Air pollution II

Adiabatic lapse rate

→ When air moves vertically in the atmosphere, how does its temperature change?

→ This is close to the adiabatic expansion; the air adjust to the decreasing atmospheric pressure by expanding in volume, with a negligible exchange of heat between it and the surrounding air

Adiabatic lapse rate

- First law of thermodynamics

$$dU \quad = \quad dQ \quad - \quad dW$$

change in internal energy of the system

Heat transfer to the system

Change in energy due to work done by the system

For a adiabatic system, $dQ = 0$

$dW = pdV$ *p = pressure; V=volume*

$dU = C_v dT$ *C_v = heat capacity; T = temperature*

So: $C_v dT = -pdV$

As air moves up, V ↑ ➡ T ↓

Adiabatic lapse rate and air stability

- Dry adiabatic lapse rate

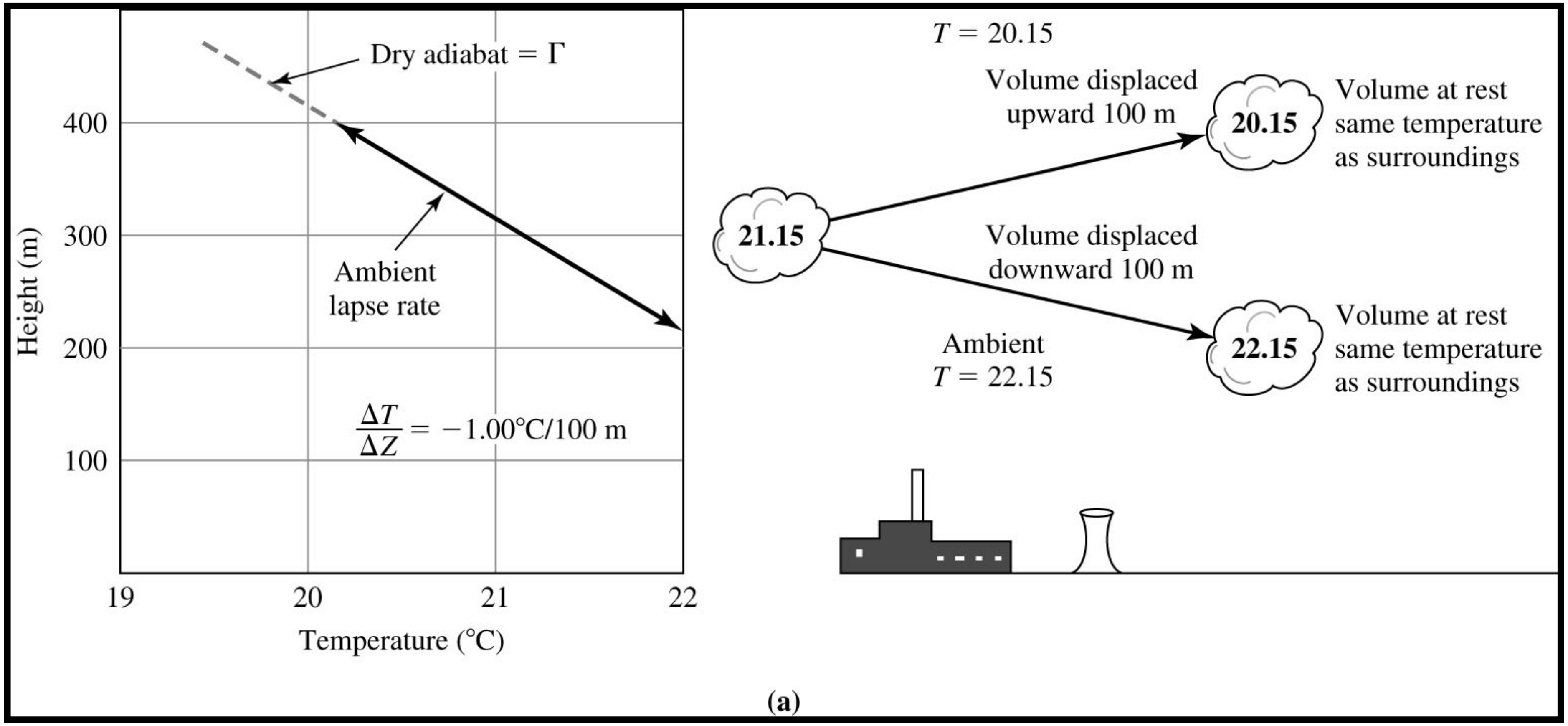
$$\Gamma = -\frac{dT}{dz} = 1^{o}C\ /\ 100\ m$$

- Air stability based on dry adiabatic lapse rate

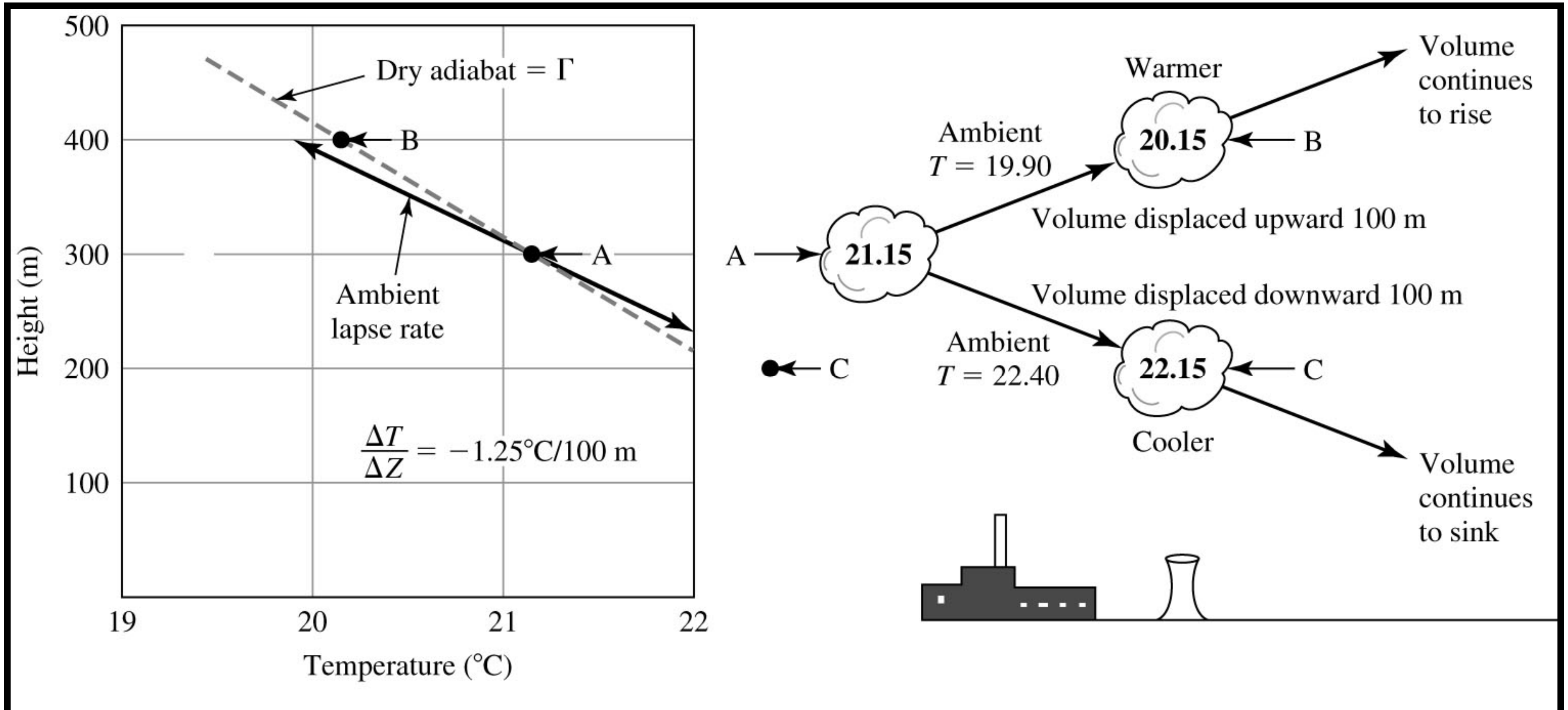
$\Lambda = \Gamma$	Neutral stability
$\Lambda > \Gamma$	Unstable atmosphere
$\Lambda < \Gamma$	Stable atmosphere

$\Lambda = actual\ lapse\ rate\ of\ the\ atmosphere$

Neutral stability



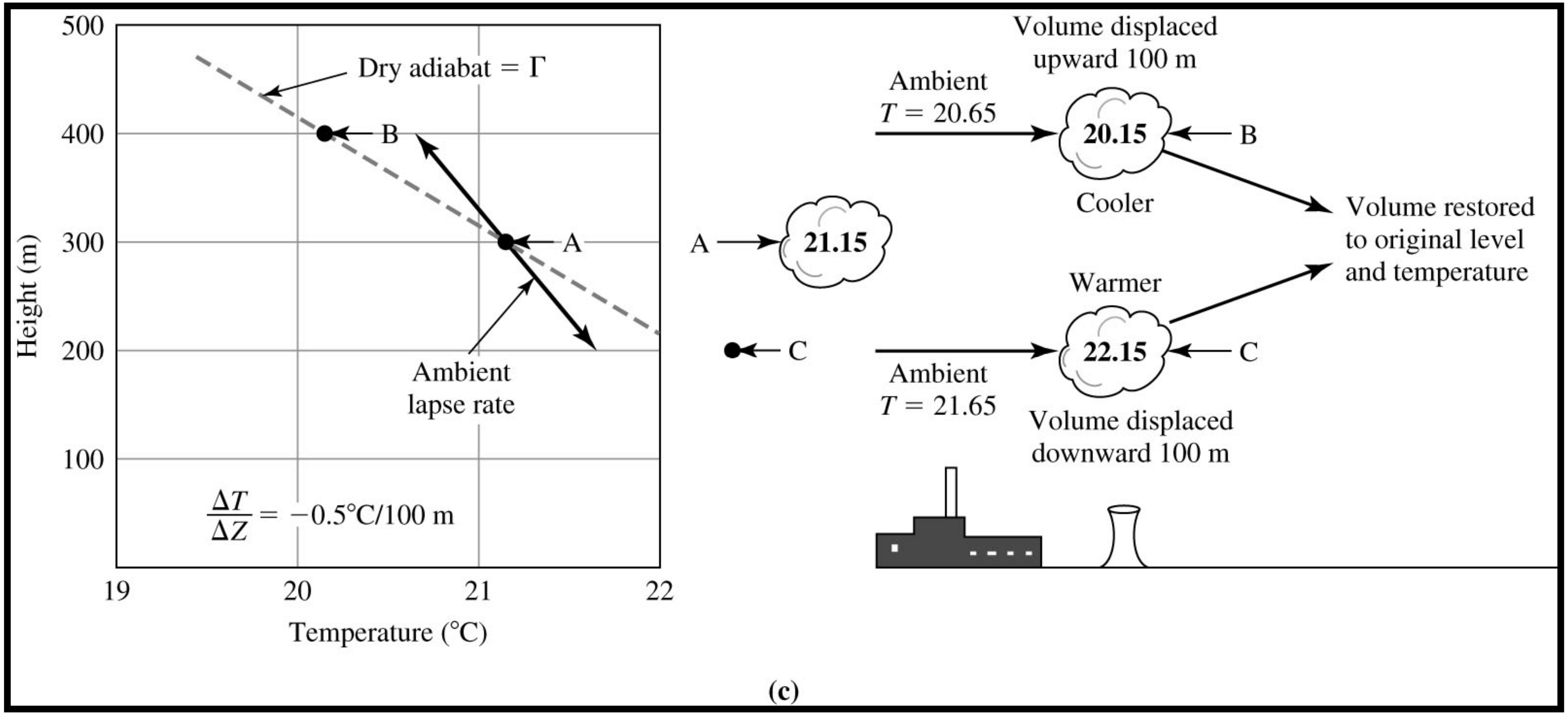
Unstable



500
400
300
200
100
Height (m)
Dry adiabat = Γ
B
A
Ambient
lapse rate
$\frac{\Delta T}{\Delta Z} = -1.25°C/100\ m$
19
20
21
22
Temperature (°C)
C
Warmer
Volume
continues
to rise
Ambient
T = 19.90
20.15
B
Volume displaced upward 100 m
A
21.15
Volume displaced downward 100 m
Ambient
T = 22.40
22.15
C
Cooler
Volume
continues
to sink

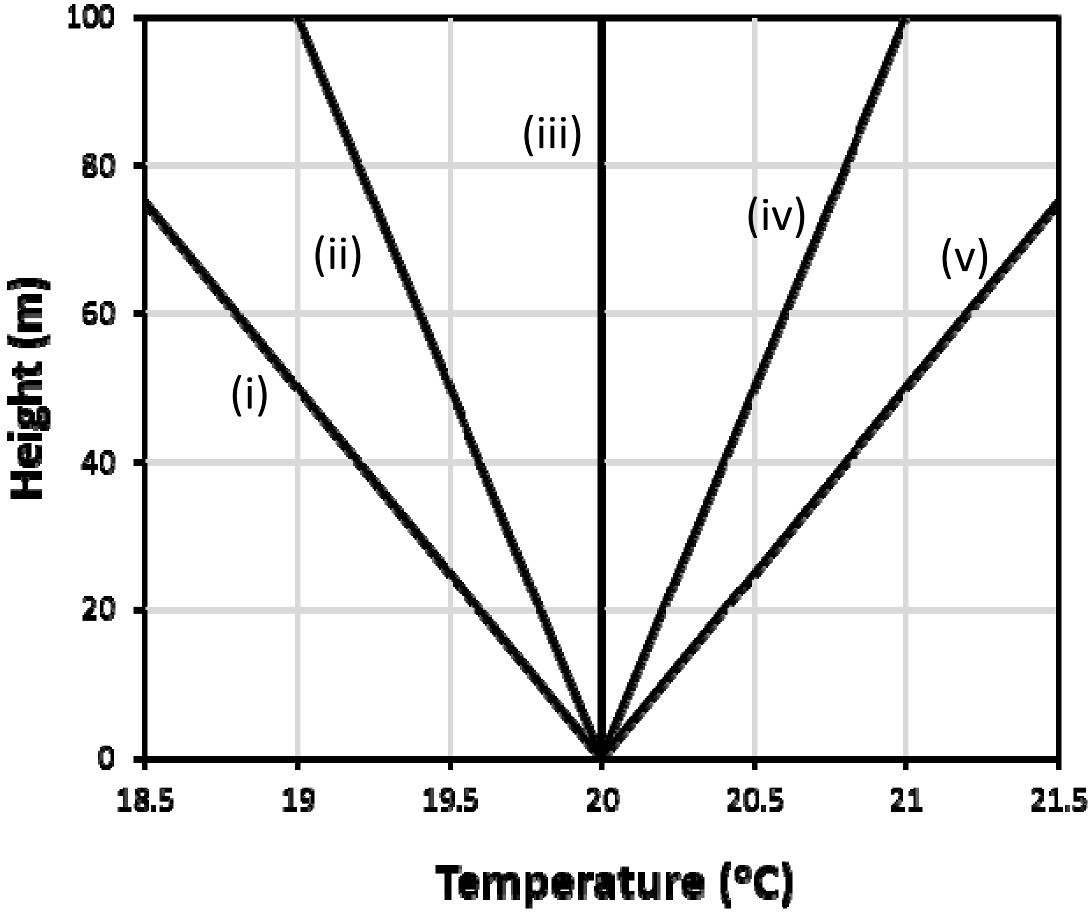
(b)

Stable



Dry adiabat = Γ
B
A
Ambient lapse rate
$\frac{\Delta T}{\Delta Z} = -0.5°C/100$ m
Height (m)
Temperature (°C)
500
400
300
200
100
19
20
21
22
A
21.15
C
Volume displaced upward 100 m
Ambient T = 20.65
20.15
B
Cooler
Volume restored to original level and temperature
Warmer
22.15
C
Ambient T = 21.65
Volume displaced downward 100 m
(c)

Air stability



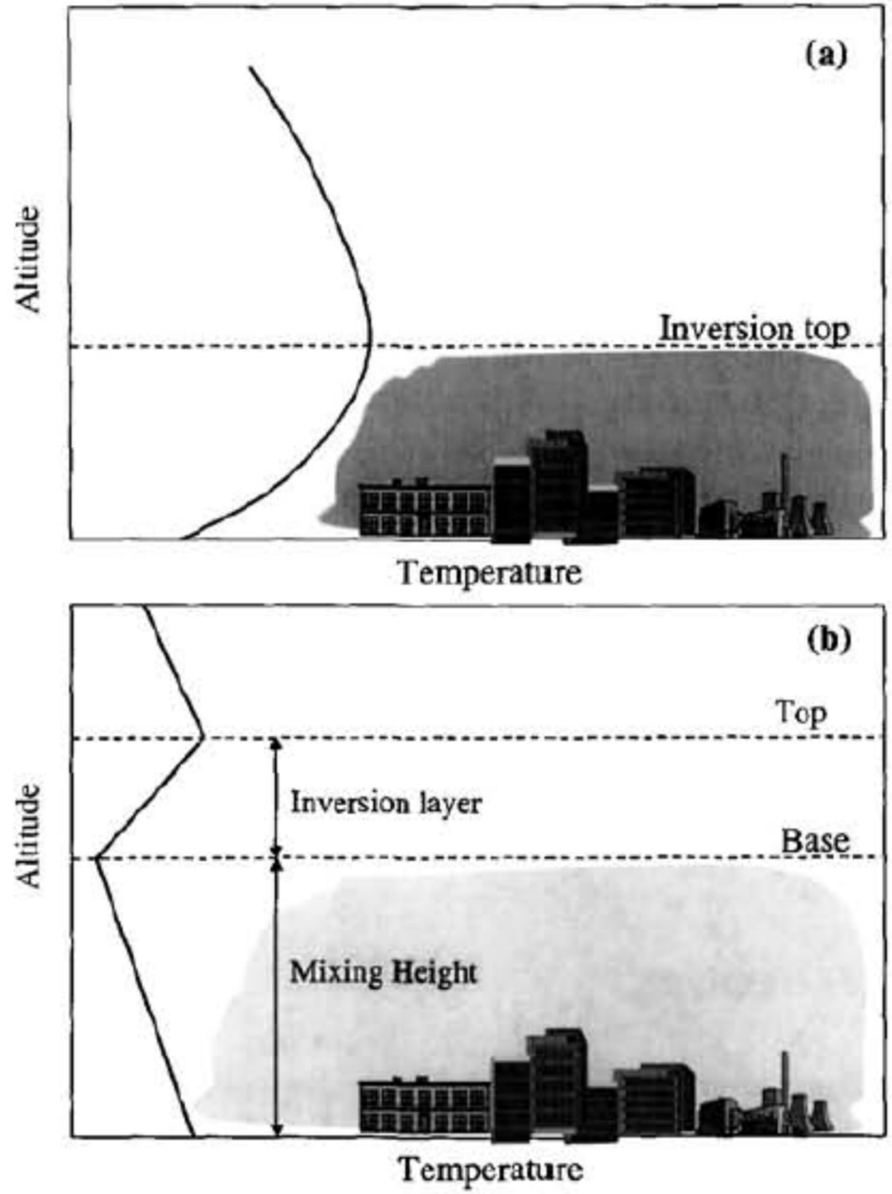
Neutral:

Unstable:

Stable:

Inversion layer

- Inversion: an increase in atmospheric temperature with height
- Radiation inversion: form by nighttime cooling of the ground
- Subsidence inversion: form by sinking (→ warming) of air

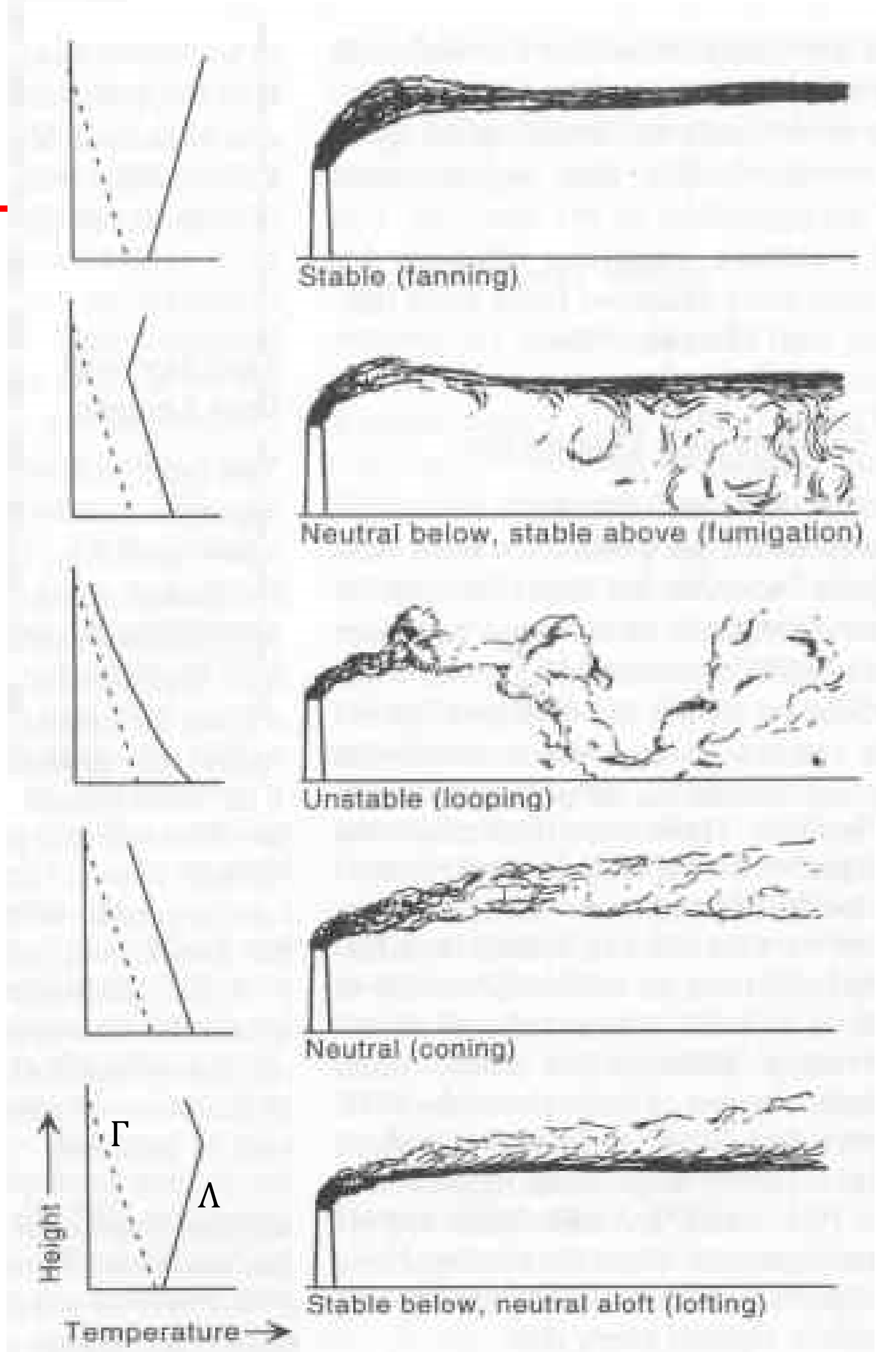


Atmospheric Chemistry and Physics, 1997

Plume behavior

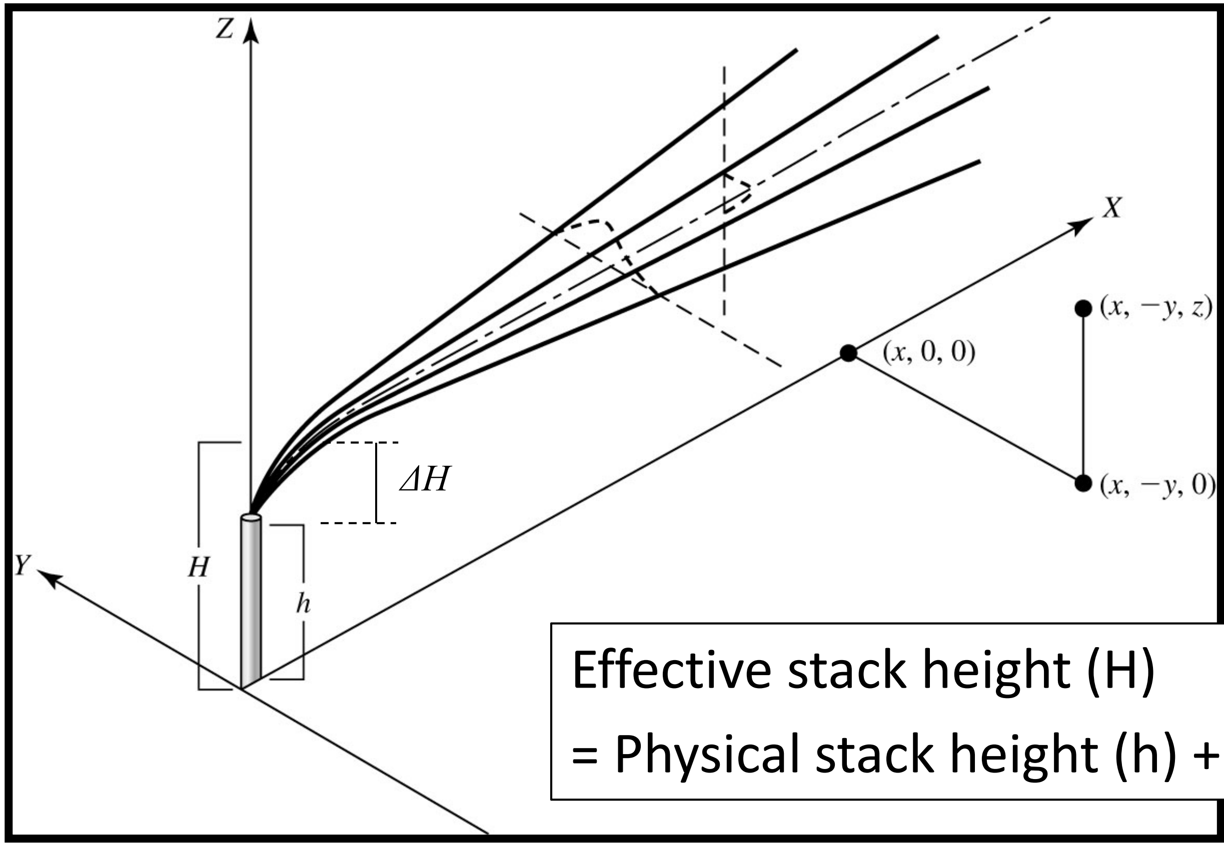
- Effect of atmospheric lapse rates on plume behavior

Slade, 1967



Atmospheric dispersion of air pollutants

- Coordination system



Effective stack height (H)

= Physical stack height (h) + **Plume rise** **(ΔH)**

Atmospheric dispersion of air pollutants

- Plume rise, ΔH
  - Due to buoyancy of the hot gas and inertia of the gas leaving the stack

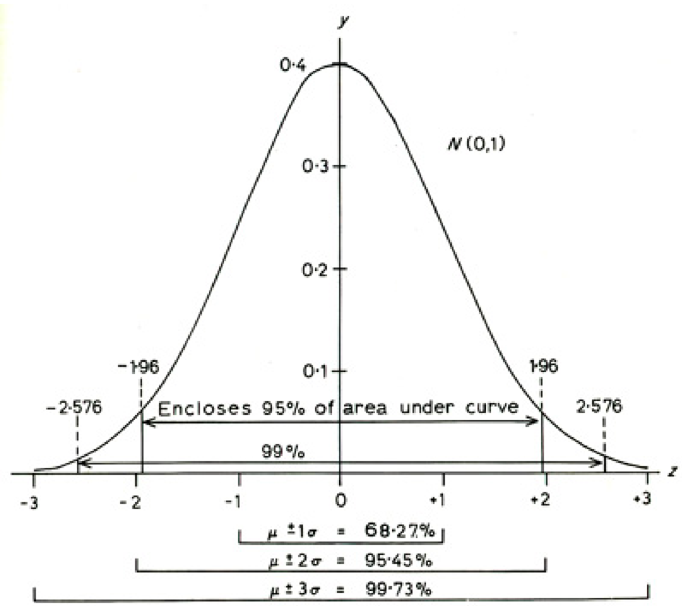
$$\Delta H = \frac{v_s d}{u}\left[1.5 + \left(2.68 \times 10^{-2} \cdot P \cdot \left(\frac{T_s - T_a}{T_s}\right) \cdot d\right)\right]$$

v_s = stack velocity (m/s)
d = stack diameter (m)
u = wind speed (m/s)
P = pressure (kPa)
T_s = stack temperature (K)
T_a = air temperature (K)

Atmospheric dispersion of air pollutants

- We assume Gaussian (normal) distribution of pollutants

Gaussian distribution



$$y = \frac{1}{\sigma(2\pi)^{1/2}} exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]$$

When the area of the curve is **1**

μ = mean
σ = standard deviation

Atmospheric dispersion of air pollutants

… But in two directions (y and z) at a certain distance downwind

So, for a continuous point source of an air pollutant located at (x, y, z) = (0, 0, H):

$$C(x,y,z) = \left(\frac{E}{u}\right) \times \left(\frac{1}{\sigma_y (2\pi)^{1/2}} exp\left[\frac{-(y-0)^2}{2{\sigma_y}^2}\right]\right) \times \left(\frac{1}{\sigma_z (2\pi)^{1/2}} exp\left[\frac{-(z-H)^2}{2{\sigma_z}^2}\right]\right)$$

Total mass of pollutant between ***x*** m and ***(x+1)*** *m*

C = concentration (g/m^3)
E = emission rate (g/s)
u = wind speed (m/s)

Atmospheric dispersion of air pollutants

Therefore,

$$C(x,y,z) = \left(\frac{E}{2\pi u \sigma_y \sigma_z}\right)\left[exp\left(\frac{-y^2}{2{\sigma_y}^2}\right)\right]\left[exp\left(\frac{-(z-H)^2}{2{\sigma_z}^2}\right)\right]$$

where σ_y and σ_z are functions of *x* and atmospheric conditions (wind speed, stability, etc.)

Atmospheric dispersion of air pollutants

How do we account for the ground?

1) No reflection: apply the equation we derived!

$$C(x, y, z) = \left(\frac{E}{2\pi u \sigma_y \sigma_z}\right)\left[exp\left(\frac{-y^2}{2{\sigma_y}^2}\right)\right]\left[exp\left(\frac{-(z-H)^2}{2{\sigma_z}^2}\right)\right]$$

2) Total reflection: assume a virtual source at (x, y, z) = (0, 0, -H)

$$C(x, y, z) = \left(\frac{E}{2\pi u \sigma_y \sigma_z}\right)\left[exp\left(\frac{-y^2}{2{\sigma_y}^2}\right)\right]$$

$$\times\left(\left[exp\left(\frac{-(z-H)^2}{2{\sigma_z}^2}\right)\right]+\left[exp\left(\frac{-(z+H)^2}{2{\sigma_z}^2}\right)\right]\right)$$

Atmospheric dispersion of air pollutants

Concentration of a pollutant **at the ground level with total reflection**:

$$C(x,y,0) = \left(\frac{E}{\pi u \sigma_y \sigma_z}\right)\left[exp\left(\frac{-y^2}{2{\sigma_y}^2}\right)\right]\left[exp\left(\frac{-H^2}{2{\sigma_z}^2}\right)\right]$$

Eq. (12-18) of the textbook

Now, how do we obtain σ_y and σ_z (functions of *x* and atmospheric stability)?

Key to stability categories

Surface wind speed (at 10 m) (m/s)	Day[a] Incoming solar radiation			Night[a]	
	Strong	Moderate	Slight	Thinly overcast or ≥ 1/2 Low cloud	≤ 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]The neutral class, D, should be assumed for overcast conditions during day or night. Note that "thinly overcast" is not equivalent to "overcast."

Notes: Class A is the most unstable and class F is the most stable class considered here. Night refers to the period from one hour before sunset to one hour after sunrise. Note that the neutral class, D, can be assumed for overcast conditions during day or night, regardless of wind speed.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables, can be used in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds.

(*Source:* Turner, 1967.)

$$\sigma_y = ax^{0.894}$$

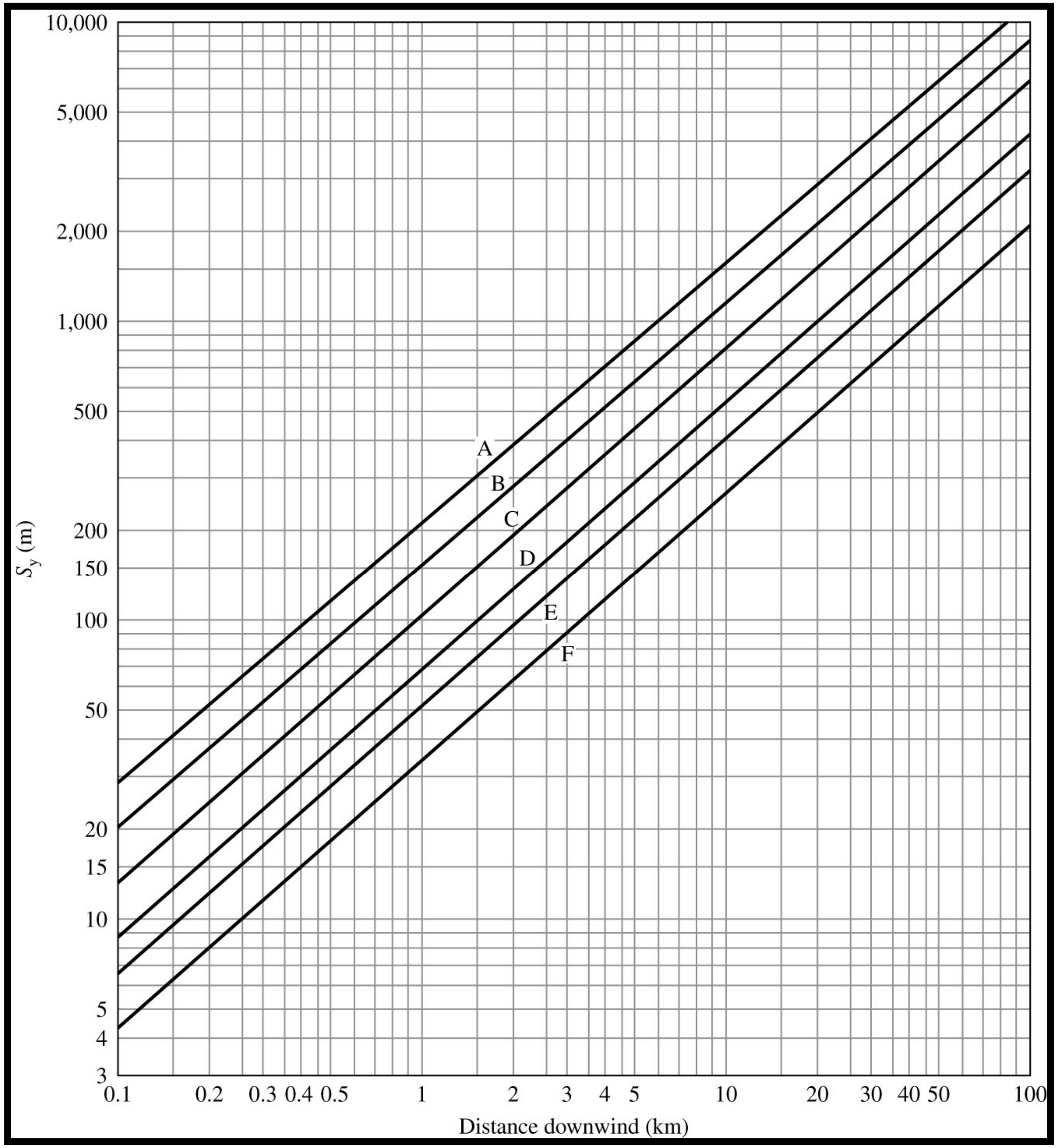
$$\sigma_z = cx^d + f$$

x = downwind distance (km)

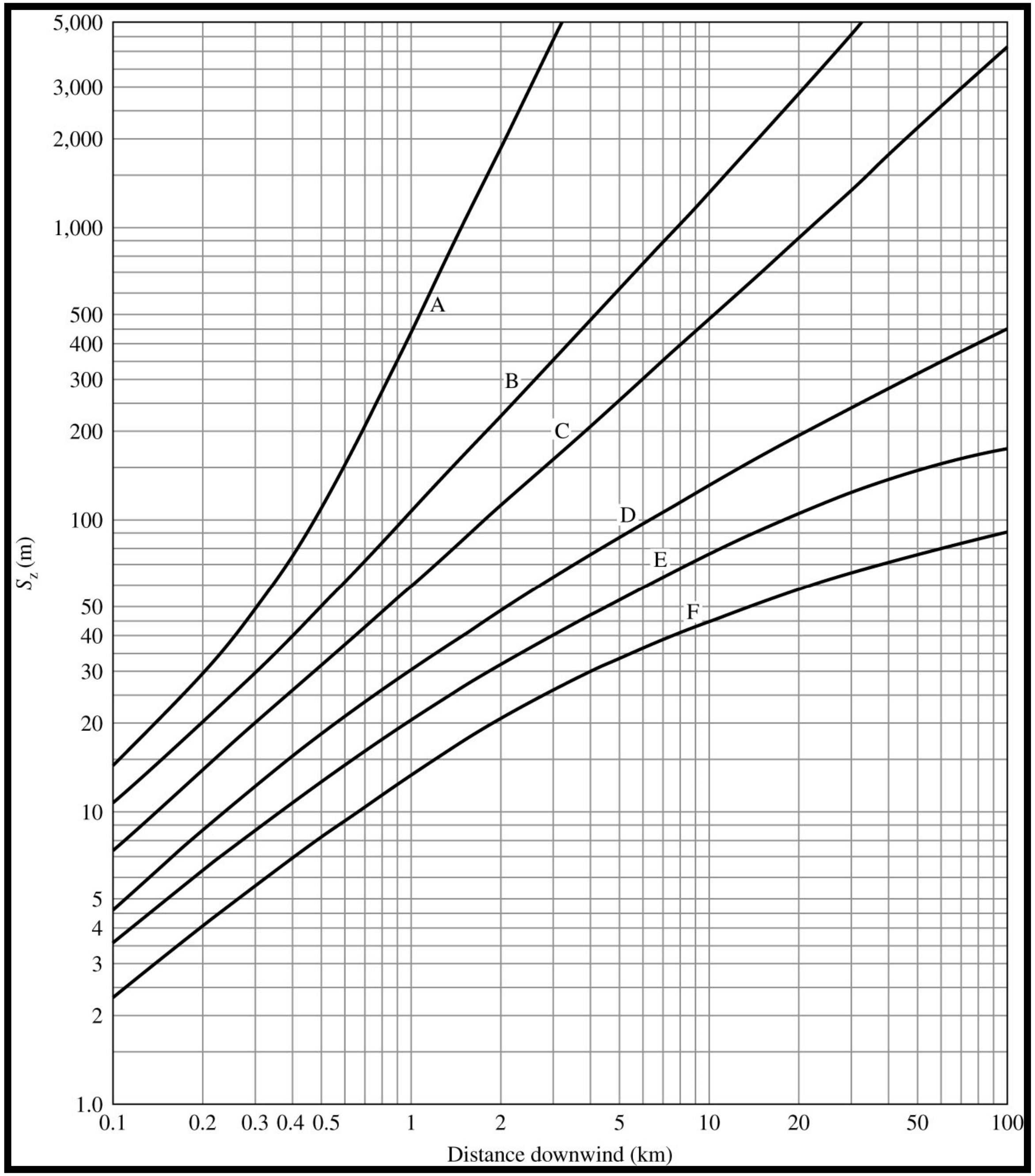
Values of *a*, *c*, *d*, and *f* for calculating s_y and s_z

Stability class	*a*	$x \leq 1$ km			$x > 1$ km		
		c	*d*	*f*	*c*	*d*	*f*
A	213	440.8	1.941	9.27	459.7	2.094	−9.6
B	156	100.6	1.149	3.3	108.2	1.098	2
C	104	61	0.911	0	61	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	0.74.0	−0.35	62.6	0.18	−48.6

(*Source*: Martin, 1976.)



10,000
5,000
2,000
1,000
500
200
150
100
50
20
15
10
5
4
3
S_y (m)
A
B
C
D
E
F
0.1
0.2
0.3 0.4 0.5
1
2
3
4
5
10
20
30
40 50
100
Distance downwind (km)


5,000
3,000
2,000
1,000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1.0
S_z (m)
A
B
C
D
E
F
0.1
0.2
0.3
0.4
0.5
1
2
5
10
20
50
100
Distance downwind (km)

Atmospheric dispersion of air pollutants

Q: A coal-fired power plants emits SO_2 at a rate of 1656 g/s. At 3 km downwind on an overcast summer afternoon, what is the concentration of SO_2 on the ground? The following parameters apply.

Stack parameters:

Height = 120 m

Diameter = 1.2 m

Exit velocity = 10 m/s

Temperature = 315°C

Atmospheric conditions:

Pressure = 95.0 kPa

Temperature = 25°C

Wind speed = 4.5 m/s

Reading assignment

Textbook Ch 12 p. 621-631