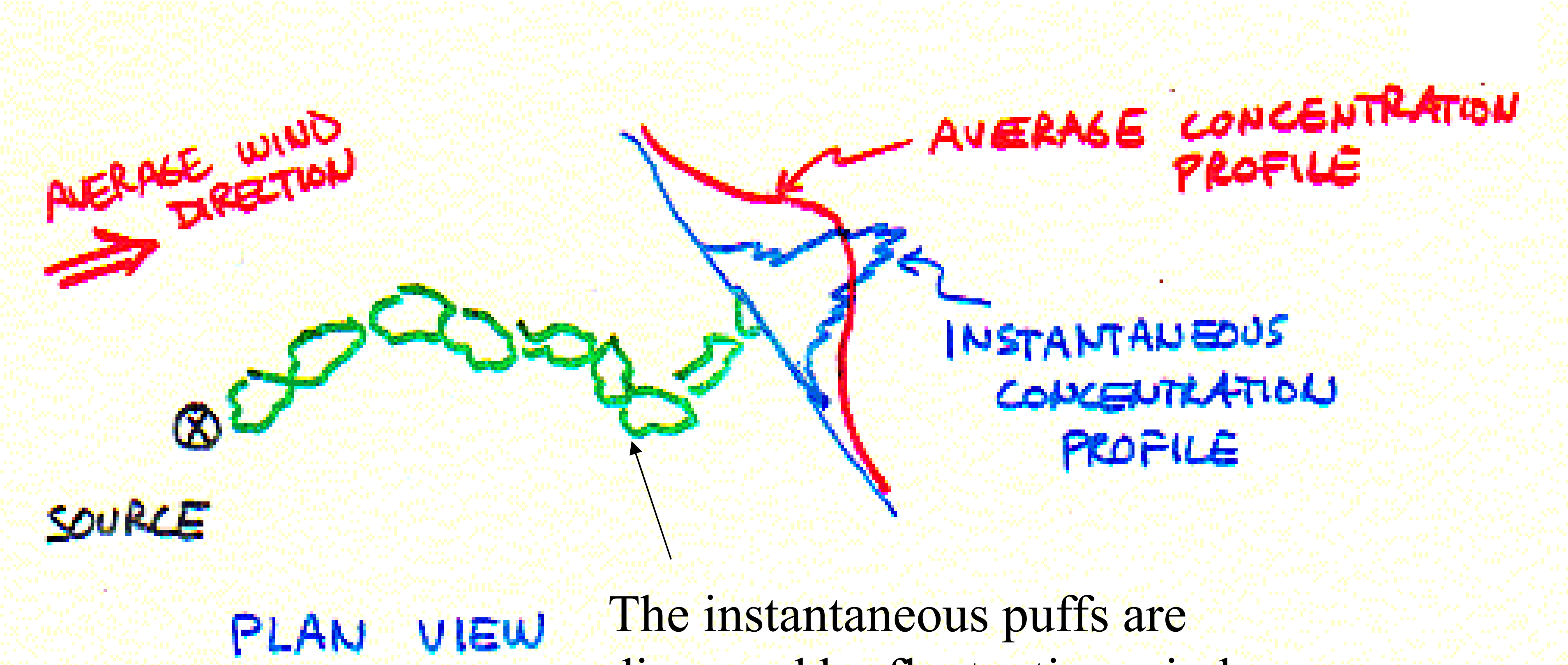
Atmospheric Dispersion Modeling

Professor Tim Larson
CEE 357

Types of Models

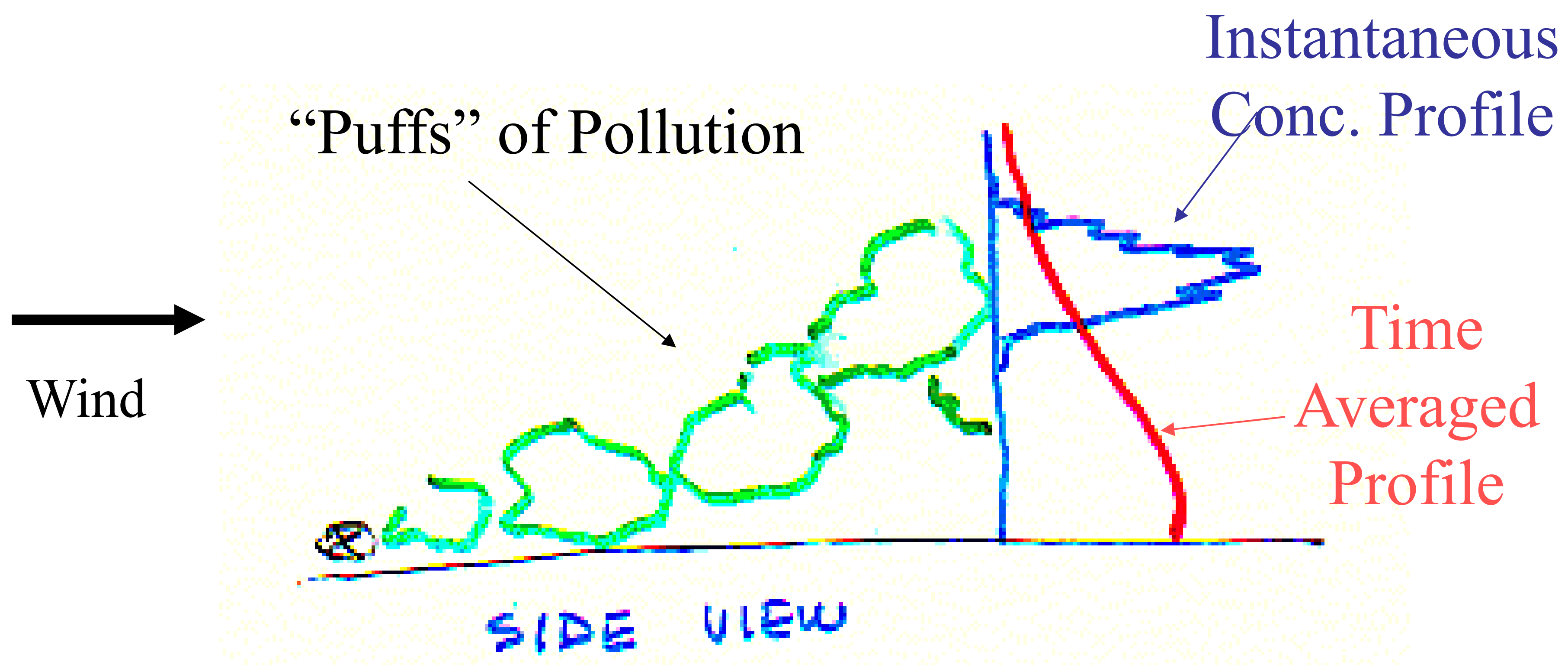
- Source → Receptor
  - Dispersion Calculations
  - Wind Tunnel
  - Empirical Scaling
  - Linear Rollback
  - Non-linear (chemistry/deposition)
- Receptor → Source
  - Deduce "source fingerprints" (statistical)
  - Microscopy (particle shape & composition)
- Receptor → Receptor
  - Forecasting and interpolation
  - Spatial and temporal

Dilution vs Dispersion: The Importance of Averaging Time



The instantaneous puffs are dispersed by fluctuating wind directions.

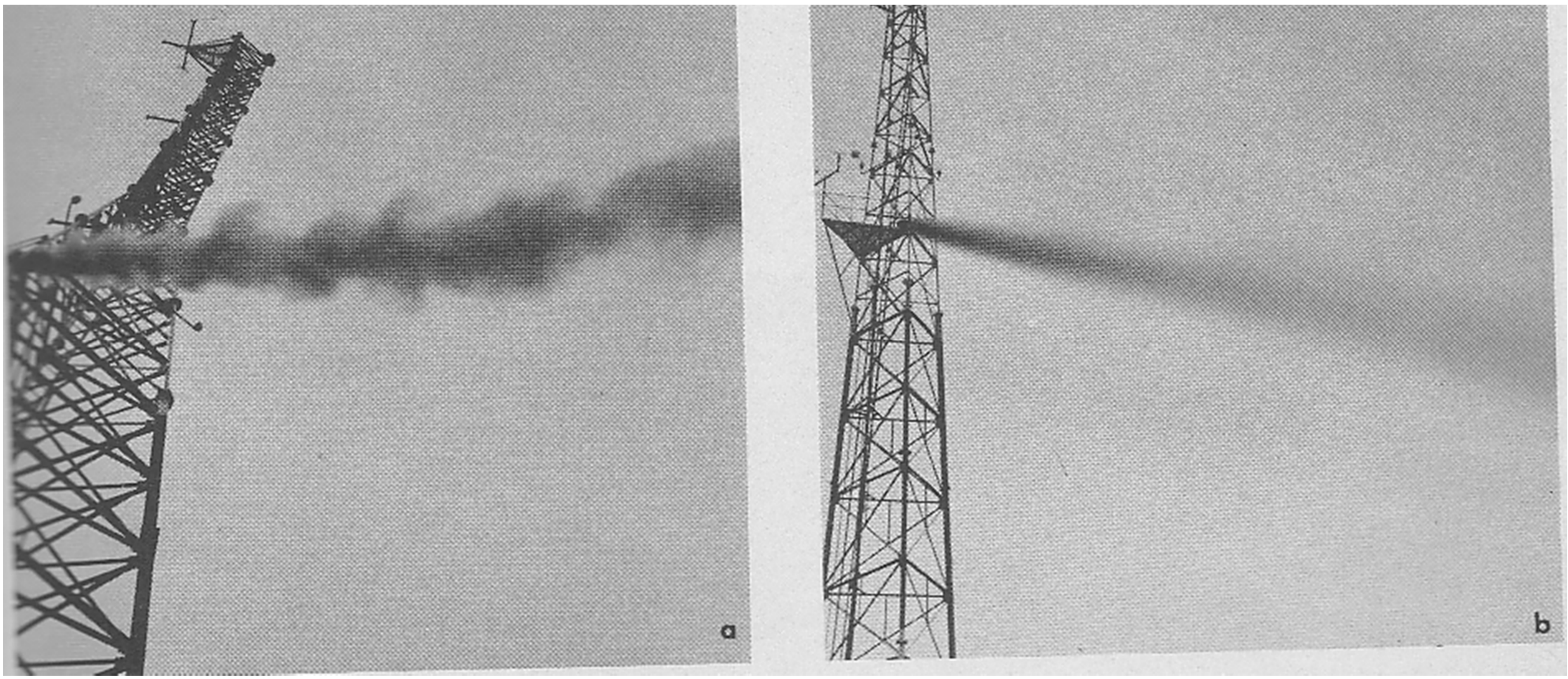
The instantaneous concentrations are not described by steady-state plume models. The time averaged values are.



Dispersion models describe time-average plumes

instantaneous

time-averaged

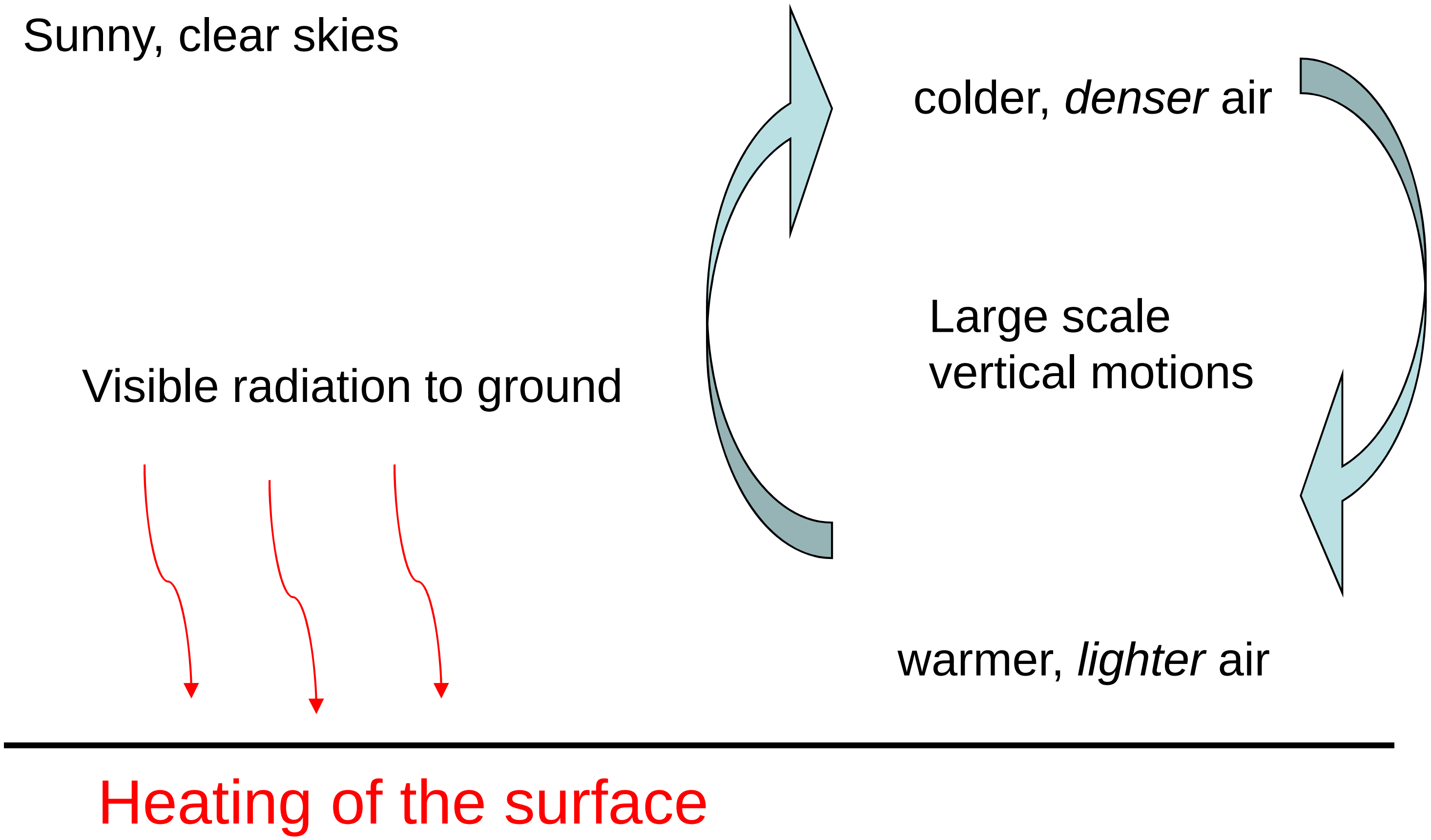


Source: Slade et al "Meteorology and Atomic Energy, 1968"

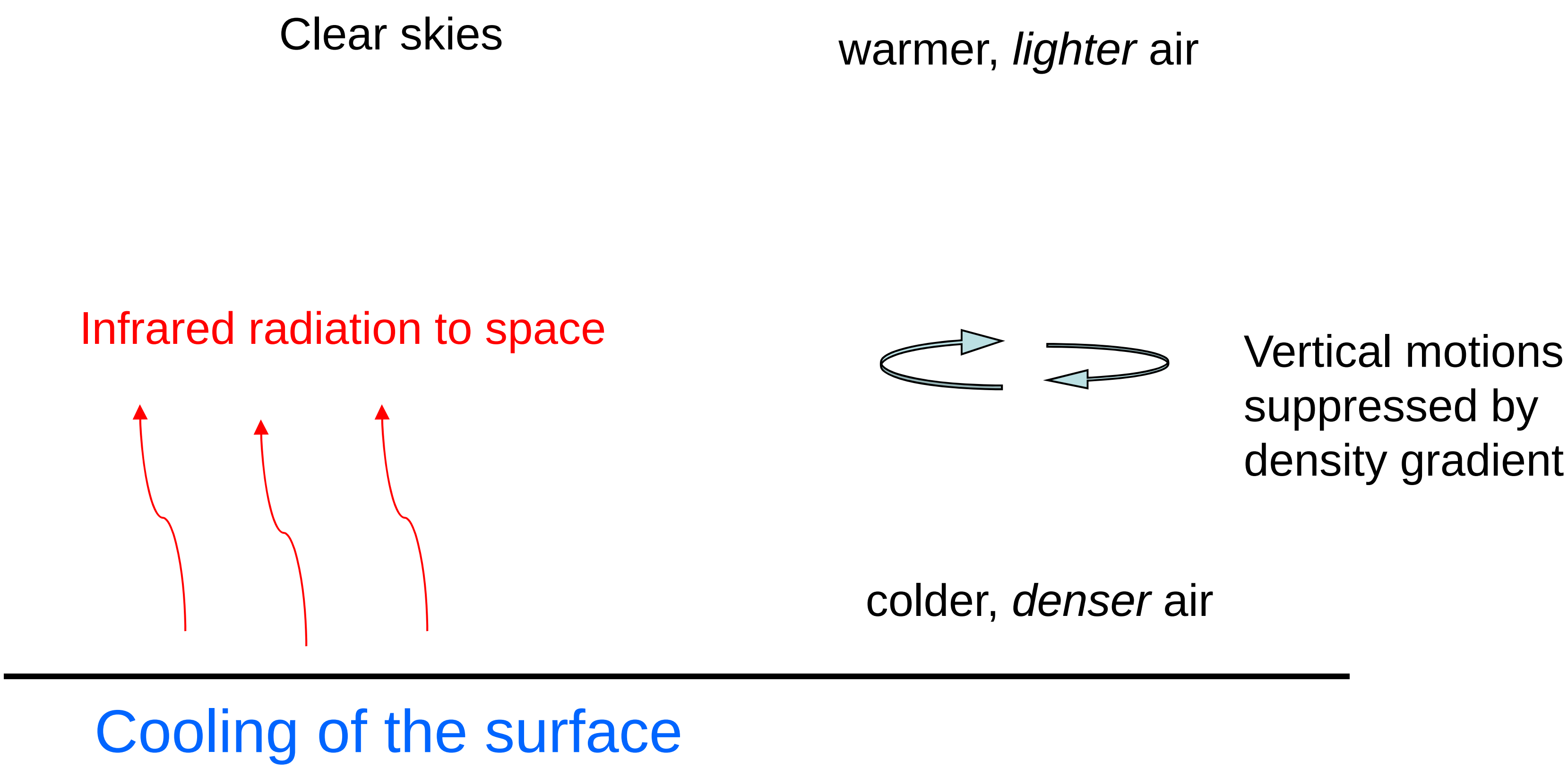
Instantaneous
Plume Shape

Time-averaged
Plume Shape

Unstable Daytime Conditions



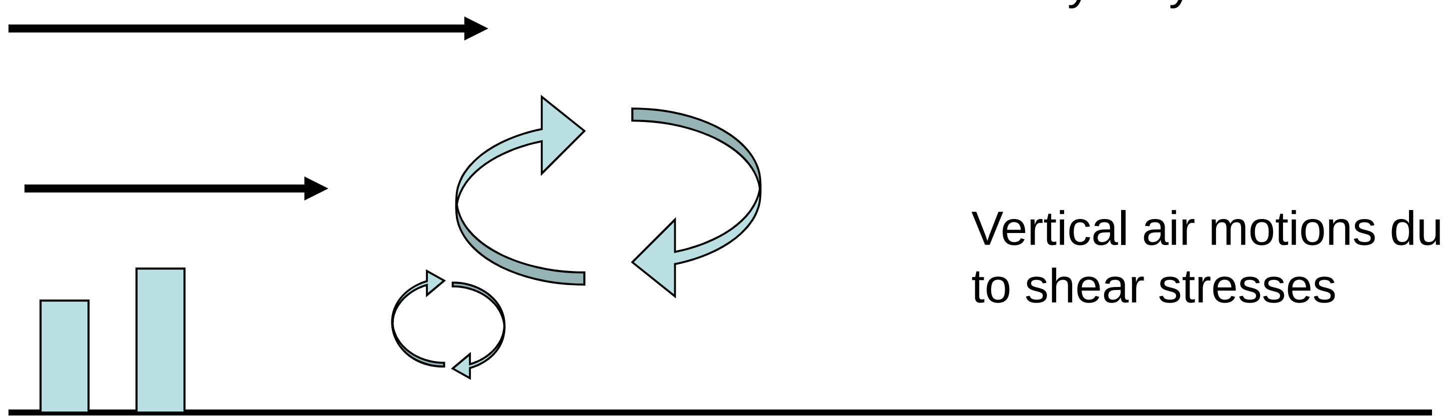
Stable Nighttime Conditions



Neutral Conditions (day or night)

relatively high wind speeds

Motions not affected by buoyancy forces



Vertical air motions due to shear stresses

Minimal heating or cooling of the surface

Pasquill-Gifford-Turner Stability Classifications

Atmospheric Stability Classifications

Surface wind speed[a] (m/s)	Day solar insolation			Night cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy ($\geq 4/8$)	Clear ($\leq 3/8$)
< 2	A	A–B[f]	B	E	F
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]Surface wind speed is measured at 10 m above the ground.

[b]Corresponds to clear summer day with sun higher than 60° above the horizon.

[c]Corresponds to a summer day wth a few broken clouds, of a clear day with sun 35–60° above the horizon.

[d]Corresponds ot a fall afternoon, or a cloudy summer day, or clear summer day with the sun 15–35° above the horizon.

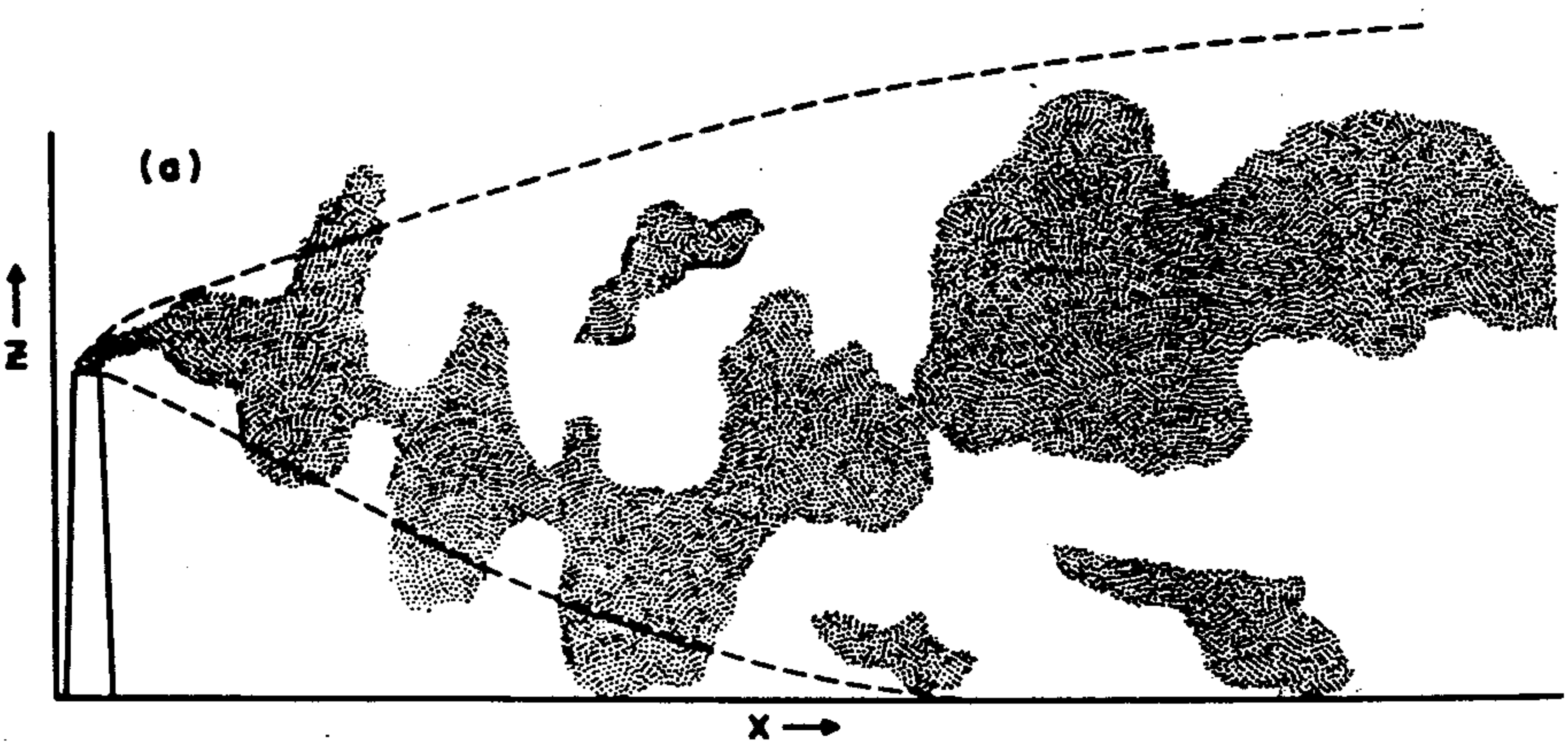
[e]Cloudiness is defined as the fraction of sky covered my clouds.

[f]For A–B, B–C, or C–D conditions, average the values obtained for each.

Note: A, Very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable. Regardless of windspeed, class D should be assumed for overcast conditions, day or night.

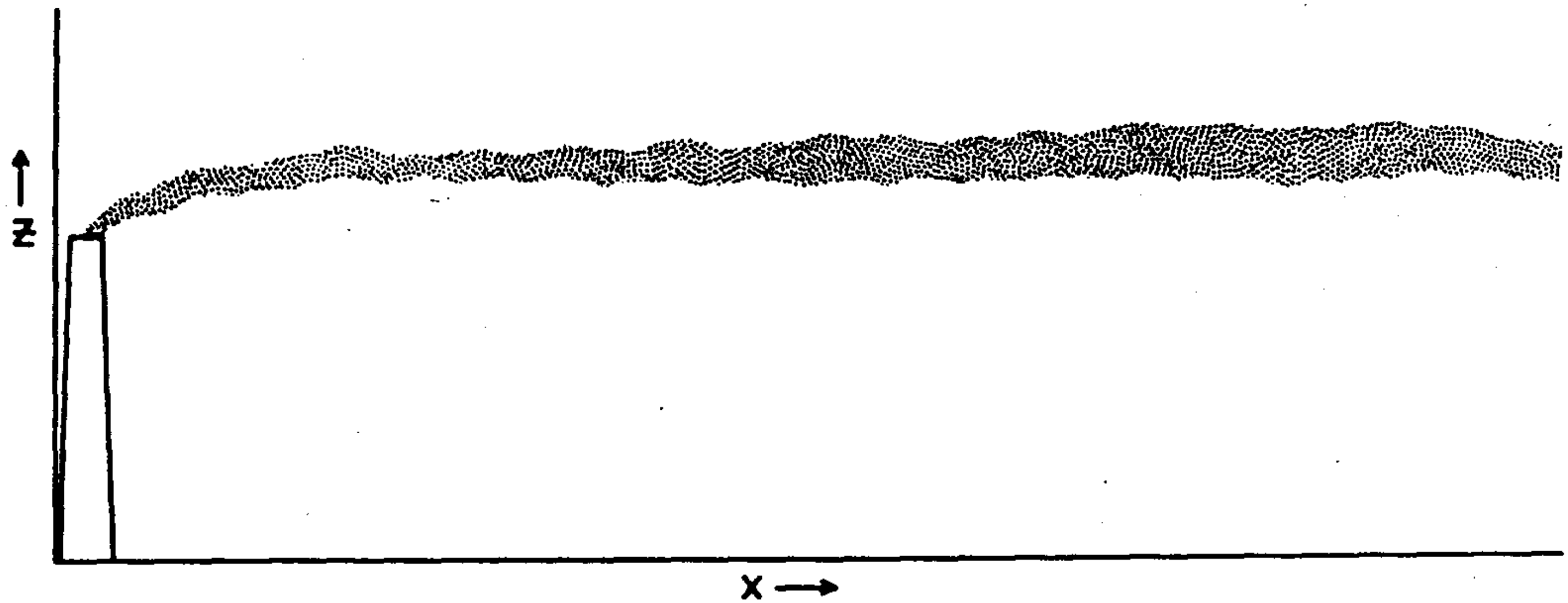
Source: Turner (1970).

Strongly Unstable



(view from side)

Stable



(view from side)

Surface Level Impacts Vary with Meteorology and Release Height

Stability	*Release Height*	*Surface Impacts*
unstable	elevated	high
	surface	high/moderate
stable	elevated	not significant
	surface	very high
neutral	elevated	moderate/low
	surface	high/moderate

Describing Plume Concentrations

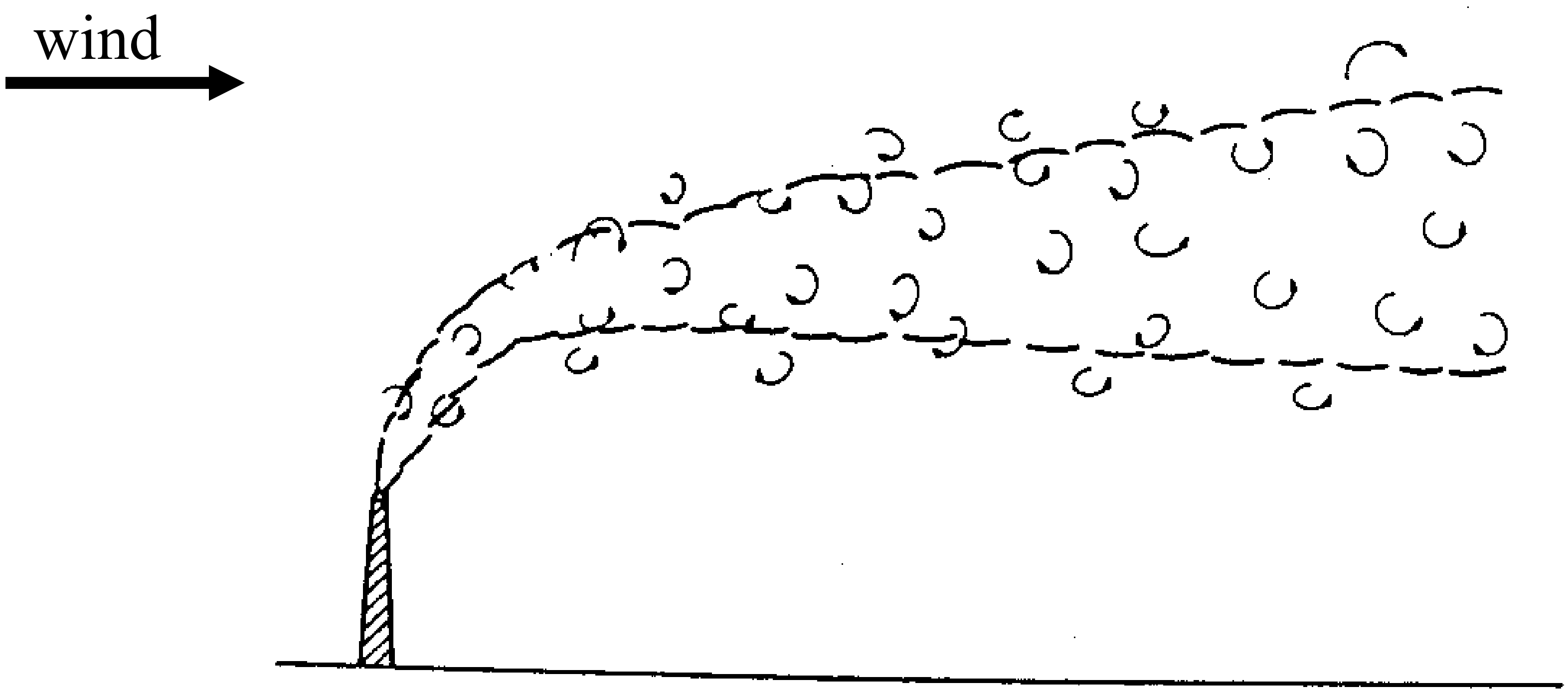
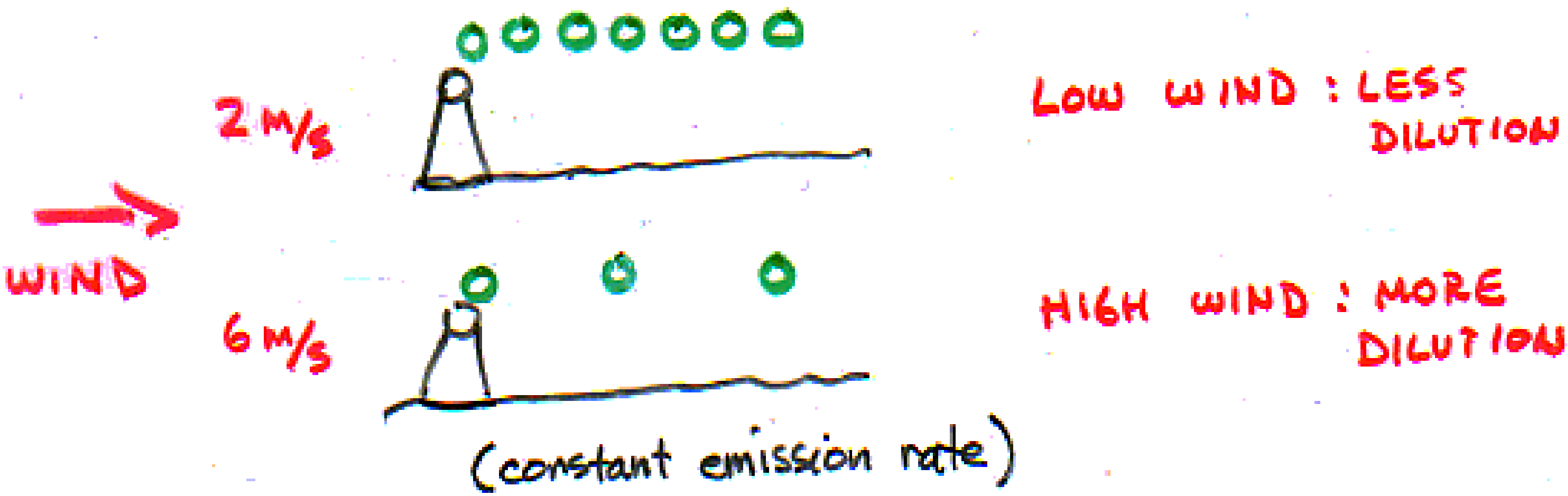


Fig 4-3, p.44 in Martin et al

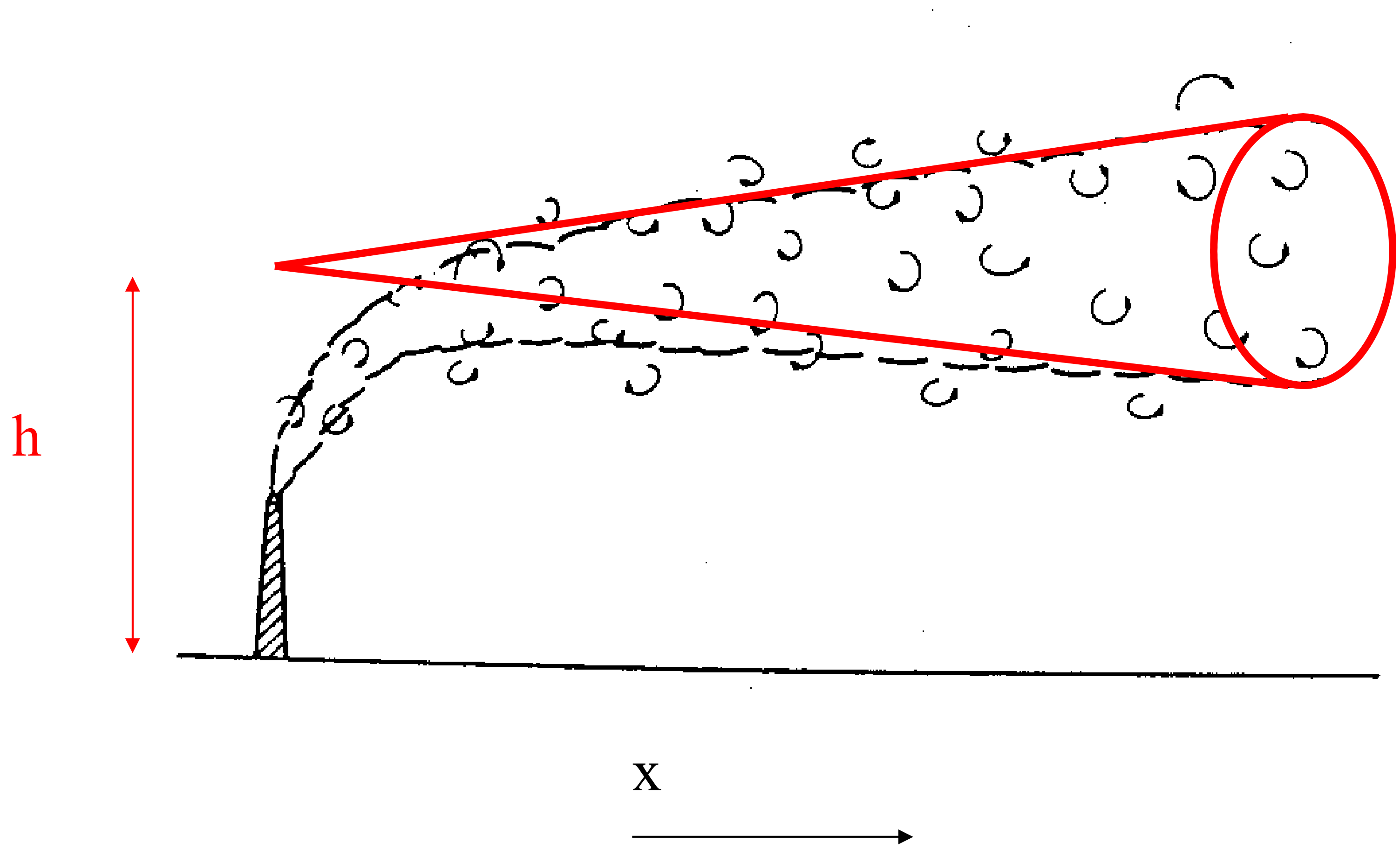
Factors Affecting Atmospheric Dilution (Mixing)

- Wind Speed



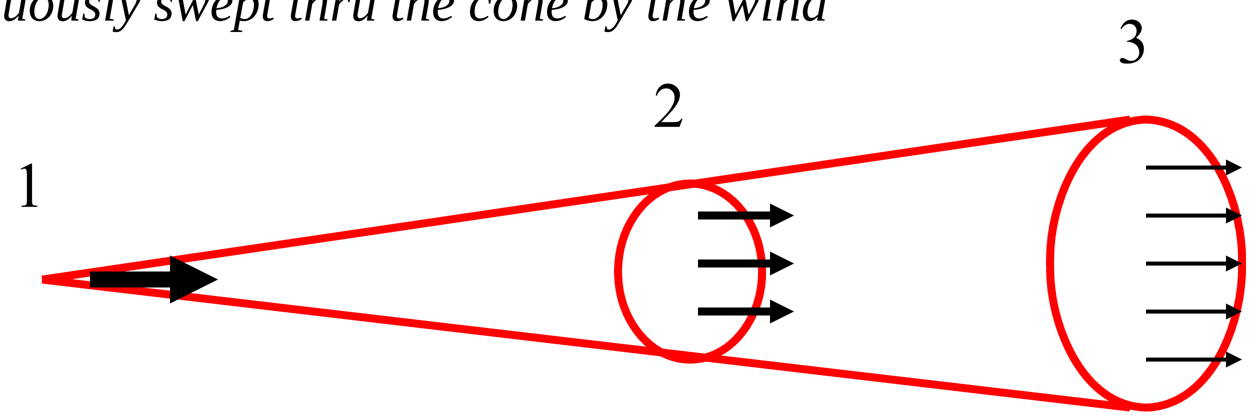
Concentration is inversely proportional to wind speed

Tim's Simple Plume Model



Simplified Steady-State Plume Model

**Pollutant is well mixed and confined within the cone*
**Pollutant is continuously swept thru the cone by the wind*



mass/time passing point 1 = mass/time passing thru disk area 2 = mass/time passing thru disk area 3

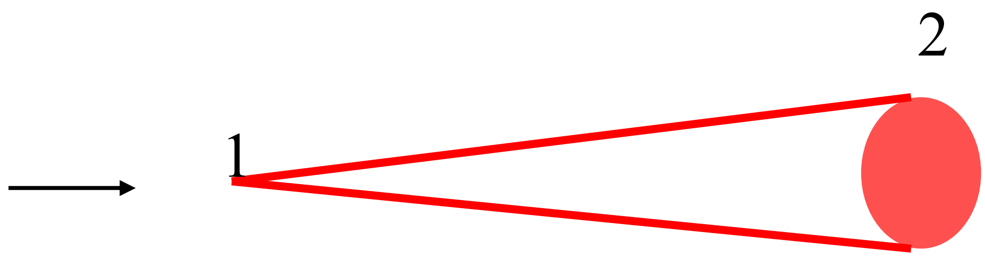
$C_1 > C_2 > C_3$

Concentration vs. distance downwind depends upon cone shape

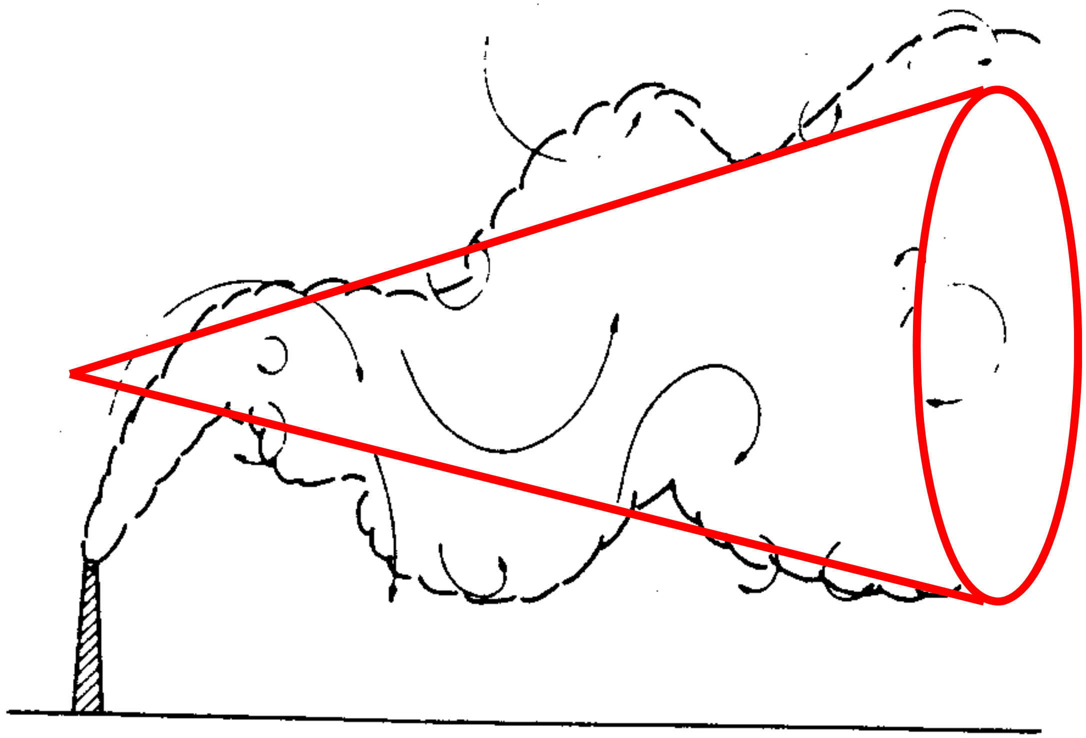
Simple Model #1:

$$\text{Conc. of air at 2} = \frac{\text{Mass emission rate}}{(\text{wind speed})(\text{area of disk 2})}$$

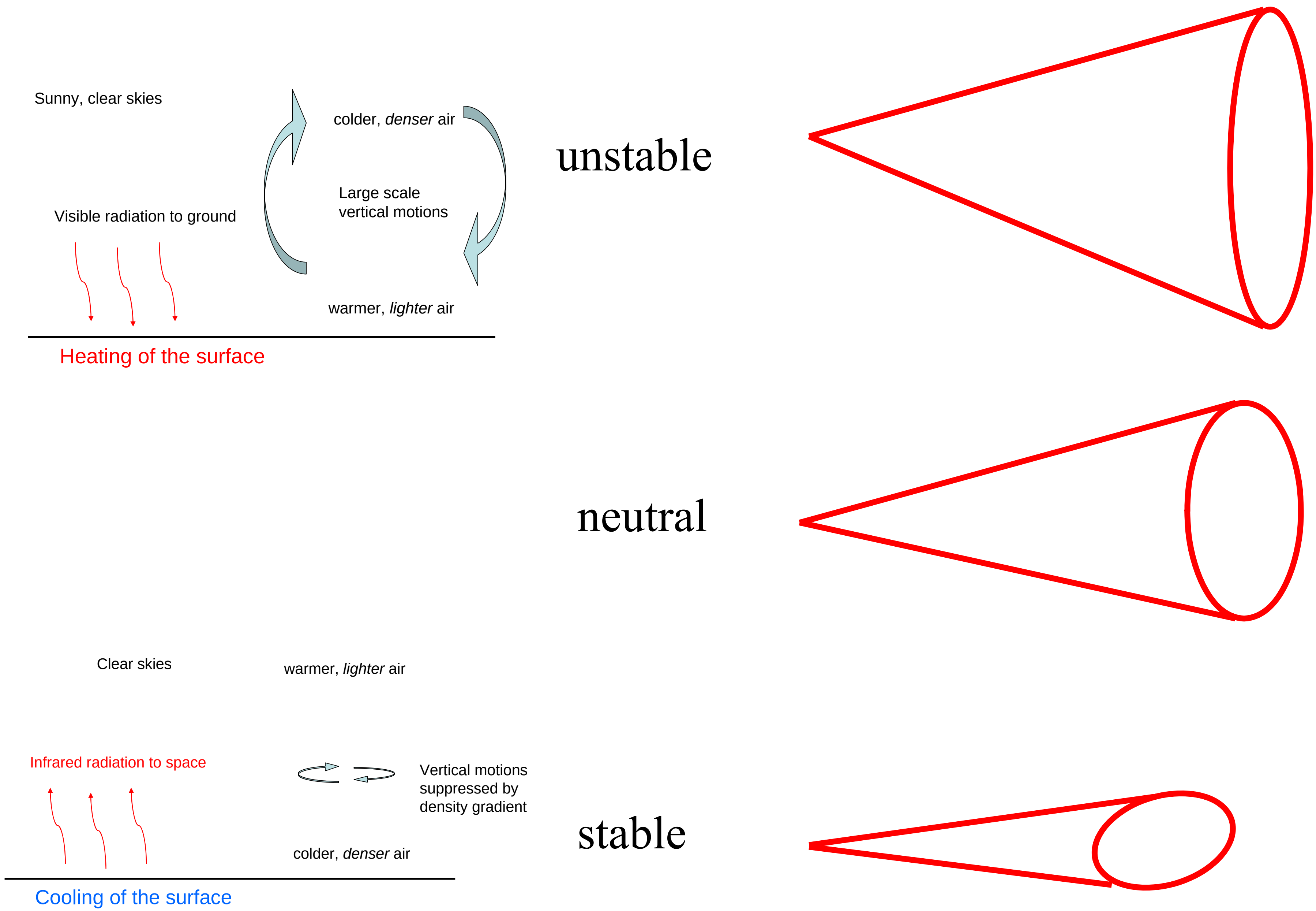
$$\frac{\mu g}{m^3} = \frac{\mu g/\sec}{(m/\sec)(m^2)}$$



Disk shape depends upon stability category

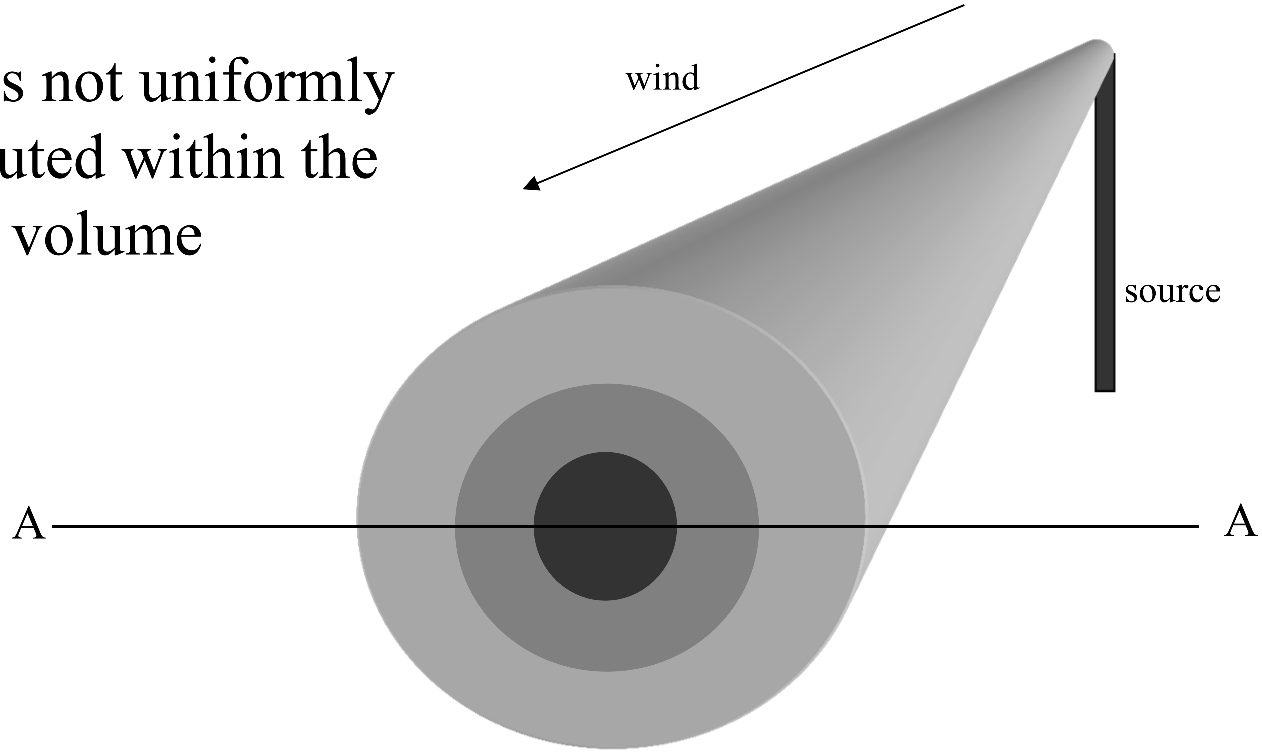


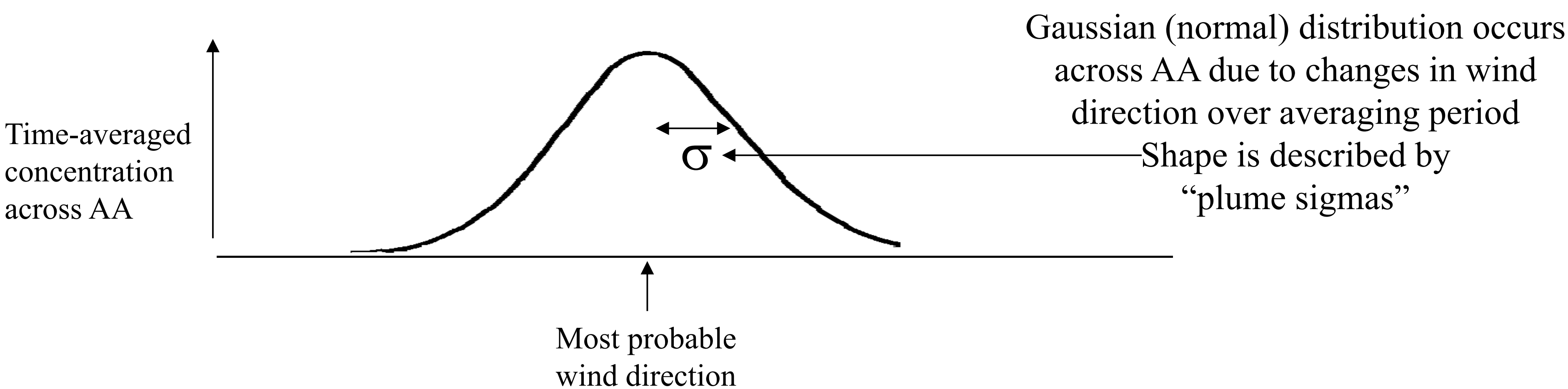
More unstable and thus more pronounced vertical spreading


Sunny, clear skies
colder, *denser* air
Large scale
vertical motions
Visible radiation to ground
warmer, *lighter* air
Heating of the surface
unstable
neutral
Clear skies
warmer, *lighter* air
Infrared radiation to space
Vertical motions
suppressed by
density gradient
colder, *denser* air
Cooling of the surface
stable

More Detailed Plume Model

Mass is not uniformly distributed within the cone's volume

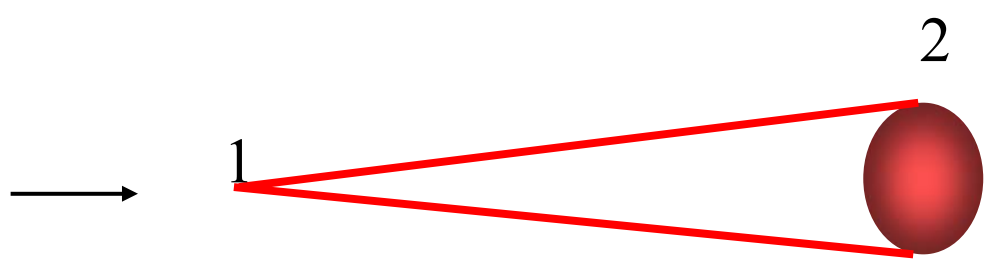


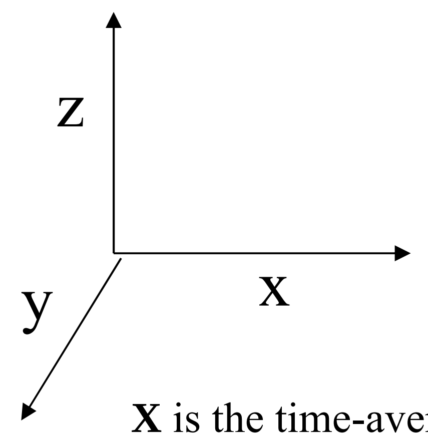


Simple Model #2:

$$\text{Conc at 2} = \frac{\text{Mass emission rate}}{(\text{wind speed})(\text{area of disk 2})}[\text{Gaussian distribution function}]$$

$$\frac{\mu g}{m^3} = \frac{\mu g/\sec}{(m/\sec)(m^2)}[-]$$

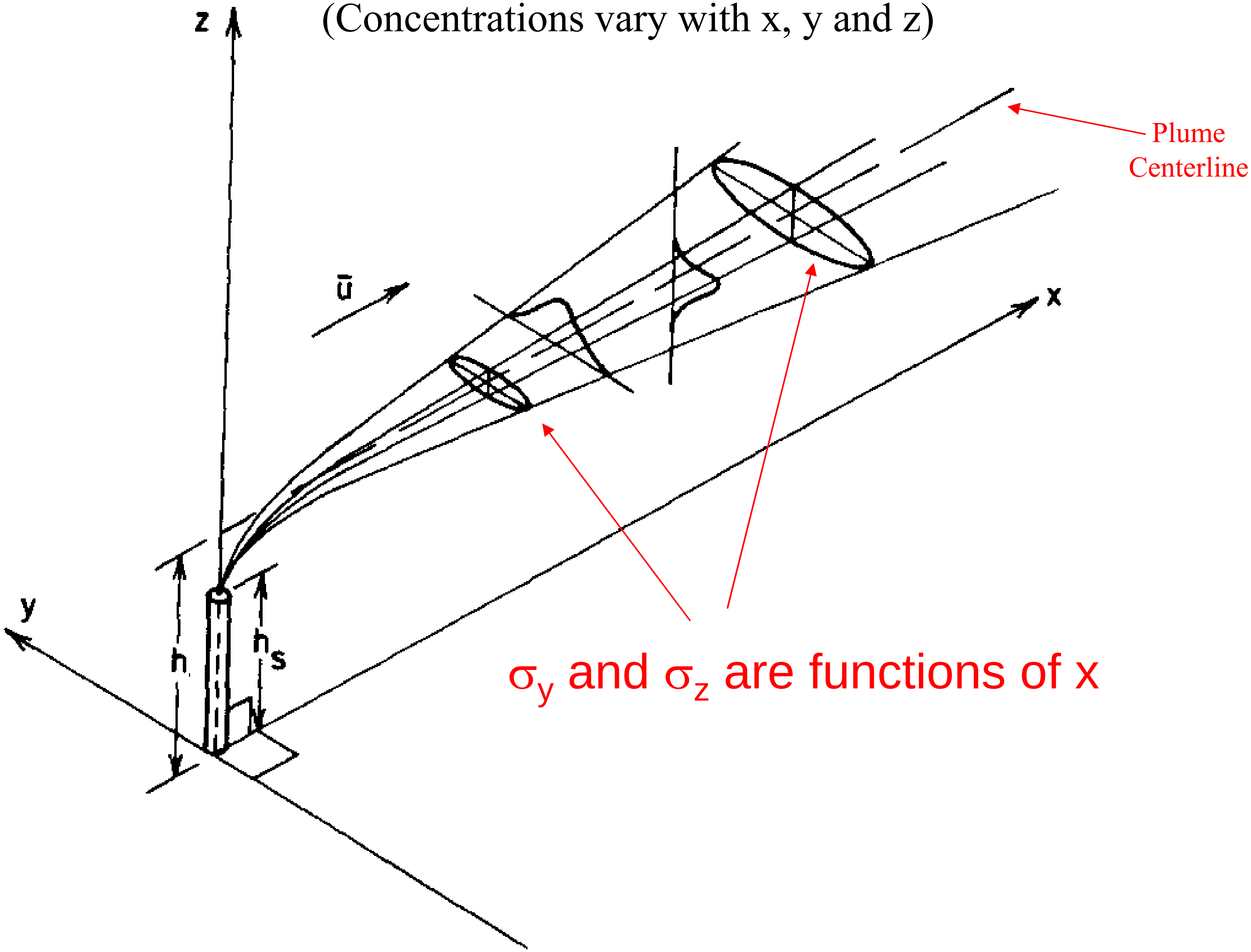




X is the time-averaged wind direction,
Y is the cross-wind direction,
Z is the vertical dimension

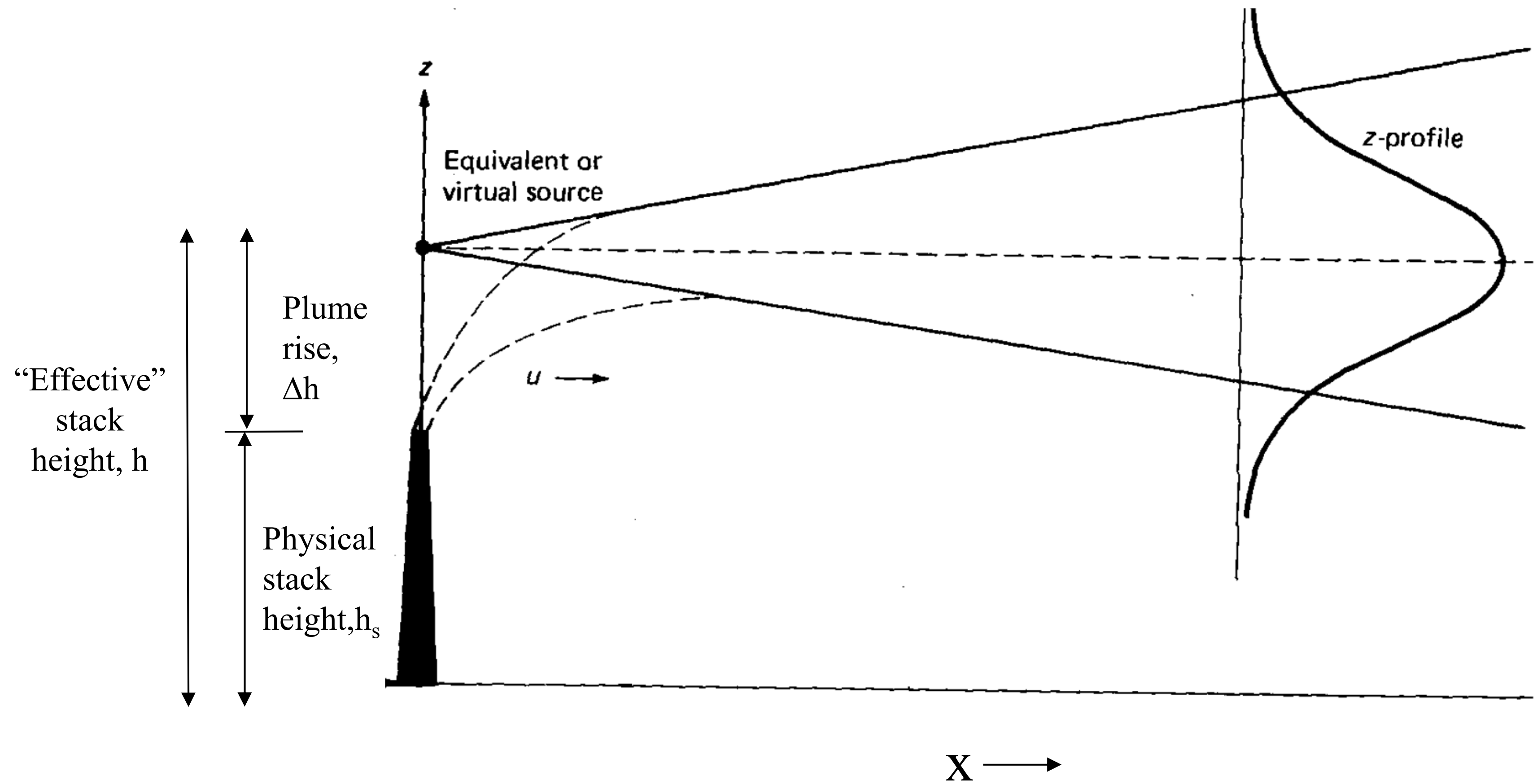
Gaussian Plume

(Concentrations vary with x, y and z)



σ_y and σ_z are functions of x

$$h = h_s + \Delta h$$

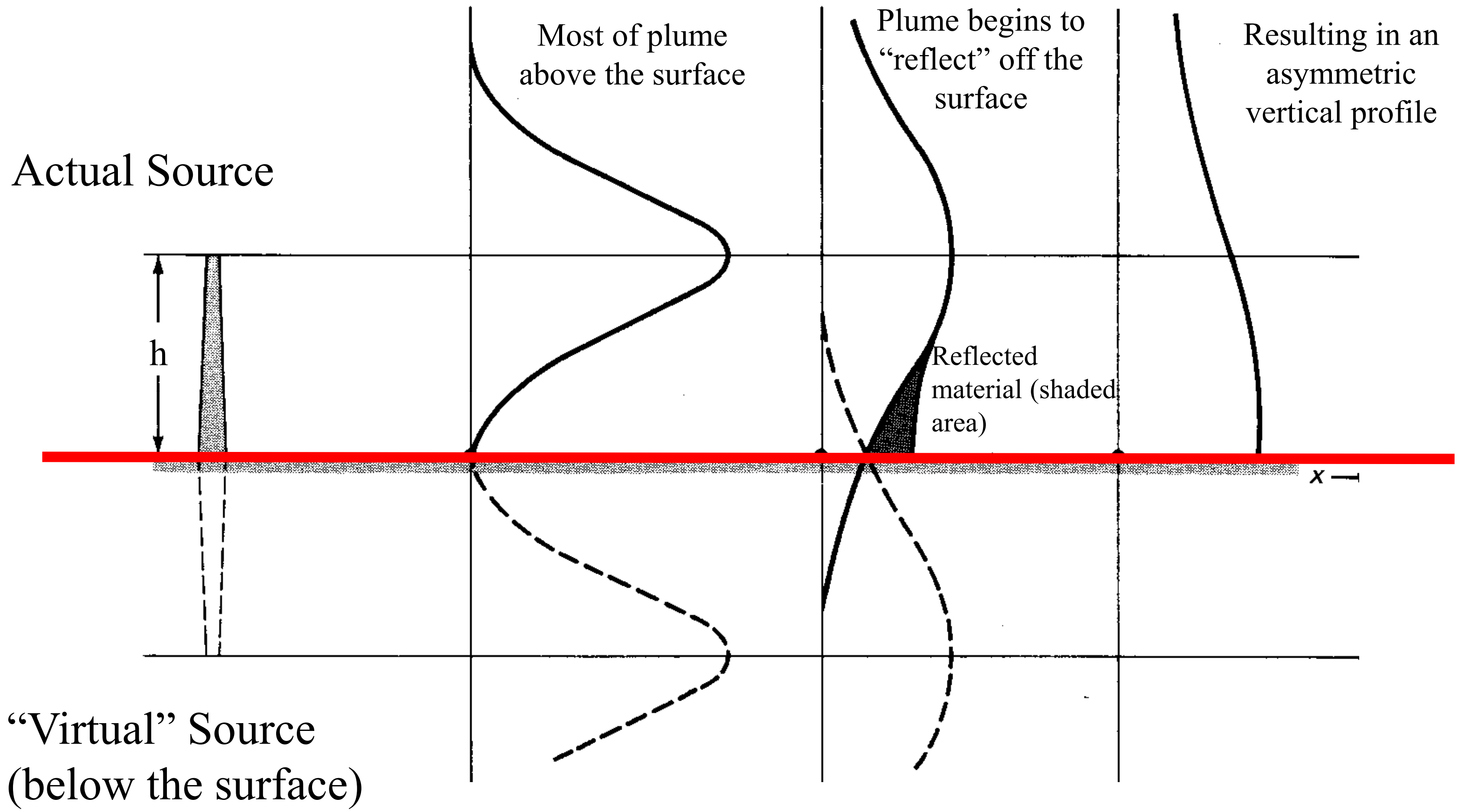


z
Equivalent or
virtual source
z-profile
u
Plume
rise,
Δh
"Effective"
stack
height, h
Physical
stack
height,h_s
X

Plume "Reflection" off of the Ground

(pollutant cannot penetrate the ground)

Reflection is modeled by adding a "virtual" source contribution to the "real" one



Gaussian "Point" Source Plume Model:

Pollutant concentration as a function of downwind position (x,y,z)

Mass emission rate

"Effective" stack height, including rise of the hot plume near the source

$$C(x, y, z) = \frac{Q}{2\pi\, u\, \sigma_y \sigma_z} \left\{ \exp\left(\frac{-(z-h)^2}{2\sigma_z^2} \right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2} \right) \right\} \left\{ \exp\left(\frac{-(y)^2}{2\sigma_y^2} \right) \right\}$$

Wind speed evaluated at "effective" stack height

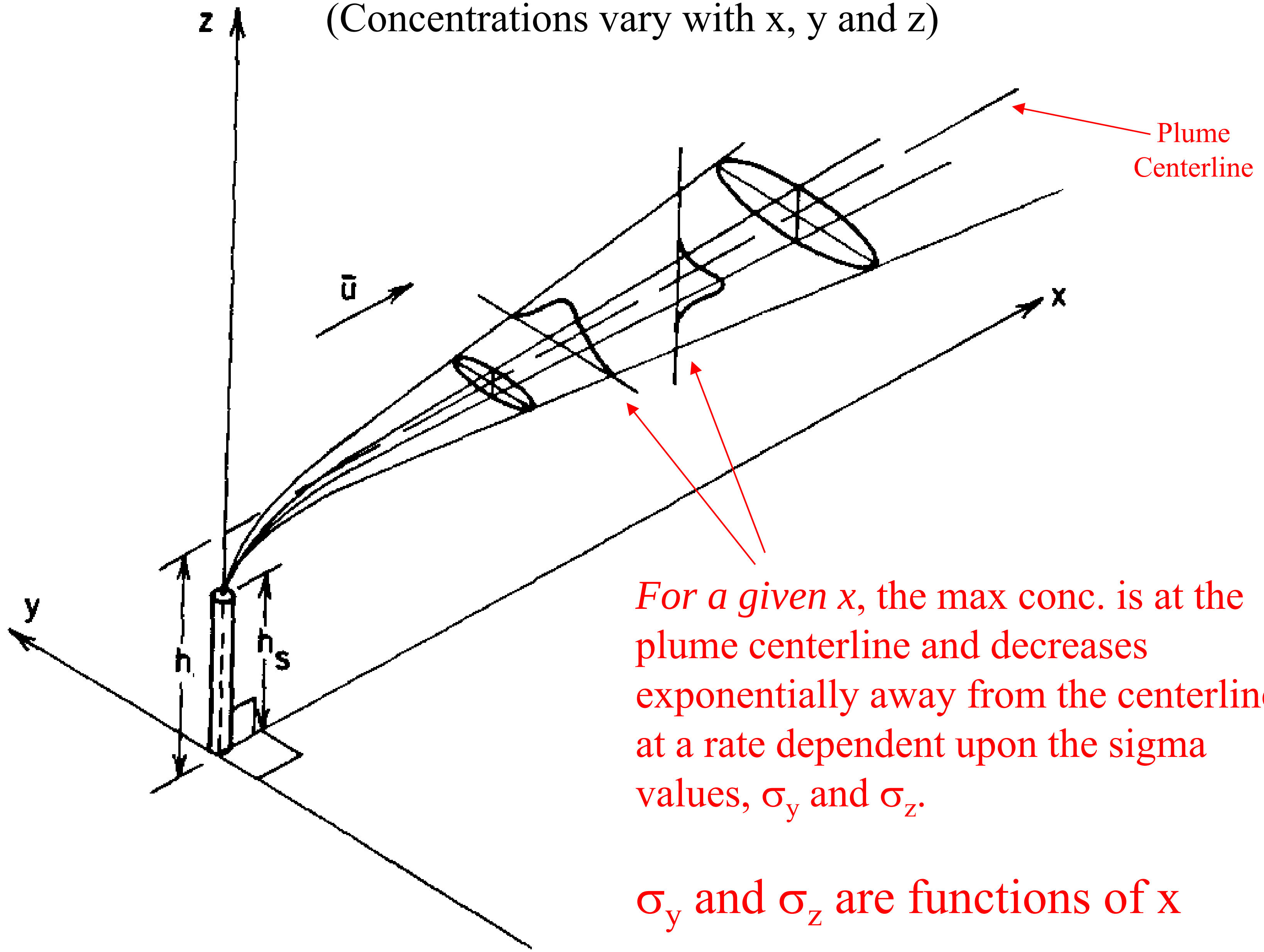
Corresponds to disk area in simple model (values depend upon stability class & downwind distance, x)

Distribution of mass in vertical dimension (z) at a given downwind distance, x (includes the effect of surface reflection)

Distribution of mass in cross-wind dimension (y) at a given downwind distance, x

Gaussian Plume

(Concentrations vary with x, y and z)



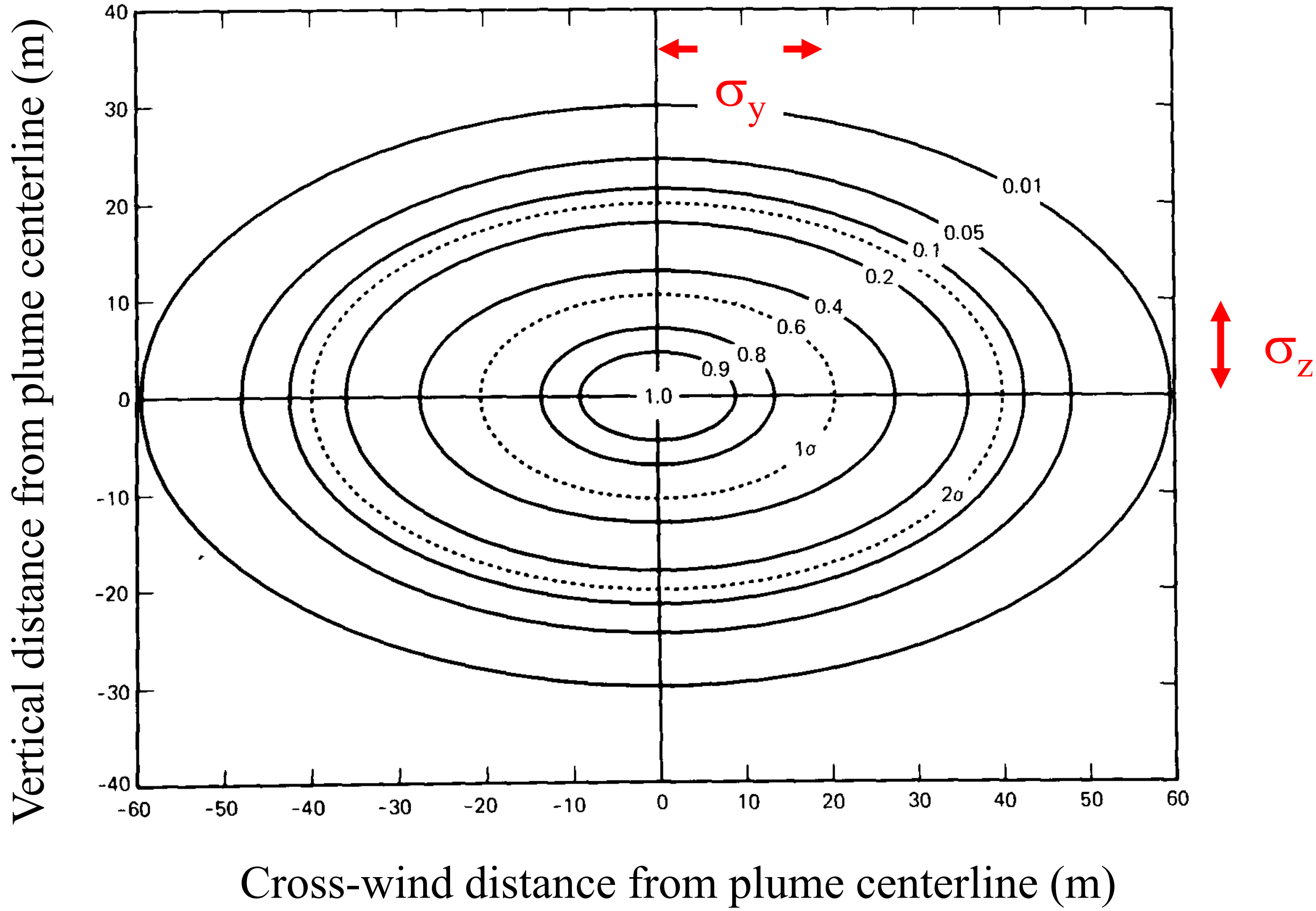
For a given x, the max conc. is at the plume centerline and decreases exponentially away from the centerline at a rate dependent upon the sigma values, σ_y and σ_z.

σ_y and σ_z are functions of x

Concentration distribution in a Gaussian plume

(σ_y = 20 m; σ_z = 10m; centerline concentration = 1.0)

Note: theoretical plume has infinite extent in all directions!



Source: Hanna et al, 1981

Calculation Procedure

1. Determine stability class from meteorology
2. Compute wind speed at “effective” stack height, h
3. Compute σ_y and σ_z at a given downwind distance, x
4. Choose appropriate receptor height, z
5. Compute C(x,y,z) using Gaussian plume equation

Pasquill-Gifford-Turner Stability Classifications

Atmospheric Stability Classifications

Surface wind speed[a] (m/s)	Day solar insolation			Night cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy ($\geq 4/8$)	Clear ($\leq 3/8$)
< 2	A	A–B[f]	B	E	F
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]Surface wind speed is measured at 10 m above the ground.
[b]Corresponds to clear summer day with sun higher than 60° above the horizon.
[c]Corresponds to a summer day wth a few broken clouds, of a clear day with sun 35–60° above the horizon.
[d]Corresponds ot a fall afternoon, or a cloudy summer day, or clear summer day with the sun 15–35° above the horizon.
[e]Cloudiness is defined as the fraction of sky covered my clouds.
[f]For A–B, B–C, or C–D conditions, average the values obtained for each.

Note: A, Very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable. Regardless of windspeed, class D should be assumed for overcast conditions, day or night.

Source: Turner (1970).

Calculation Procedure

1. Determine stability class from meteorology
2. Compute wind speed at “effective” stack height, h
3. Compute σ_y and σ_z at a given downwind distance, x
4. Choose appropriate receptor height, z
5. Compute C(x,y,z) using Gaussian plume equation

Calculating Wind Speed as a Function of Height

"Power Law" Method

This approach is used with the EPA models and employs a simple "power law" function. The wind speed at any elevation is estimated as a function of the height of the actual wind speed measurement, the stability category, and the "wind profile exponent", as follows:

$$U_z = U_{zref}\left(\frac{z}{z_{ref}}\right)^p$$

Where

u_z	= wind speed at some arbitrary elevation z [meters]
u_{zref}	= wind speed at the "reference" (actual measurement) height [m/sec]
z_{ref}	= the elevation of the actual wind speed measurement [m]
p	= wind profile exponent, a function of stability category.

Values of p as a function of stability category are summarized in the following table. These are the “default” p values recommended by EPA for use when $z_{ref} = 10$ m.

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

The "urban" and "rural" classifications attempt to capture the effect of surface roughness. The largest effect is seen under very stable conditions (“F”).

Example Calculation:

For the “rural’ case, if the wind speed is 3 m/sec measured at an elevation of 10 meters and the stability category is "D", then p = 0.15 and the wind speed at z=100 m is:

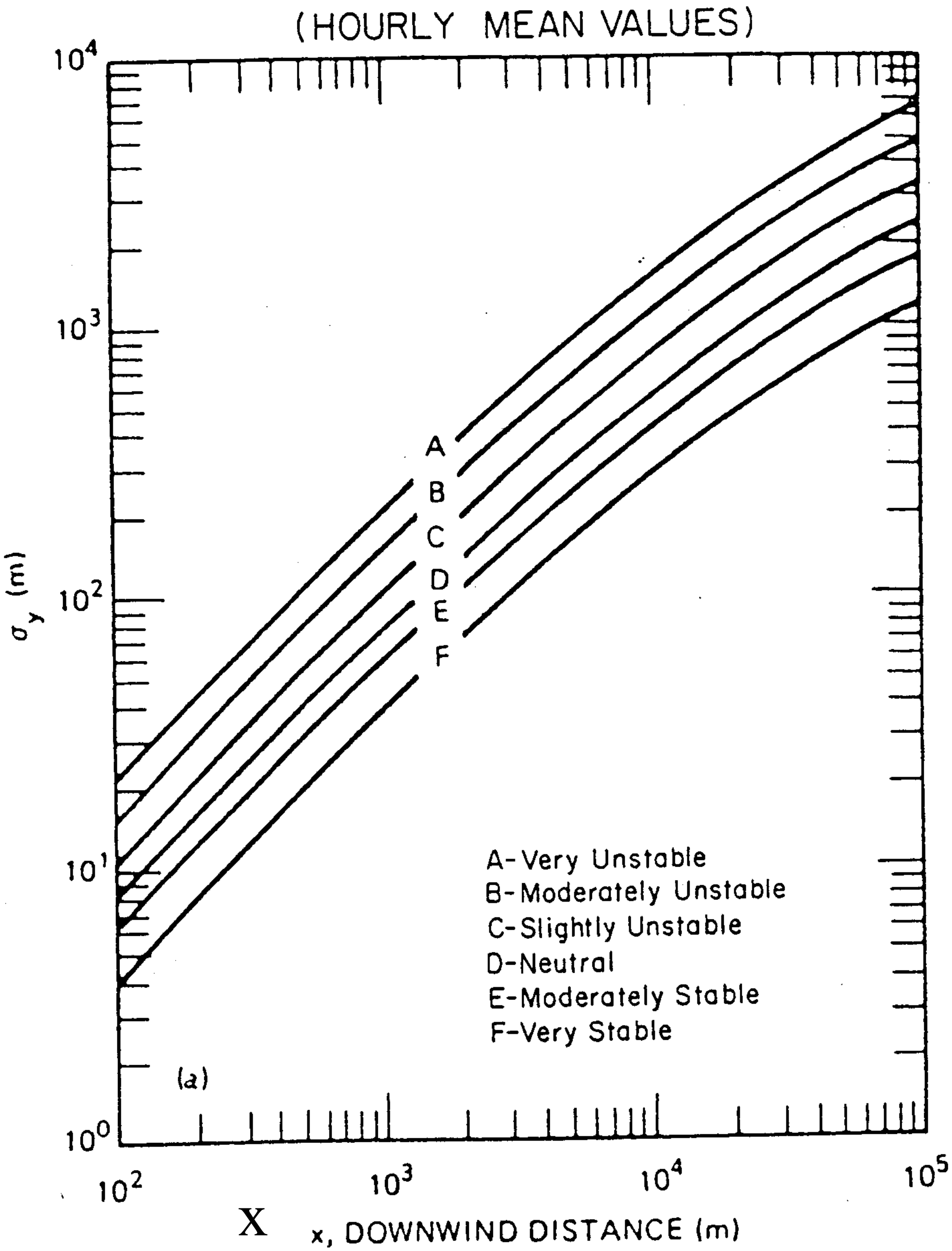
$$U_{100} = \{3.5 \text{ m/s}\}\left(\frac{100 \text{ m}}{10 \text{ m}}\right)^{0.15} = 4.94 \text{ m/s}$$

There are other ways to estimate the wind speeds as a function of height, but the “power law” approach is probably the simplest and most straightforward method.

Calculation Procedure

1. Determine stability class from meteorology
2. Compute wind speed at “effective” stack height, h
3. Compute σ_y and σ_z at a given downwind distance, x
4. Choose appropriate receptor height, z
5. Compute C(x,y,z) using Gaussian plume equation

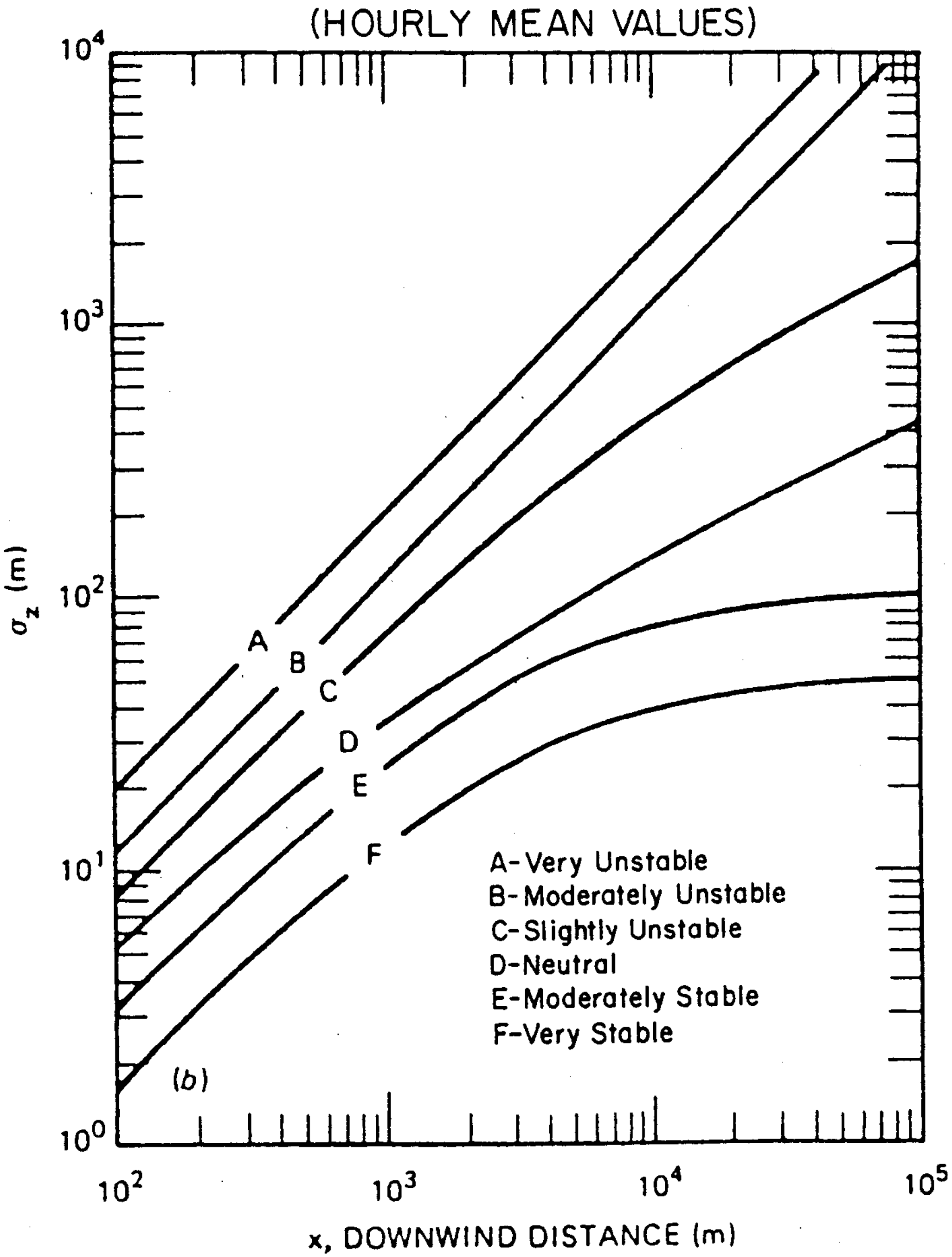
Sigma-y



(HOURLY MEAN VALUES)
σ_y (m)
x, DOWNWIND DISTANCE (m)
A
B
C
D
E
F
A-Very Unstable
B-Moderately Unstable
C-Slightly Unstable
D-Neutral
E-Moderately Stable
F-Very Stable
(a)

X

Sigma-z



(HOURLY MEAN VALUES)
10^4
10^3
10^2
10^1
10^0
σ_z (m)
A
B
C
D
E
F
A-Very Unstable
B-Moderately Unstable
C-Slightly Unstable
D-Neutral
E-Moderately Stable
F-Very Stable
(b)
10^2
10^3
10^4
10^5
x, DOWNWIND DISTANCE (m)

Plume sigma formulas from EPA's ISC Model

Vertical distribution:

$$\sigma_z = ax^b$$

x is in *kilometers*
σ_z is in *meters*
a, *b* depend on *x*

Cross-wind distribution:

$$\sigma_y = 465.11628x(\tan\Theta)$$

$$\Theta = 0.017453293(c - d\ln(x))$$

x is in *kilometers*
σ_y is in *meters*
Θ is in *radians*

$$\sigma_z = ax^b$$

Pasquill Stability Category	x (km)	a	b
A*	<.10	122.800	0.94470
	0.10 - 0.15	158.080	1.05420
	0.16 - 0.20	170.220	1.09320
	0.21 - 0.25	179.520	1.12620
	0.26 - 0.30	217.410	1.26440
	0.31 - 0.40	258.890	1.40940
	0.41 - 0.50	346.750	1.72830
	0.51 - 3.11	453.850	2.11660
	>3.11	**	**

* If the calculated value of σ_z exceed 5000 m, σ_z is set to 5000 m.

$$\sigma_z = ax^b$$

Pasquill Stability Category	x (km)	a	b
B*	<.20	90.673	0.93198
	0.21 - 0.40	98.483	0.98332
	>0.40	109.300	1.09710
C*	All	61.141	0.91465
D	<.30	34.459	0.86974
	0.31 - 1.00	32.093	0.81066
	1.01 - 3.00	32.093	0.64403
	3.01 - 10.00	33.504	0.60486
	10.01 - 30.00	36.650	0.56589
	>30.00	44.053	0.51179

* If the calculated value of σ_z exceed 5000 m, σ_z is set to 5000 m.

** σ_z is equal to 5000 m.

$$\sigma_z = ax^b$$

Pasquill Stability Category	x (km)	a	b
E	<.10	24.260	0.83660
	0.10 - 0.30	23.331	0.81956
	0.31 - 1.00	21.628	0.75660
	1.01 - 2.00	21.628	0.63077
	2.01 - 4.00	22.534	0.57154
	4.01 - 10.00	24.703	0.50527
	10.01 - 20.00	26.970	0.46713
	20.01 - 40.00	35.420	0.37615
	>40.00	47.618	0.29592
F	<.20	15.209	0.81558
	0.21 - 0.70	14.457	0.78407
	0.71 - 1.00	13.953	0.68465
	1.01 - 2.00	13.953	0.63227
	2.01 - 3.00	14.823	0.54503
	3.01 - 7.00	16.187	0.46490
	7.01 - 15.00	17.836	0.41507
	15.01 - 30.00	22.651	0.32681
	30.01 - 60.00	27.074	0.27436
	>60.00	34.219	0.21716

$$\Theta = 0.017453293\left(c - d\ln(x)\right)$$

Pasquill Stability Category	c	d
A	24.1670	2.5334
B	18.3330	1.8096
C	12.5000	1.0857
D	8.3330	0.72382
E	6.2500	0.54287
F	4.1667	0.36191

Calculation Procedure

1. Determine stability class from meteorology
2. Compute wind speed at “effective” stack height, h
3. Compute σ_y and σ_z at a given downwind distance, x
4. Choose appropriate receptor height, z
5. Compute C(x,y,z) using Gaussian plume equation

Steady State Gaussian "Point" Source Plume Model:

Pollutant concentration as a function of downwind position (x,y,z)

Mass emission rate

"Effective" stack height, including rise of the hot plume near the source

$$C(x,y,z) = \frac{Q}{2\pi\, u\, \sigma_y \sigma_z} \left\{ \exp\left(\frac{-(z-h)^2}{2\sigma_z^2} \right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2} \right) \right\} \left\{ \exp\left(\frac{-(y)^2}{2\sigma_y^2} \right) \right\}$$

Wind speed evaluated at "effective" release height

Corresponds to disk area in simple model (values depend upon downwind distance, x)

Distribution of mass in vertical dimension (z) at a given downwind distance, x (includes the effect of surface reflection)

Distribution of mass in cross-wind dimension (y) at a given downwind distance, x

Example Calculation

Given:

Q = 10 grams/sec; h (=h_{eff}) = 50m; x = 500 m = 0.5 km; u_{50} = 6 m/s;
Stability Class "D"

Compute:

C(500, 0, 0) ,i.e., the ground level concentration (z = 0) at plume centerline, 500 meters downwind.

$$\sigma_z = ax^b = 32.093(0.5)^{0.81066} = 18.3\text{m}$$

$$\Theta = 0.017453293(8.3330 - 0.72382\ln[0.5]) = 0.1542\text{radians}$$

$$\sigma_y = 465.11628x(\tan\Theta) = 465.11628(0.5)[\tan(0.1542)] = 36.1\text{m}$$

$$C(x, y, z) = \frac{Q}{2\pi\, u\, \sigma_y \sigma_z}\left\{\exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)\right\}\left\{\exp\left(\frac{-(y)^2}{2\sigma_y^2}\right)\right\}$$

$$C(500,0,0) = \frac{10}{2\pi(6)(36.1)(18.3)}\left\{\exp\left(\frac{-(0-50)^2}{2(18.3)^2}\right) + \exp\left(\frac{-(0+50)^2}{2(18.3)^2}\right)\right\}\left\{\exp\left(\frac{-(0)^2}{2(36.1)^2}\right)\right\}$$

$$C(500,0,0) = \frac{10}{2\pi(6)(36.1)(18.3)}\{0.0479\}\{1\} = 1.92\text{x}10^{-5}\ \text{g/m}^3 = 19.2\mu\text{g/m}^3$$

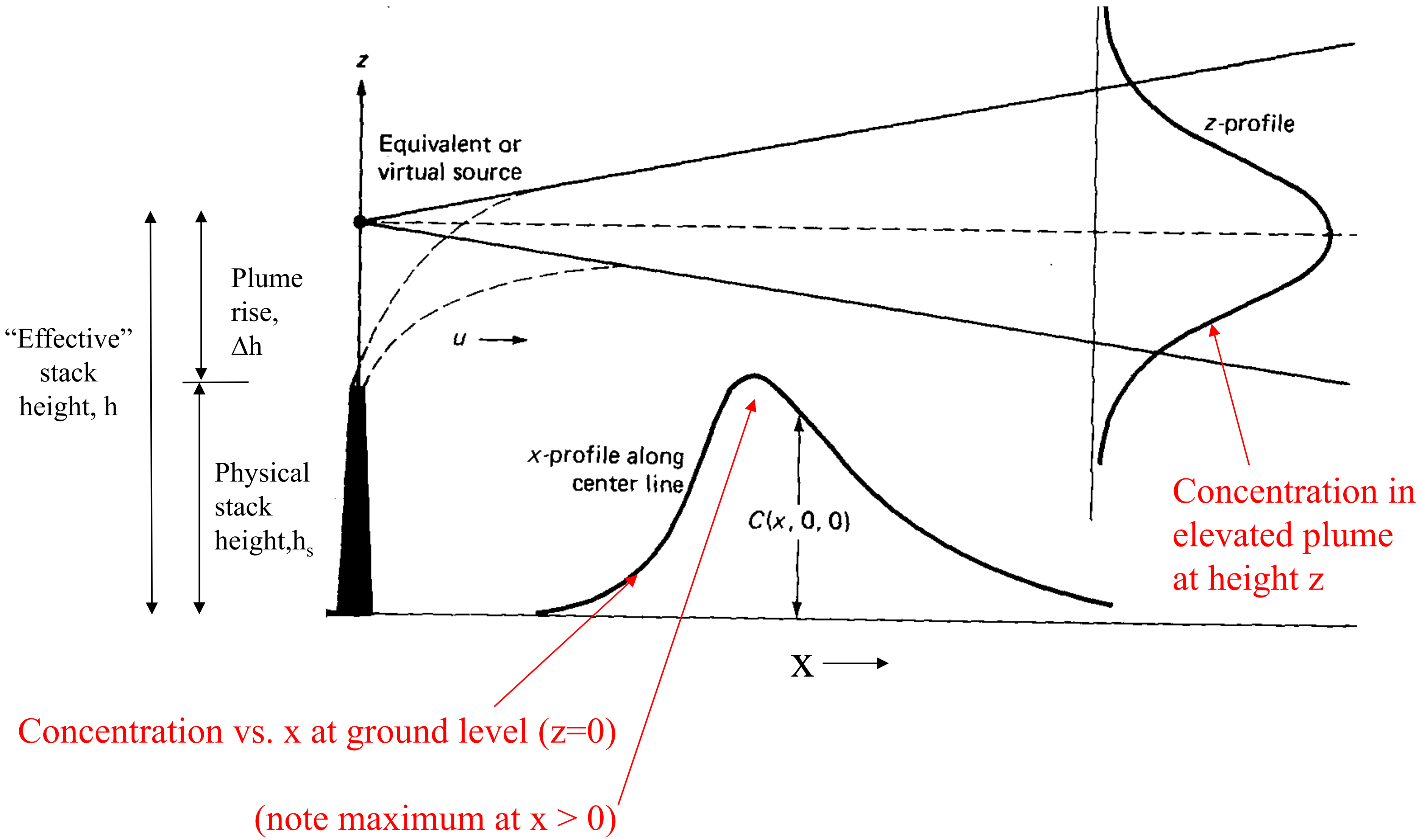
Simplified Plume Equation for z = 0

$$C(x,y,z) = \frac{Q}{2\pi\, u\, \sigma_y \sigma_z}\left\{\exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)\right\}\left\{\exp\left(\frac{-(y)^2}{2\sigma_y^2}\right)\right\}$$

$$C(x,y,z) = \frac{Q}{2\pi\, u\, \sigma_y \sigma_z}\left\{\exp\left(\frac{-(-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(+h)^2}{2\sigma_z^2}\right)\right\}\left\{\exp\left(\frac{-(y)^2}{2\sigma_y^2}\right)\right\}$$

$$C(x,y,z) = \frac{Q}{\cancel{2}\pi\, u\, \sigma_y \sigma_z}\left\{\cancel{2}\exp\left(\frac{-(h)^2}{2\sigma_z^2}\right)\right\}\left\{\exp\left(\frac{-(y)^2}{2\sigma_y^2}\right)\right\}$$

Another classic computation involves finding the location and value of the maximum ground level concentration downwind of a tall stack.

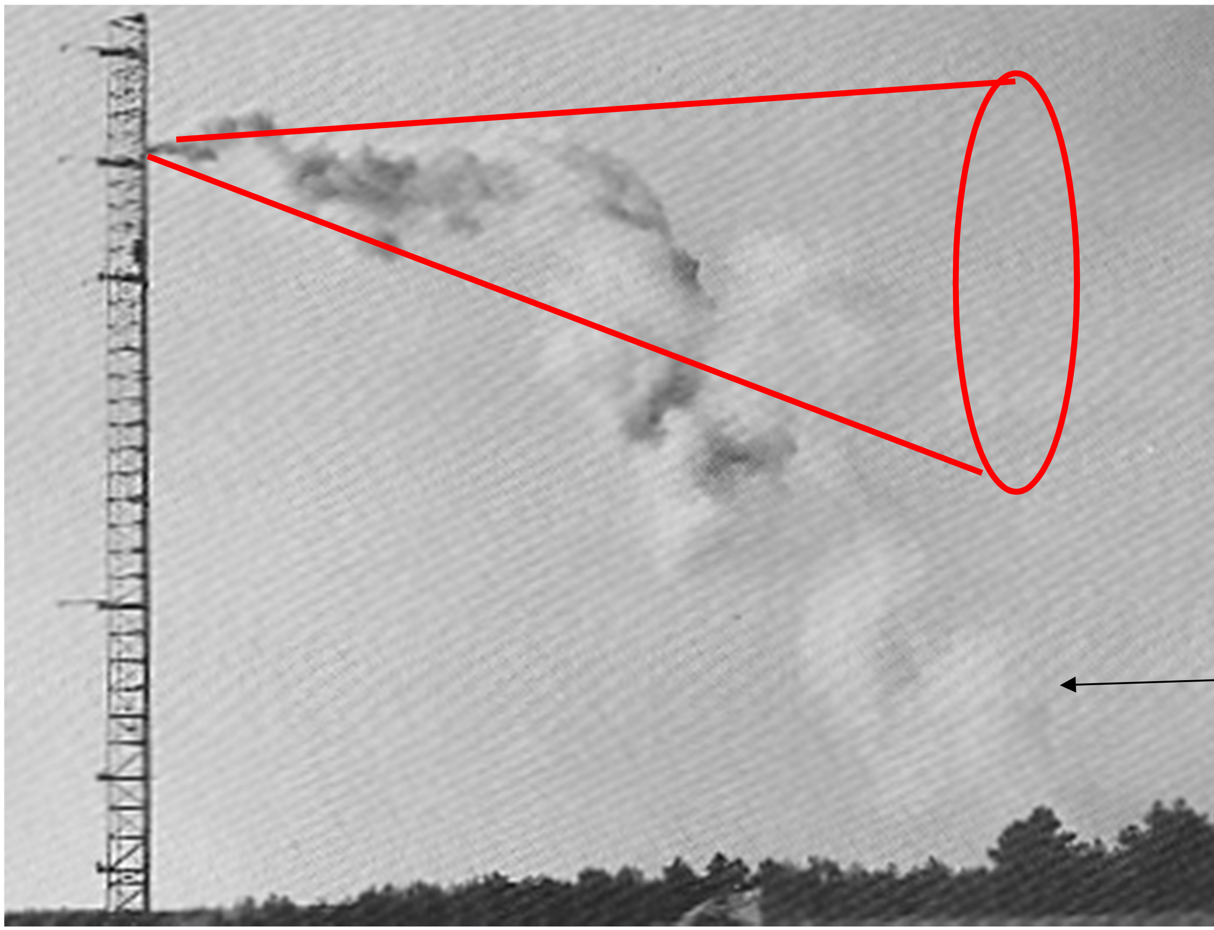


Non-Gaussian Plumes

Non- Gaussian Plume "Trapped" in Building Wake

Non-Gaussian Plume “Looping” During Unstable Conditions

(large-scale vertical motions)

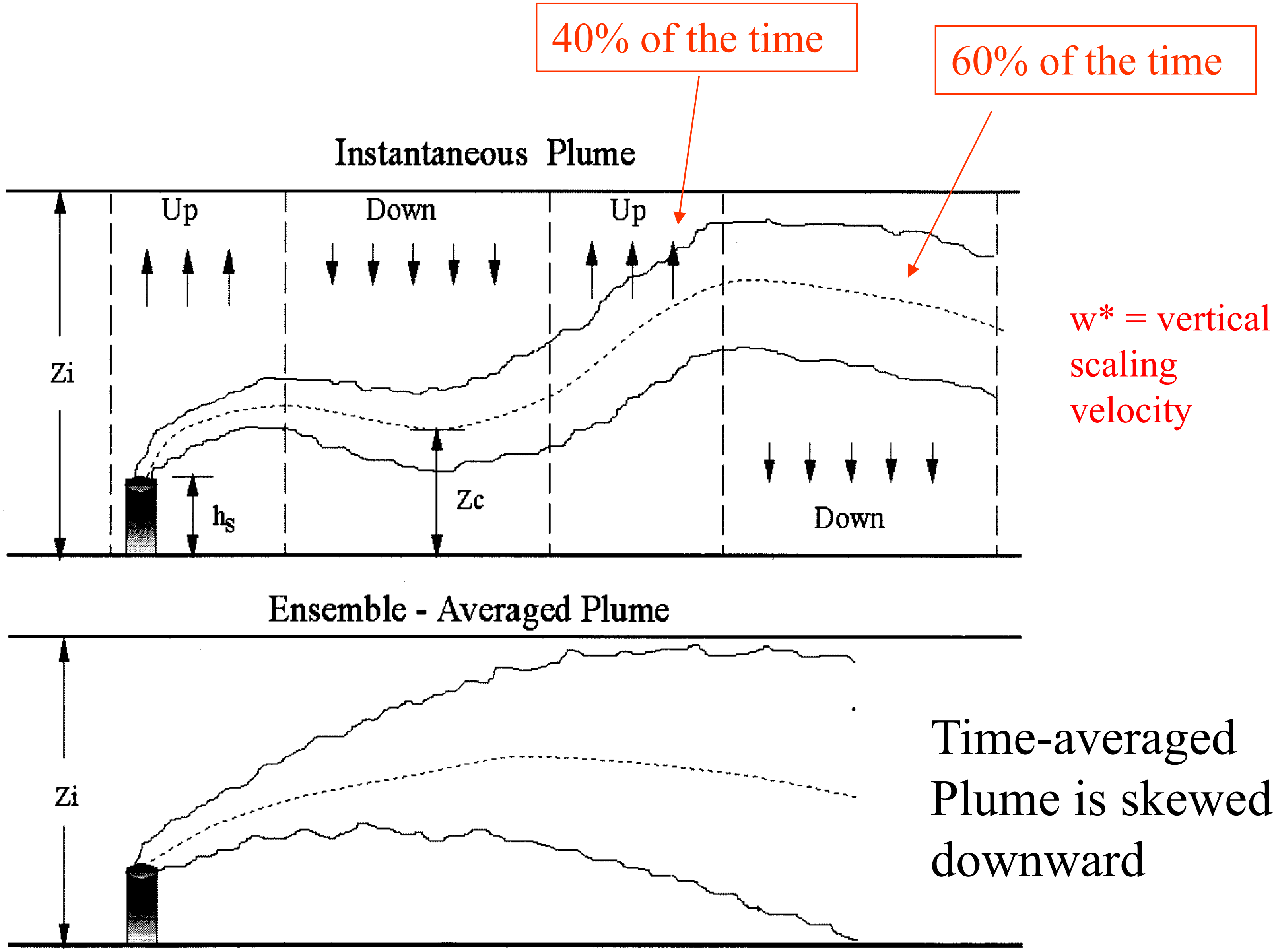


Extreme
Departure
From
Gaussian

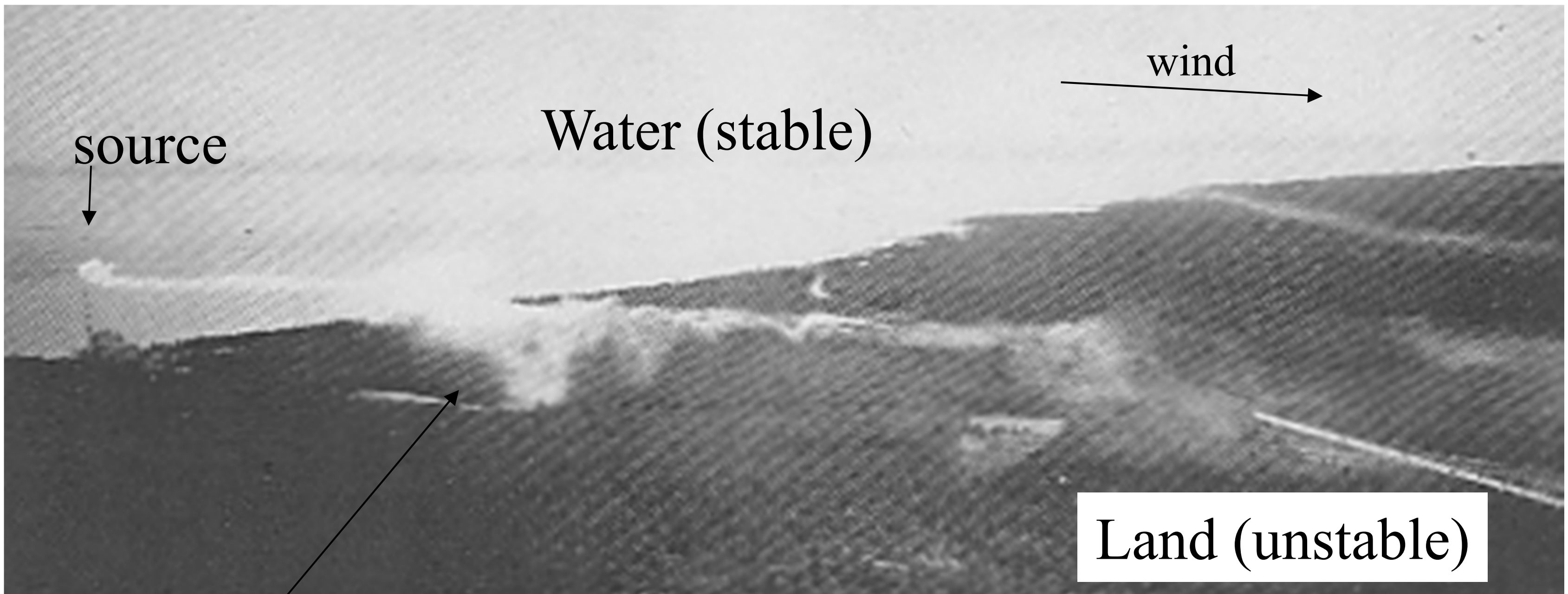
Large-Scale Vertical Motions

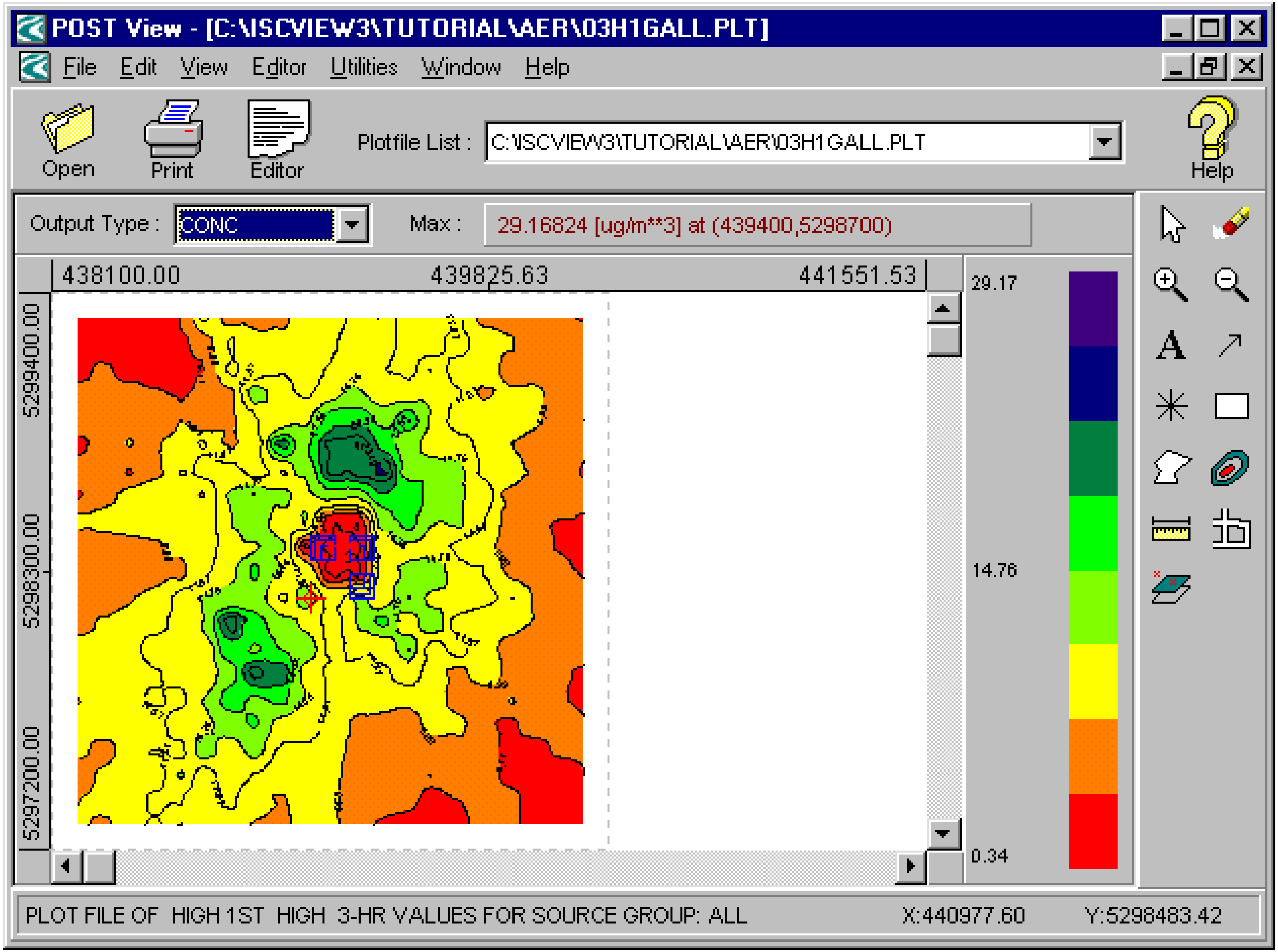
The newest EPA plume model is called ‘Aermod’ and incorporates this downdraft effect.

Aermod uses two superimposed Gaussian models, one for downdrafts and one for updrafts



Plume Fumigation During On-shore Flow




POST View - [C:\ISCVIEW3\TUTORIAL\AER\03H1GALL.PLT]
File Edit View Editor Utilities Window Help
Open
Print
Editor
Plotfile List :
C:\ISCVIEW3\TUTORIAL\AER\03H1GALL.PLT
Help
Output Type :
CONC
Max :
29.16824 [ug/m**3] at (439400,5298700)
438100.00
439825.63
441551.53
5299400.00
5298300.00
5297200.00
29.17
14.76
0.34
PLOT FILE OF HIGH 1ST HIGH 3-HR VALUES FOR SOURCE GROUP: ALL
X:440977.60
Y:5298483.42