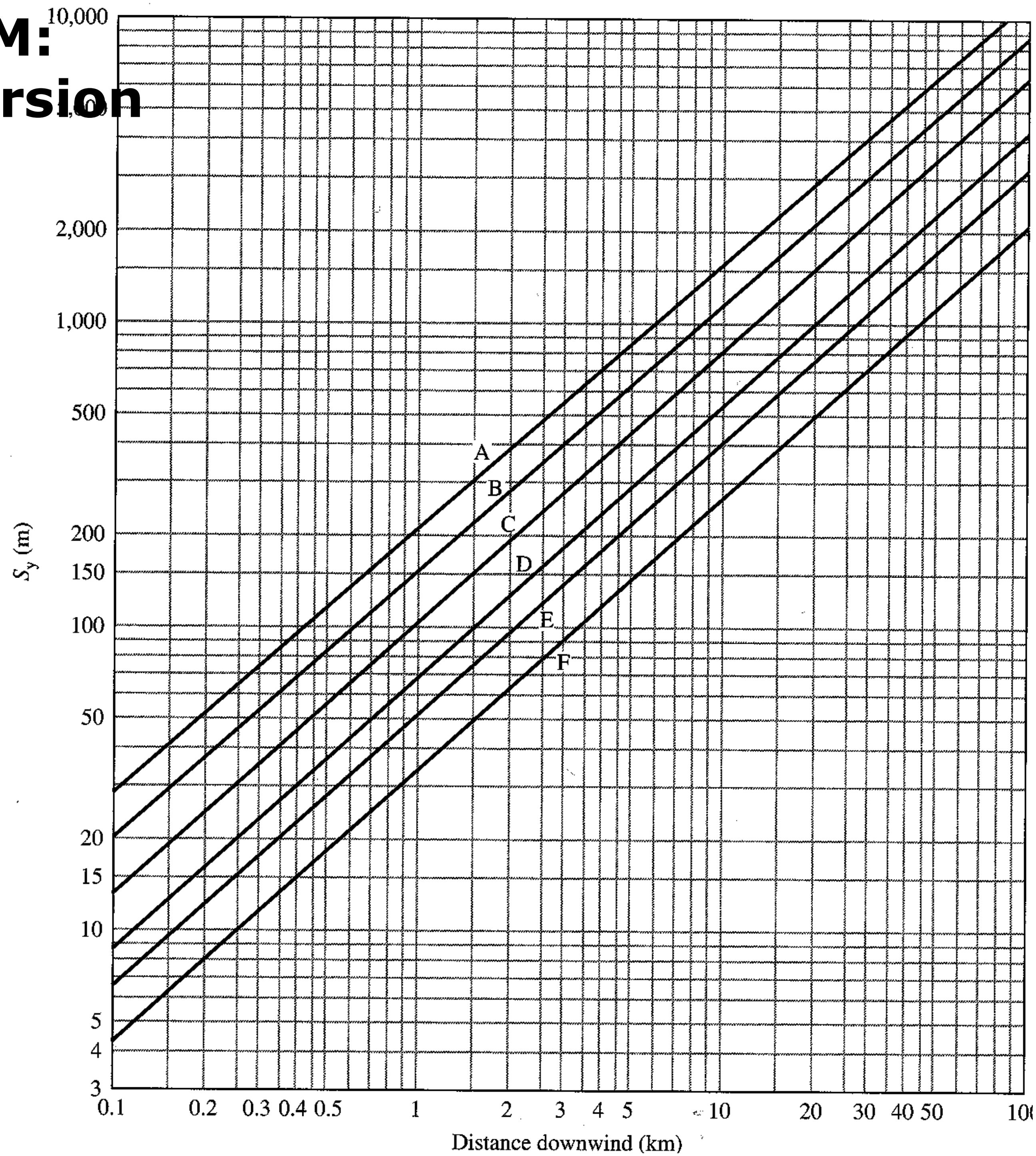
C Slightly Unstable

D Neutral

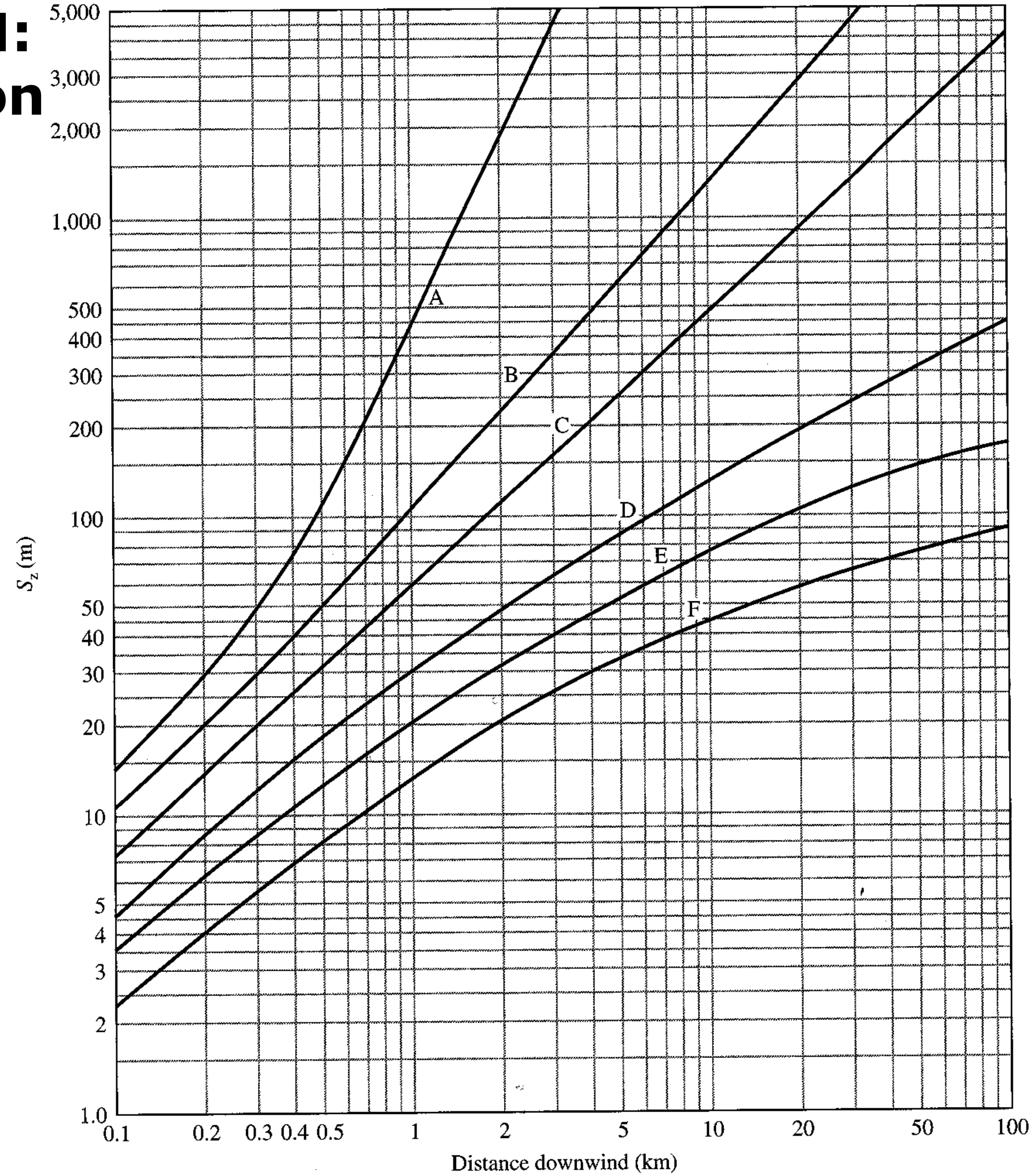
E Slightly Stable

F Moderately Stable

Point Source GPM: Horizontal Dispersion (s_y)



Point Source GPM: Vertical Dispersion (s_z)



Point Source GPM:
Vertical & horizontal Dispersion (sy, s_z)

$$\sigma_y = a\, x^{0.894}$$

$$\sigma_z = c x^d + f$$

TABLE 7.8

Values of the Constants *a*, *c*, *d*, and *f* for Use in (7.47) and (7.48)

		$x \le 1$ km			$x \ge 1$ km		
Stability	a	c	d	f	c	d	f
A	213	440.8	1.941	9.27	459.7	2.094	−9.6
B	156	106.6	1.149	3.3	108.2	1.098	2.0
C	104	61.0	0.911	0	61.0	0.911	0
D	68	33.2	0.725	−1.7	44.5	0.516	−13.0
E	50.5	22.8	0.678	−1.3	55.4	0.305	−34.0
F	34	14.35	0.740	−0.35	62.6	0.180	−48.6

Note: The computed values of σ will be in meters when x is given in kilometers.
Source: Martin, 1976.

Masters & Ela, 2008

Point Source GPM: Wind Speed Correction

- Unless the wind speed at the virtual stack height is known, it must be estimated from the ground wind speed

$$u_2 = u_1 \left(\frac{z_2}{z_1} \right)^p$$

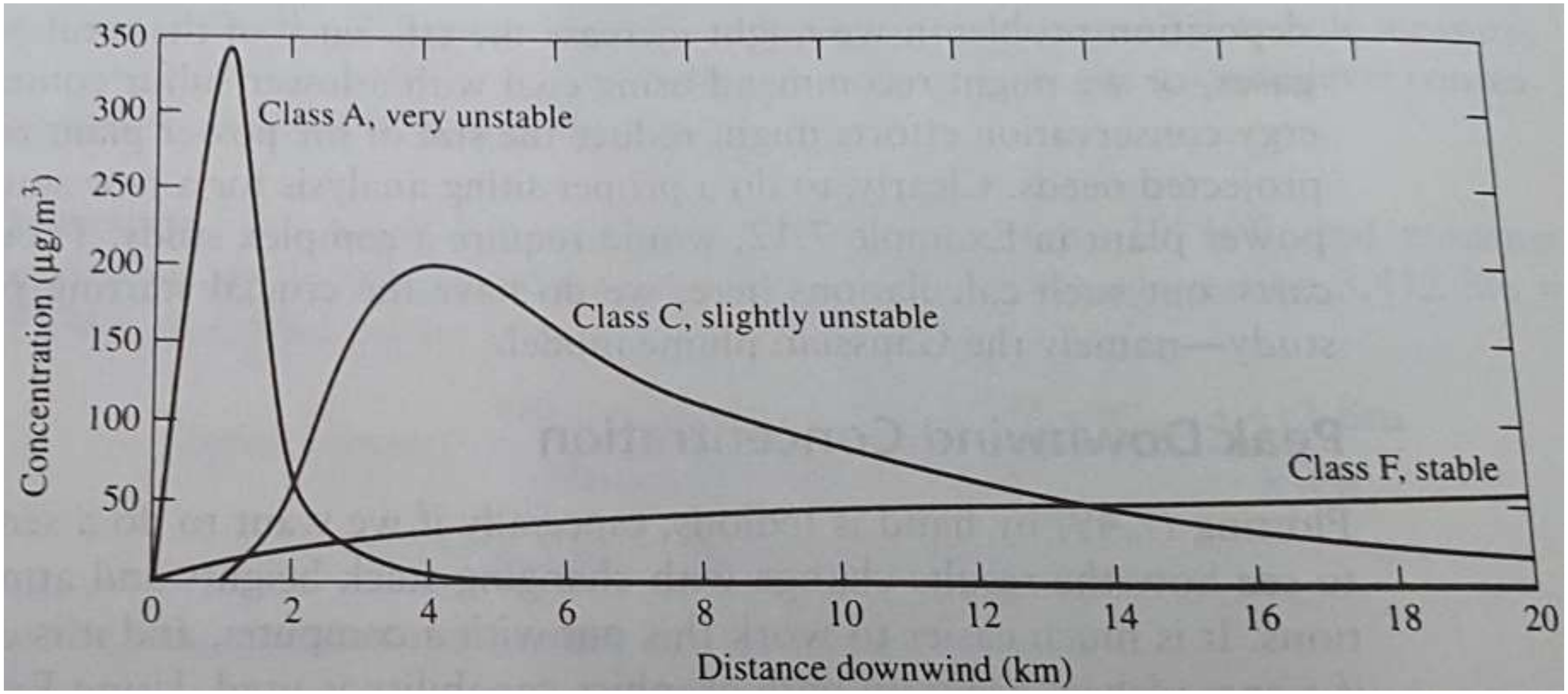
where u_x = wind speed at elevation z_x

p = empirical constant

TABLE 11–8 Exponent p Values for Rural and Urban Regimes

Stability Class	Rural	Urban	Stability Class	Rural	Urban
A	0.07	0.15	D	0.15	0.25
B	0.07	0.15	E	0.35	0.30
C	0.10	0.20	F	0.55	0.30

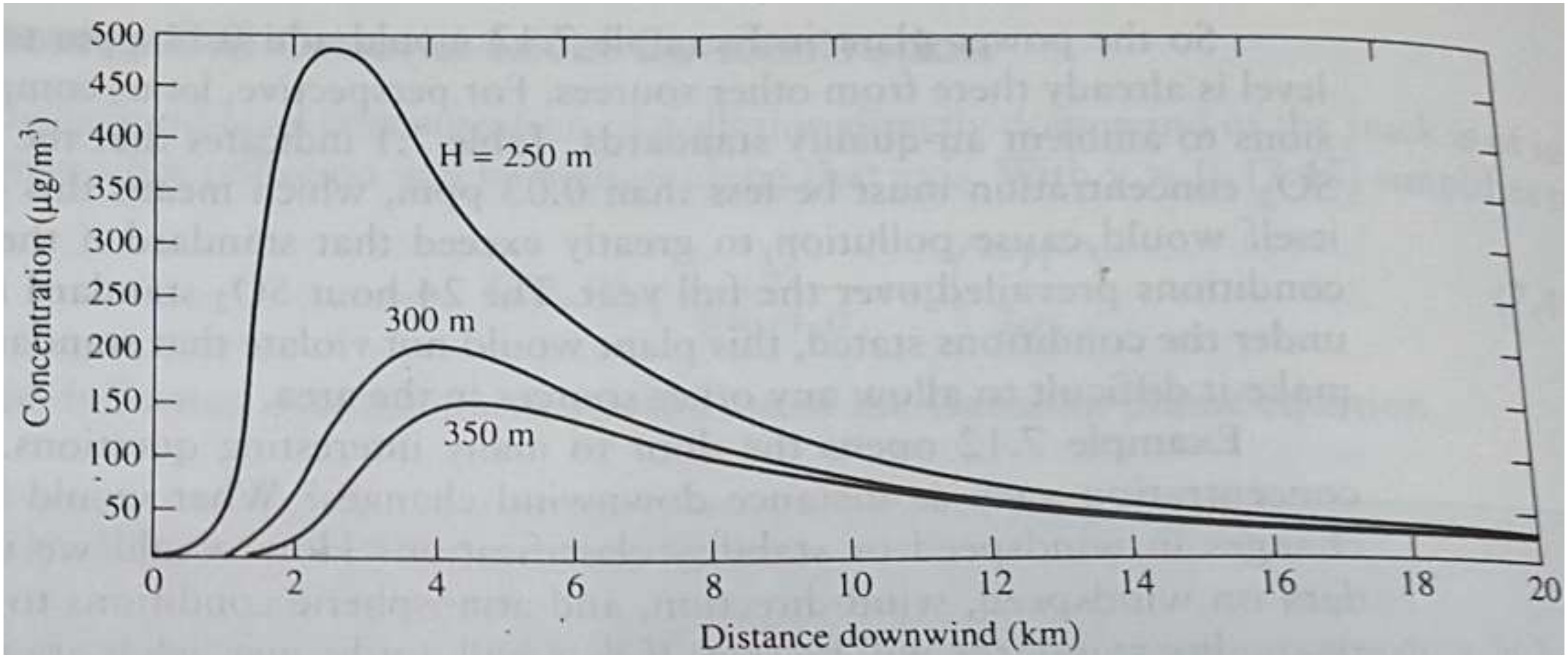
Point Source GPM:
Effect of atmospheric stability classification



For a given stack height, maximum ground level pollutant concentration observed for very unstable atmosphere and reaches a maximum nearer to the source/earlier in time compared to other atmospheric stabilities.

Masters & Ela, 2008

Point Source GPM:
Effect of effective stack height



For a given atmospheric stability, maximum ground level pollutant concentration observed for lower effective stack height and reaches a maximum nearer to the source/earlier in time compared to sources with higher effective stack heights

⇨ Gaussian dispersion model estimates may have an uncertainty up to 50% due to several assumption involved

Masters & Ela, 2008

Point Source GPM

Example !

A stack in an urban area is emitting 80 g/s of NO. It has an effective stack height of 100m. The wind speed is 4 m/s at 10 m. It is a clear summer day with the sun nearly overhead. Estimate the ground level concentration at:

a. 2 km downwind on the centerline, and

b. 2 km downwind, 0.1 km off the centerline.

Point Source GPM: Example !

1. Determine stability class

   Assume wind speed is 4 m/s at ground surface.
   Description suggests strong solar radiation.

   hence *stability class* is **B**

clear summer day with the sun nearly overhead; wind speed 4 m/s at 10 m.

TABLE 11–6 Key to Stability Categories

Surface Wind Speed (at 10 m) ($m \cdot s^{-1}$)	Day[a] Incoming Solar Radiation: Strong	Day[a] Incoming Solar Radiation: Moderate	Day[a] Incoming Solar Radiation: Slight	Night[a]: Thinly Overcast or $\geq \frac{4}{8}$ Low Cloud	Night[a]: $\leq \frac{3}{8}$ Cloud
<2	A	A–B	B		
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

Point Source GPM: Example !

2. Estimate the wind speed at the effective stack height

   Note: effective stack height given – no need to calculate using Holland's formula

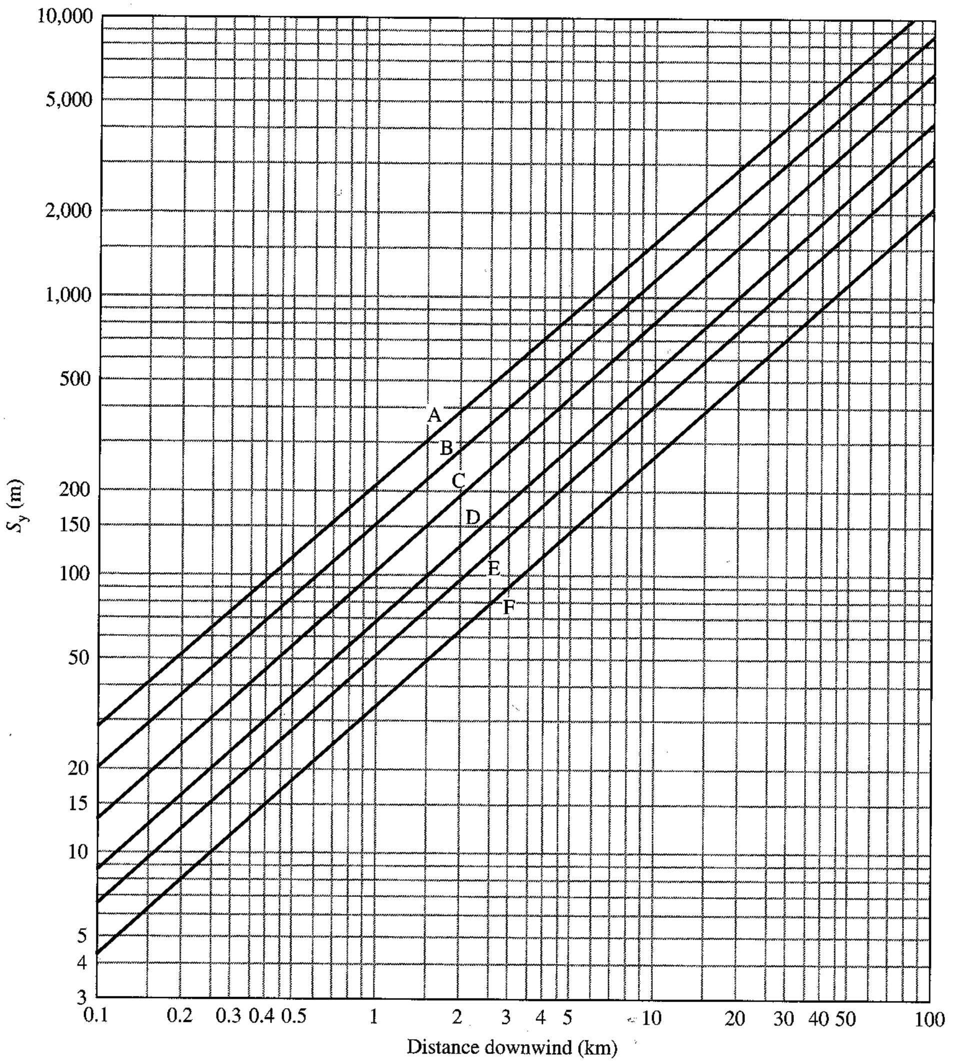
TABLE 11–8 Exponent p Values for Rural and Urban Regimes

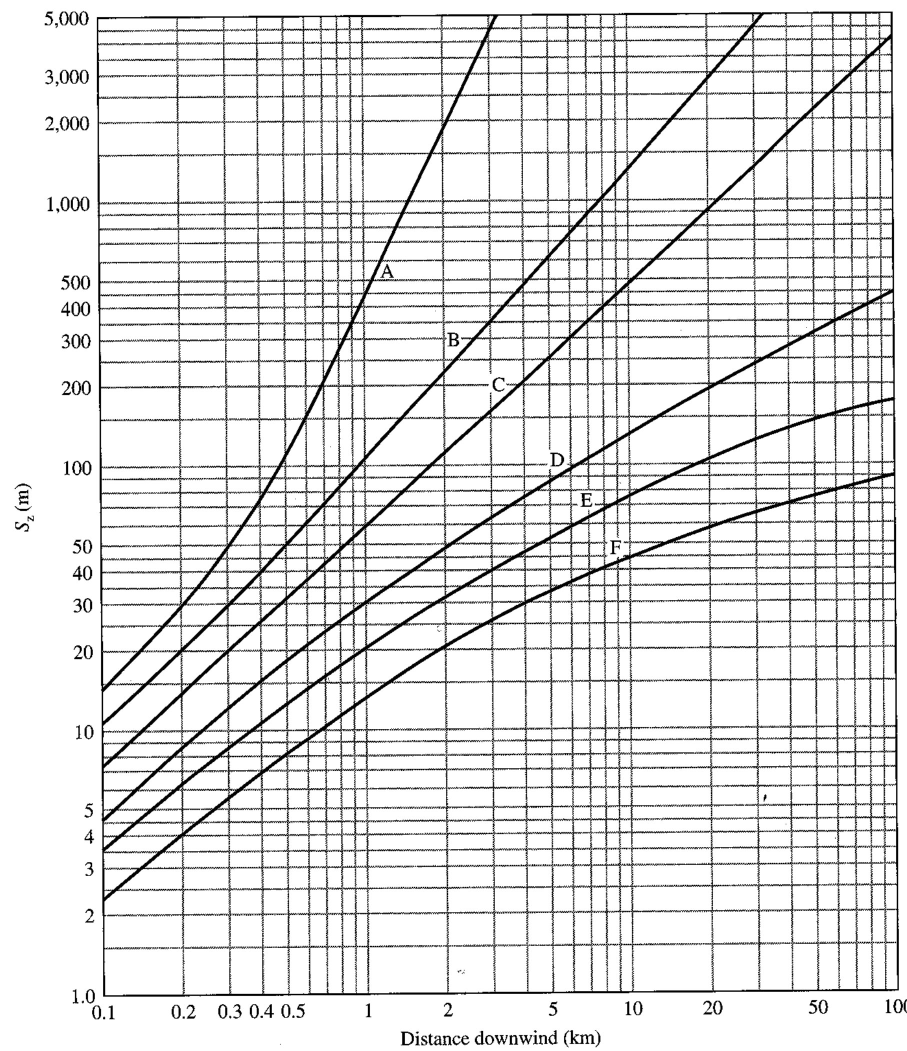
Stability Class	Rural	Urban	Stability Class	Rural	Urban
A	0.07	0.15	D	0.15	0.25
B	0.07	0.15	E	0.35	0.30
C	0.10	0.20	F	0.55	0.30

$$u_2 = u_1\left(\frac{z_2}{z_1}\right)^p = 4\left(\frac{100}{10}\right)^{0.15} = 5.65\ \text{m/s}$$

Point Source GPM: Example !

3. Determine σ_y and σ_z

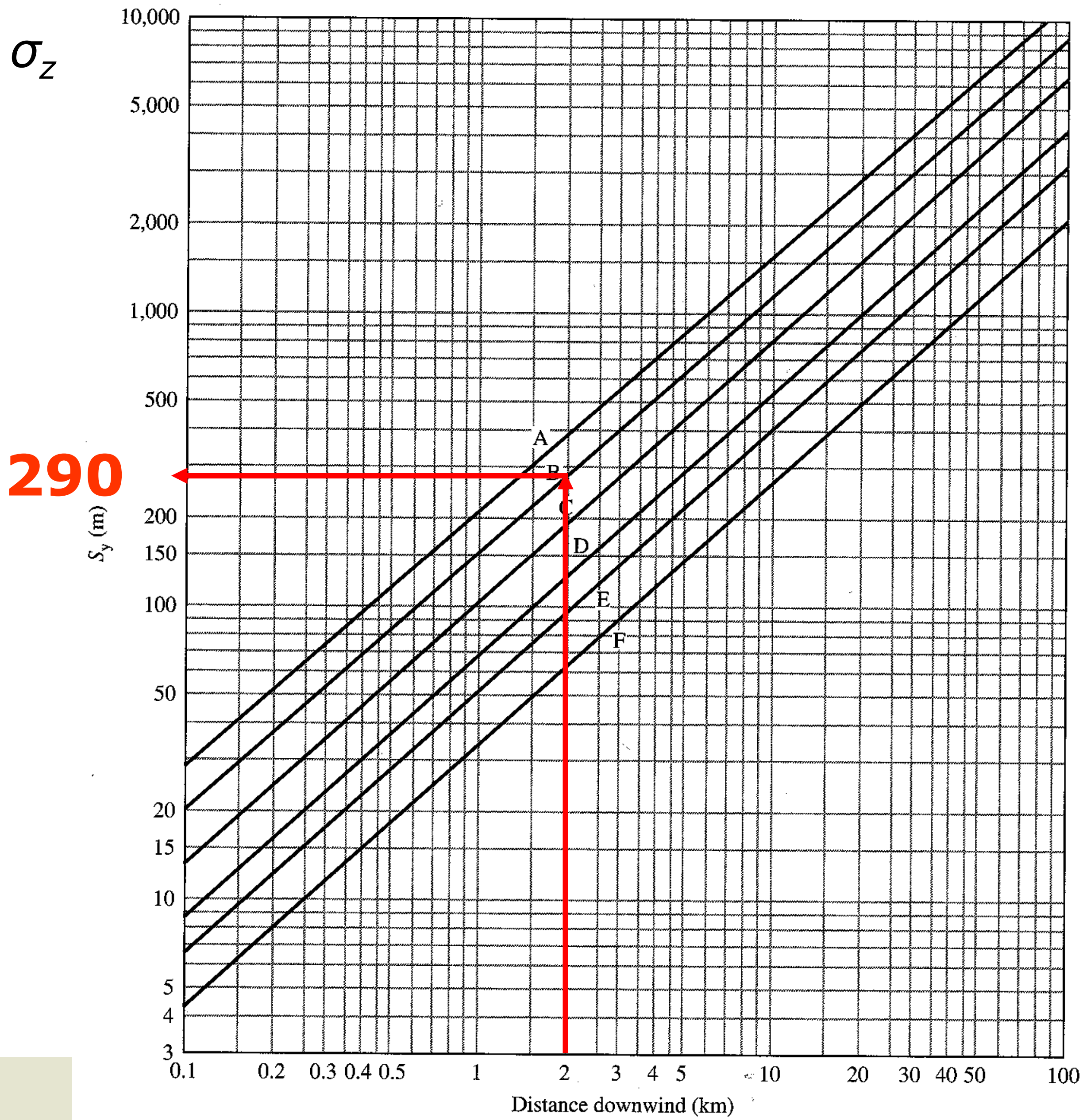




Point Source GPM: Example !

3. Determine σ_y and σ_z

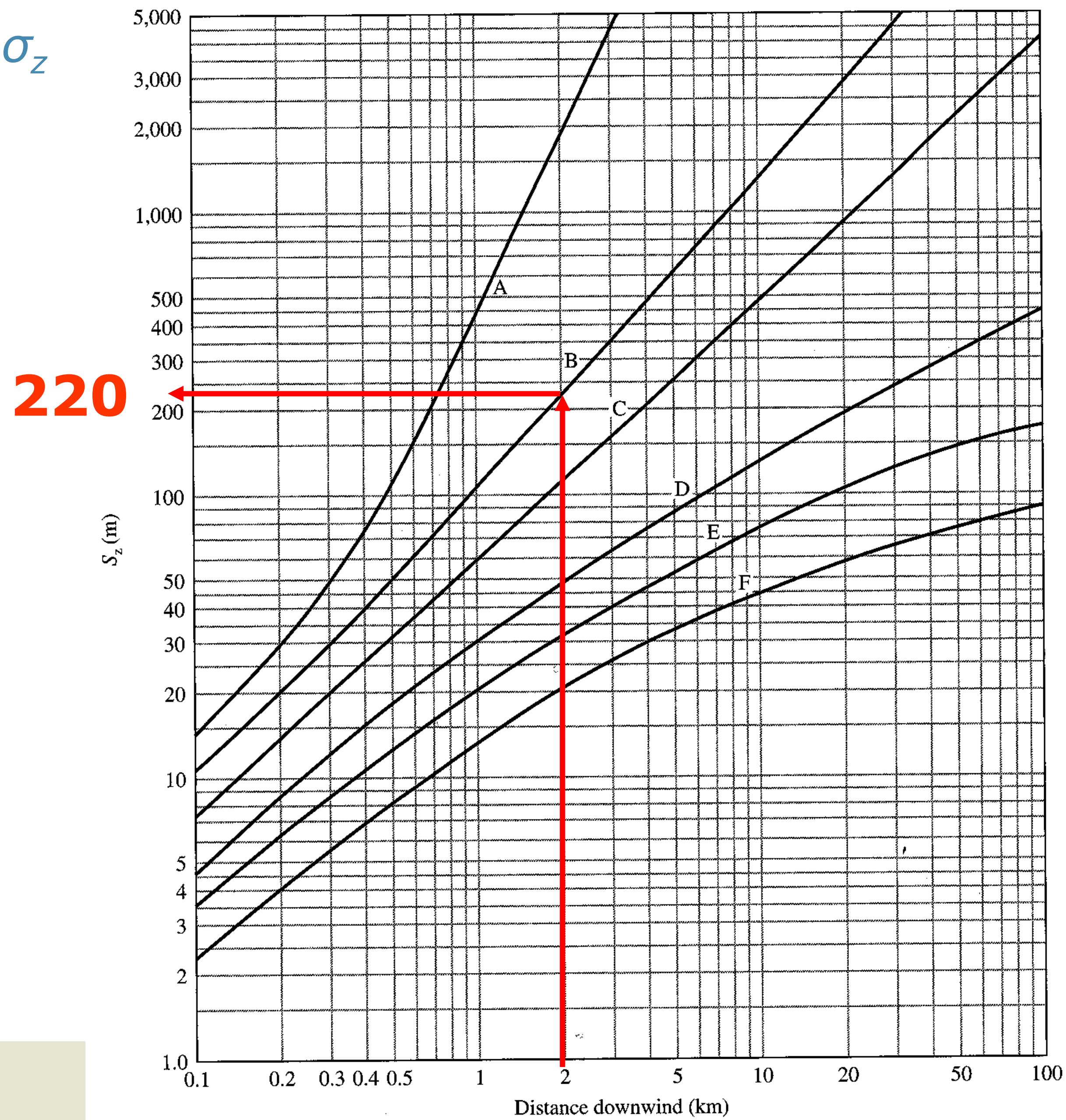
$\sigma_y = 290$



Point Source GPM: Example !

3. Determine σ_y and σ_z

σ_z = 220



Point Source GPM: Example !

4. Determine concentration using the Eqn.
   a. x = 2000, y = 0

$$C(2000,0)=\frac{80}{\pi(290)(220)(5.6)}\exp\left[-\frac{1}{2}\left(\frac{0}{290}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{100}{220}\right)^2\right]$$

$$C(2000,0)=6.37\times10^{-5}\ \text{g/m}^3=63.7\ \mu\text{g/m}^3$$

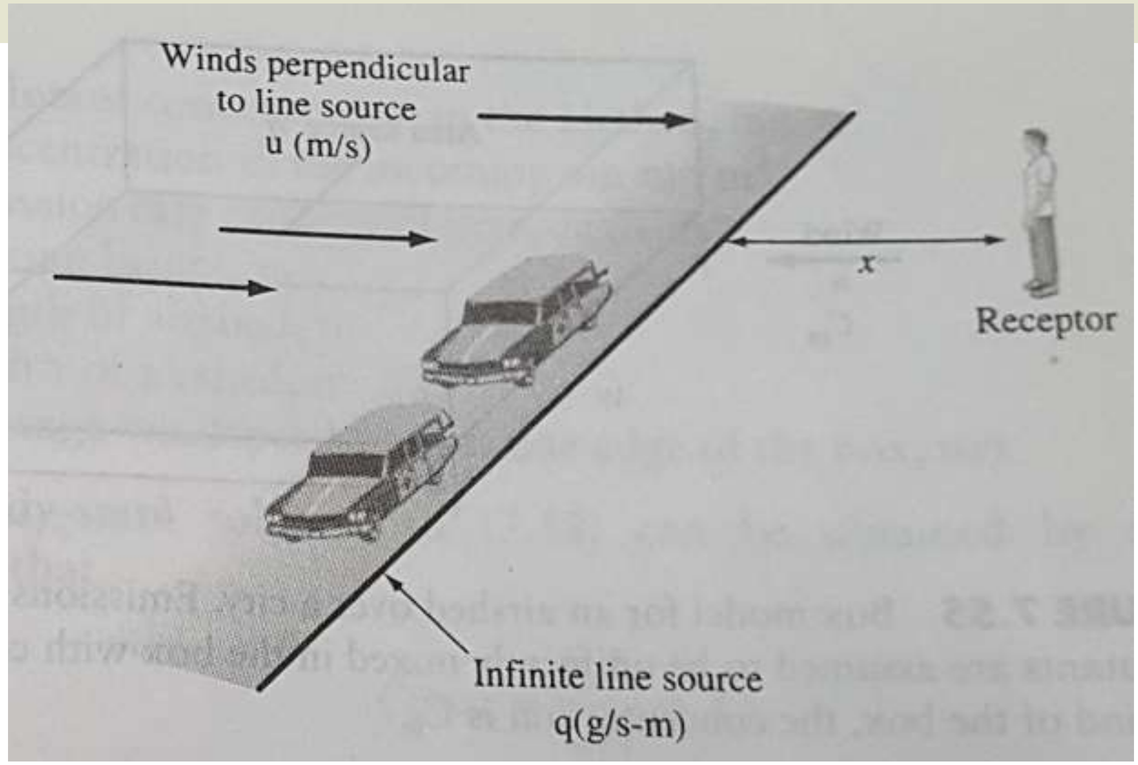
Point Source GPM: Example !

4. Determine concentration using the Eqn.
   b. x = 2000, y = 0.1 km (= 100m)

$$C(2000{,}100) = \frac{80}{\pi(290)(220)(5.6)} \exp\left[-\frac{1}{2}\left(\frac{100}{290}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{100}{220}\right)^2\right]$$

$$C(2000{,}0) = 6.00\times10^{-5}\ \text{g/m}^3 = 60\ \mu\text{g/m}^3$$

Line Source Dispersion Model



- Useful in certain conditions where source is distributed along a line with continuous emissions

- Hence, ground level conc. of pollutant at a distance perpendicular distance x can be obtained by:

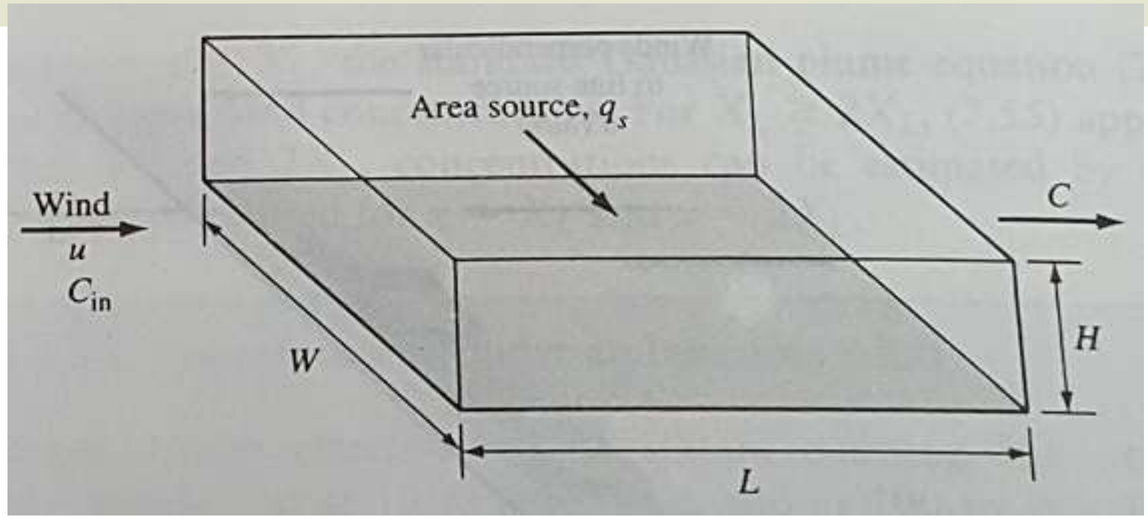
$$C(x) = \frac{2q}{\sqrt{2\pi}\,\sigma_z u}$$

Where

q = emission rate per unit distance along the line (g/m-s)

Area Source Model

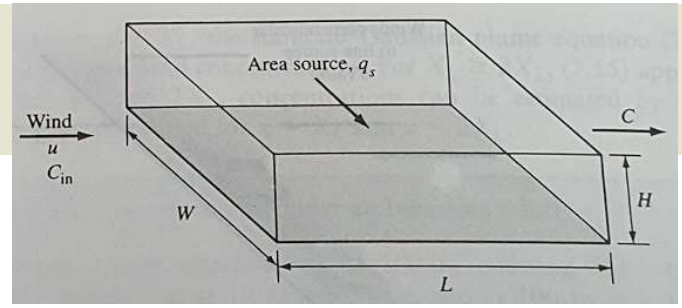
- Useful for distributed sources spread over an area
- e.g. Box model for an airshed over a city
- Pollutants are assumed to be uniformly mixed in the box



- If we assume the pollutant is conservative, then

$$\begin{pmatrix}\text{Rate of change of}\\ \text{pollution in the box}\end{pmatrix} = \begin{pmatrix}\text{Rate of pollution}\\ \text{entering the box}\end{pmatrix} - \begin{pmatrix}\text{Rate of pollution}\\ \text{leaving the box}\end{pmatrix}$$

Area Source Model



- If we assume the pollutant is conservative, then

$$LWH\frac{dC}{dt} = q_s LW + WHuC_{in} - WHuC$$

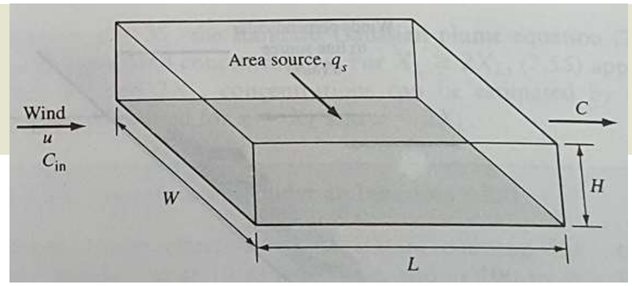
where

C = pollutant concentration in the airshed, mg/m^3
C_{in} = concentration in the incoming air, mg/m^3
q_s = emission rate per unit of area, mg/s-m^2
H = mixing height, m
L = length of airshed, m
W = width of airshed, m
u = average windspeed against one edge of the box, m/s

- Hence the steady state solution of the above equation, by simply setting $dC/dt=0$, is:

$$C(\infty) = \frac{q_s L}{uH} + C_{in}$$

Area Source Model



$$LWH\frac{dC}{dt} = q_s LW + WHuC_{in} - WHuC$$

- The time-dependent change in the pollutant concentration in the city can be obtained by following:

$$C(t) = \left(\frac{q_s L}{uH} + C_{in}\right)(1 - e^{-ut/L}) + C(0)e^{-ut/L}$$

where, C(0) is the concentration in the airshed at t=0

- If we assume incoming wind blow relatively no pollution in the box, C(0)=0 then:

$$C(t) = \frac{q_s L}{uH}(1 - e^{-ut/L})$$

Reminder !!!

Quiz next week

Syllabus: All covered until Mon, 14.08

Home work !!!

- Do you have an air quality monitoring station in your city? If not, in the nearest city? What is the current status of air quality there?

- In the last 5 years or decade has the air quality improved or worsened? Why?

- Please do this **by Thu, 17.08**; we will discuss in the class!

Please spend 3 mins. and fill the google form that was shared over moodle; discussion will be held on Mon, 21.08!