



IAEA

GNSSN

Global Nuclear Safety
and Security Network

MEREIA WEBINAR ON BASIC CONCEPTS

**MEREIA - Methods for Radiological
Environmental Impact Assessment**



“Introduction to atmospheric dispersion process and models”



INDUSTRIALES
ETSII | UPM

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POLITÉCNICA

[CONTENTS]

INTRODUCTION. ATMOSPHERIC DISPERSION.

THE GAUSSIAN DISPERSION MODEL.

- a) The Gaussian plume model.
- b) Integrated concentration. Dispersion factor χ/Q . Isopleths
- c) The dispersion parameters. Atmospheric stability.
- d) Use and limitations of the Gaussian model.

DEPLETION MECHANISMS OF THE RADIOACTIVE CLOUD.

- a) Radioactive decay.
- b) Dry deposition of aerosols.
- c) Wet deposition by rain.

BEHAVIOUR OF POLLUTANTS IN THE ATMOSPHERE.

- a) Calm conditions.
- b) Release duration.
- c) Volume sources. Building wake effects.
- d) Plume rise effects.
- e) Mixing height.
- f) Influence of topography.
- g) Coastal locations.

Applications of atmospheric dispersion models

- Site selection – dispersive capacity of the local atmosphere
- Planned routine releases
- Accident acute release

[Introduction. Atmospheric diffusion]

- The problem of atmospheric dispersion has been treated theoretically by different approaches. The two main are:
 - The gradient transfer or K-theory approach
 - The statistical theory approach
- The Gaussian plume diffusion model is compatible with both approaches.

Introduction. Atmospheric diffusion

- The early theoretical framework for atmospheric diffusion was based on **macroscale analogies to the molecular processes of heat and momentum transfer**.
- In such systems, the diffusion transfer of a property is described by **the product of the gradient of the property and a coefficient of diffusivity**.
- Transport is assumed to occur along the gradient from regions of high values of the property to regions of lower values.
- The estimation of diffusion then resolves itself into **a search for representative values of the coefficient of diffusivity and a search for the solutions of differential equations** that represent the distribution of the property in space and its variation in time.

(Slade, 1968)

$$\frac{\partial \chi}{\partial t} = \frac{\partial}{\partial x} \left(k_x \frac{\partial \chi}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial \chi}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial \chi}{\partial z} \right)$$

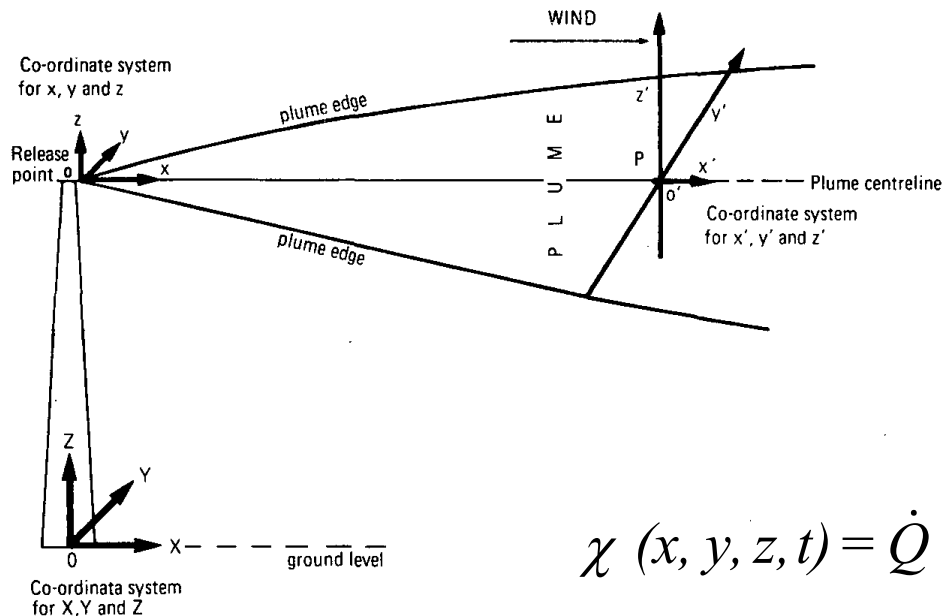
Atmospheric diffusion. Gaussian plume model

With constant coefficients

$$\frac{\partial \chi}{\partial t} = k_x \frac{\partial^2 \chi}{\partial x'^2} + k_y \frac{\partial^2 \chi}{\partial y'^2} + k_z \frac{\partial^2 \chi}{\partial z'^2}$$

In the free atmosphere, far from any boundary:

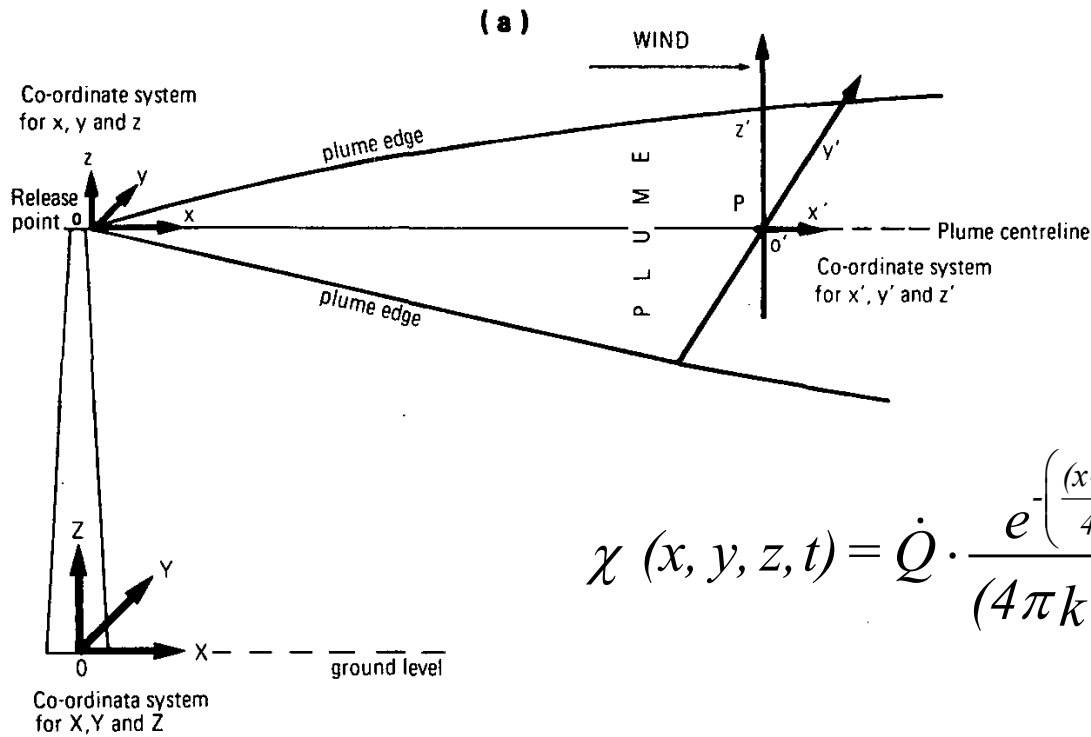
$$\chi(x', y', z', t) = \dot{Q} \cdot \frac{e^{-\left(\frac{x'^2}{4k_x t}\right)}}{(4\pi k_x t)^{1/2}} \cdot \frac{e^{-\left(\frac{y'^2}{4k_y t}\right)}}{(4\pi k_y t)^{1/2}} \cdot \frac{e^{-\left(\frac{z'^2}{4k_z t}\right)}}{(4\pi k_z t)^{1/2}}$$



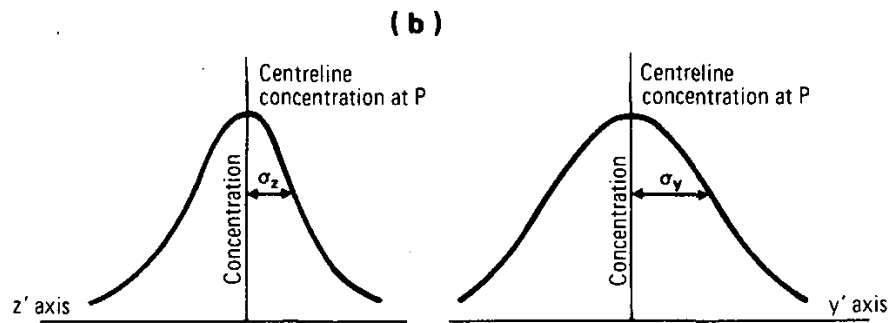
Introducing a change in the coordinate system:

$$\begin{aligned} x &= x' + \bar{u} \cdot t \\ y &= y' \\ z &= z' + h \end{aligned}$$

$$\chi(x, y, z, t) = \dot{Q} \cdot \frac{e^{-\left(\frac{(x - \bar{u} t)^2}{4k_x t}\right)}}{(4\pi k_x t)^{1/2}} \cdot \frac{e^{-\left(\frac{y^2}{4k_y t}\right)}}{(4\pi k_y t)^{1/2}} \cdot \frac{e^{-\left(\frac{(z - h)^2}{4k_z t}\right)}}{(4\pi k_z t)^{1/2}}$$



$$\chi(x, y, z, t) = \dot{Q} \cdot \frac{e^{-\left(\frac{(x-\bar{u}t)^2}{4k_x t}\right)}}{(4\pi k_x t)^{1/2}} \cdot \frac{e^{-\left(\frac{y^2}{4k_y t}\right)}}{(4\pi k_y t)^{1/2}} \cdot \frac{e^{-\left(\frac{(z-h)^2}{4k_z t}\right)}}{(4\pi k_z t)^{1/2}}$$



Schematic representation of: a) coordinate systems; b) the dispersion parameters of the plume σ_y and σ_z . (IAEA, 1980).

Atmospheric diffusion. Gaussian plume model

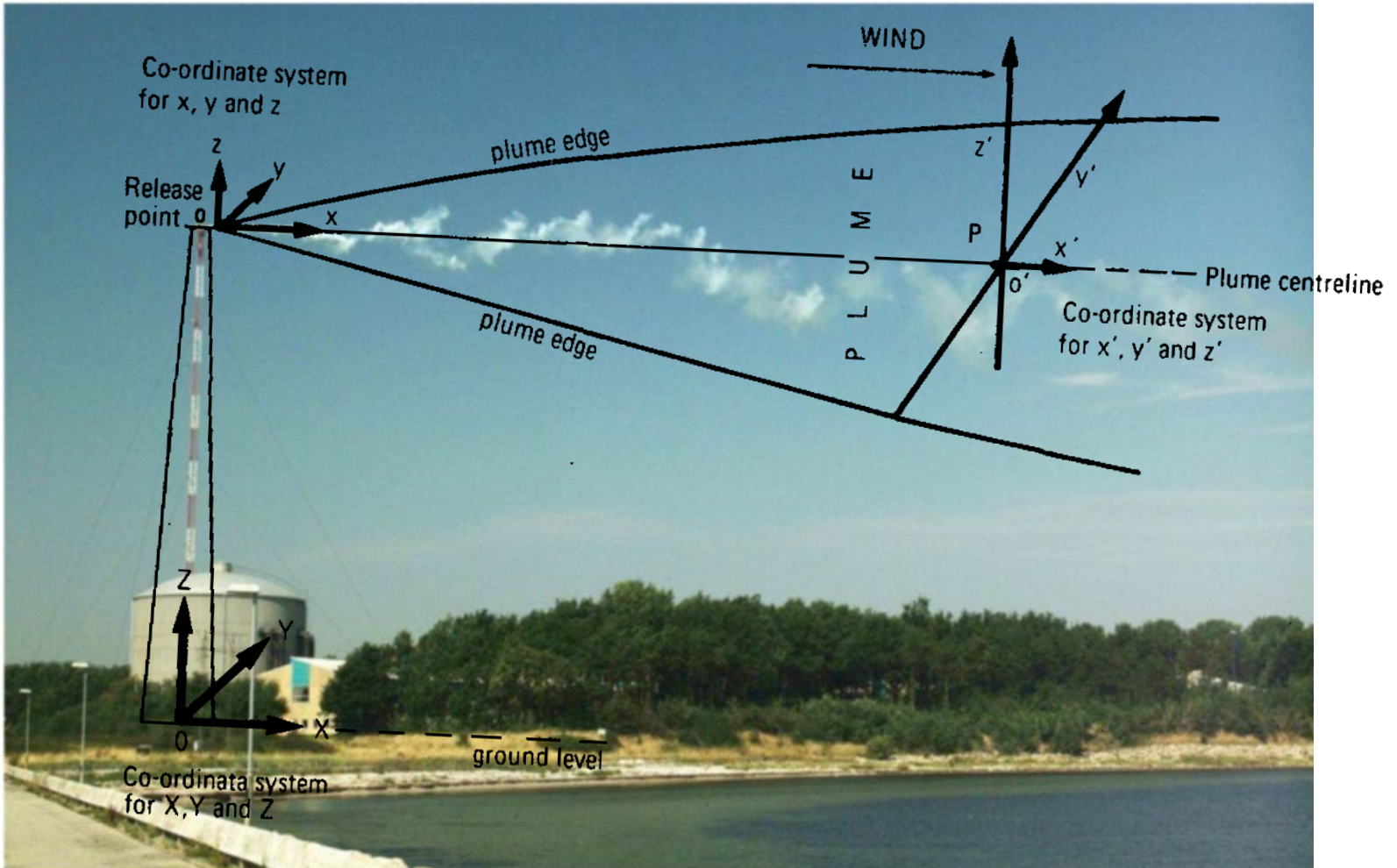
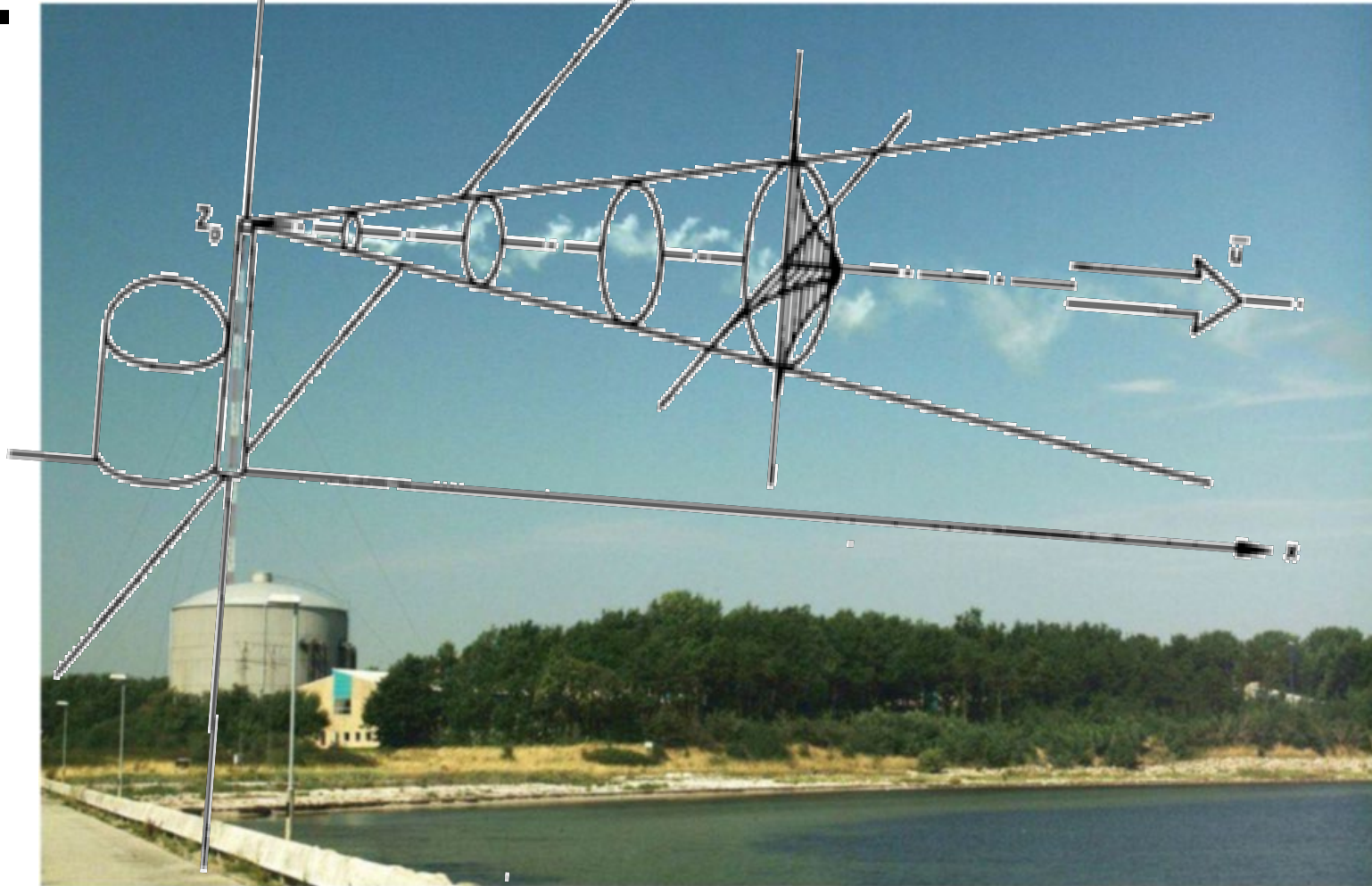


Photo: T. Mikelsen, Risø

Atmospheric diffusion. Gaussian plume model



Gaussian plume diffusion (Till & Meyer, 1983).

Photo: T. Mikelsen, Risø

Atmospheric diffusion. Gaussian plume model

Considering: $\sigma^2 = 2kt \rightarrow \sigma_y^2 \equiv \frac{2k_y x}{\bar{u}}, \text{ y } \sigma_z^2 \equiv \frac{2k_z x}{\bar{u}},$

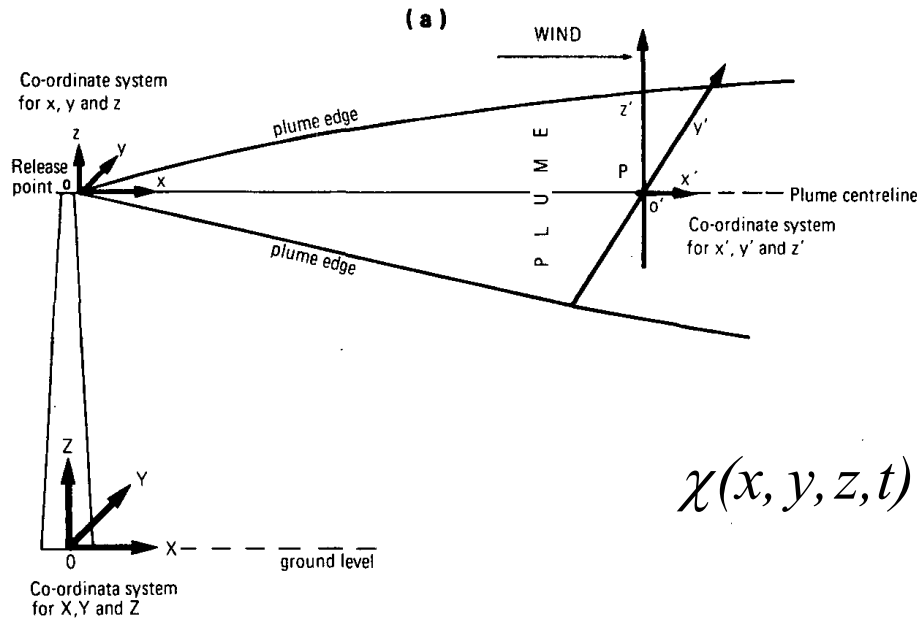
And neglecting diffusion in the x direction.

For a continuous point source:

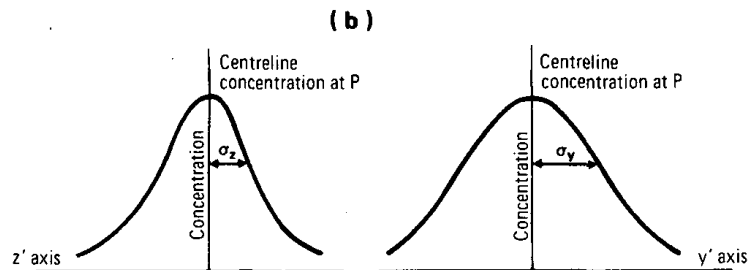
$$\chi(x, y, z, t) = \frac{\dot{Q}}{\bar{u}} \cdot \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi} \cdot \sigma_y} \cdot \frac{e^{-\left(\frac{(z-h)^2}{2\sigma_z^2}\right)}}{\sqrt{2\pi} \cdot \sigma_z}$$

$$\chi(x, y, z, t) = \frac{\dot{Q}}{2\pi \bar{u} \sigma_y \sigma_z} \cdot \exp \left[-\frac{y^2}{2\sigma_y^2} - \frac{(z-h)^2}{2\sigma_z^2} \right]$$

Atmospheric diffusion. Gaussian plume model

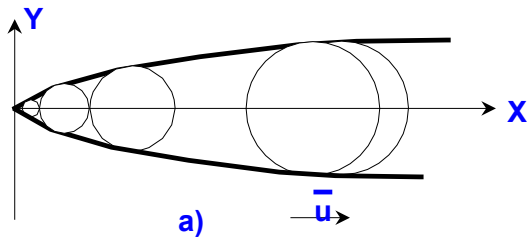


$$\chi(x, y, z, t) = \frac{\dot{Q}}{2\pi u \sigma_y \sigma_z} \cdot \exp \left[-\frac{y^2}{2\sigma_y^2} - \frac{(z-h)^2}{2\sigma_z^2} \right]$$

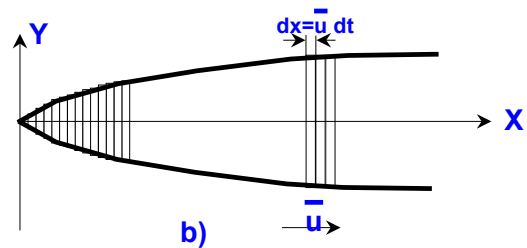


Schematic representation of: a) coordinate systems; b) the dispersion parameters of the plume σ_y and σ_z . (IAEA, 1980).

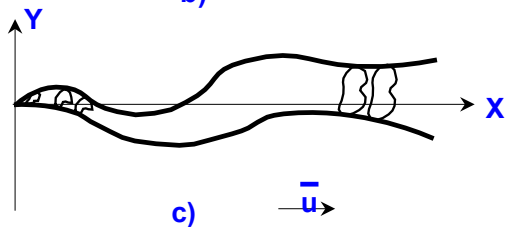
Atmospheric diffusion. Different approaches



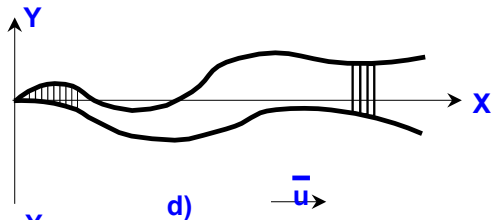
(a) Schematic formation of plume from superposition of individual averaged elements.



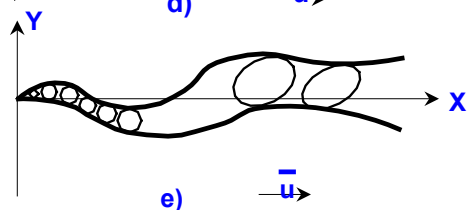
(b) Schematic spreading-disk plume model obtained by neglecting x-diffusion.



(c) Appearance of naturally occurring plumes, with "real" puff elements indicated.

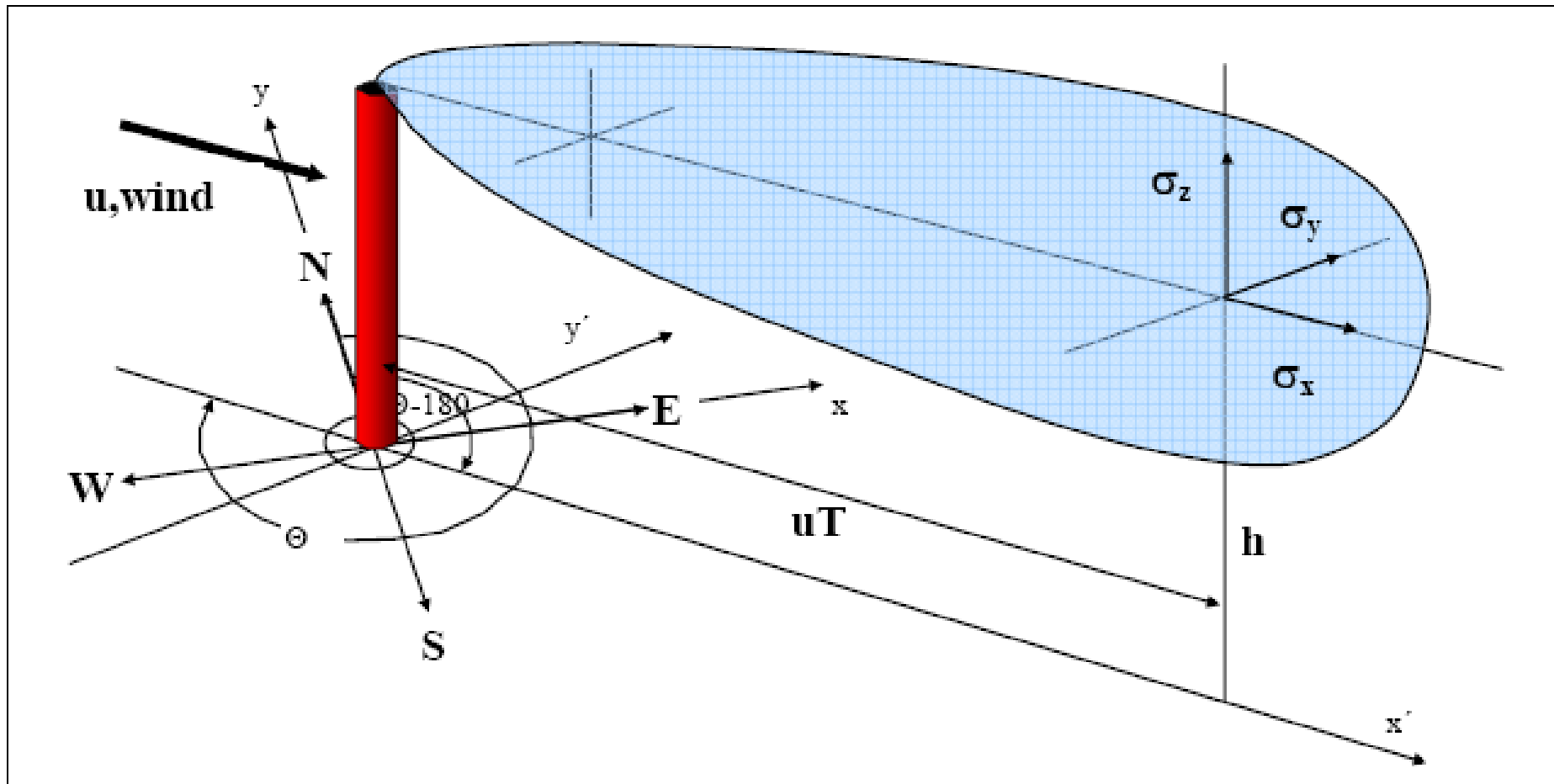


(d) Fluctuating plume model, and



(e) Approximation by averaged "puffs"

(Adapted from Slade, 1968)

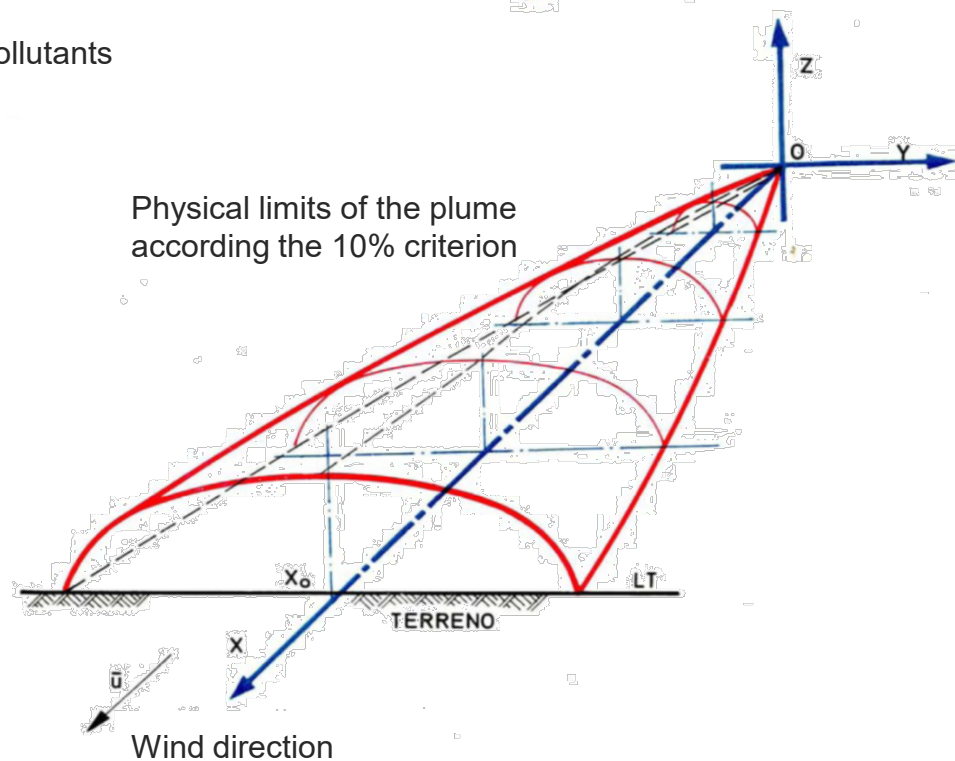
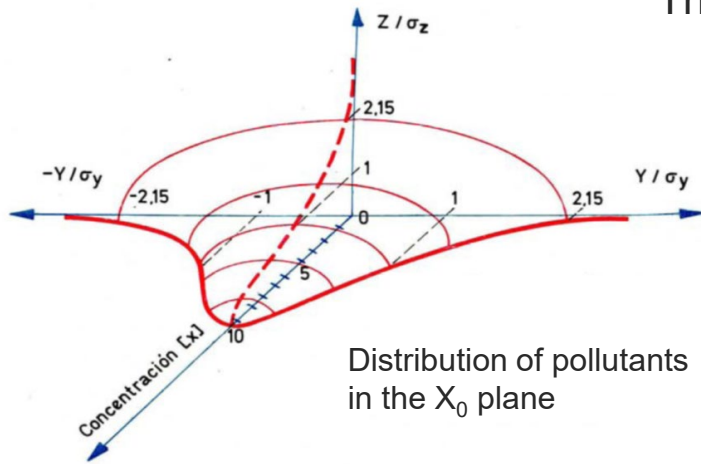


Scheme of a vertical and horizontal Gaussian distribution where u is the average wind speed, T the elapsed travel time and h the height of the release.

Gaussian plume model. Reflection on the ground

The concentration is duplicated:

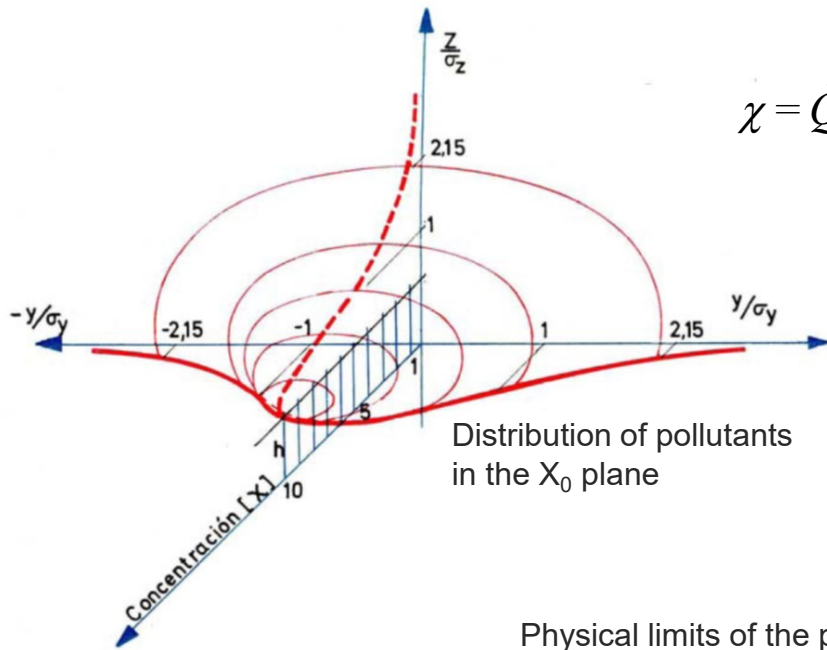
$$\chi = \frac{\dot{Q}}{\pi u \sigma_y \sigma_z} \cdot \exp \left[-\frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2} \right]$$



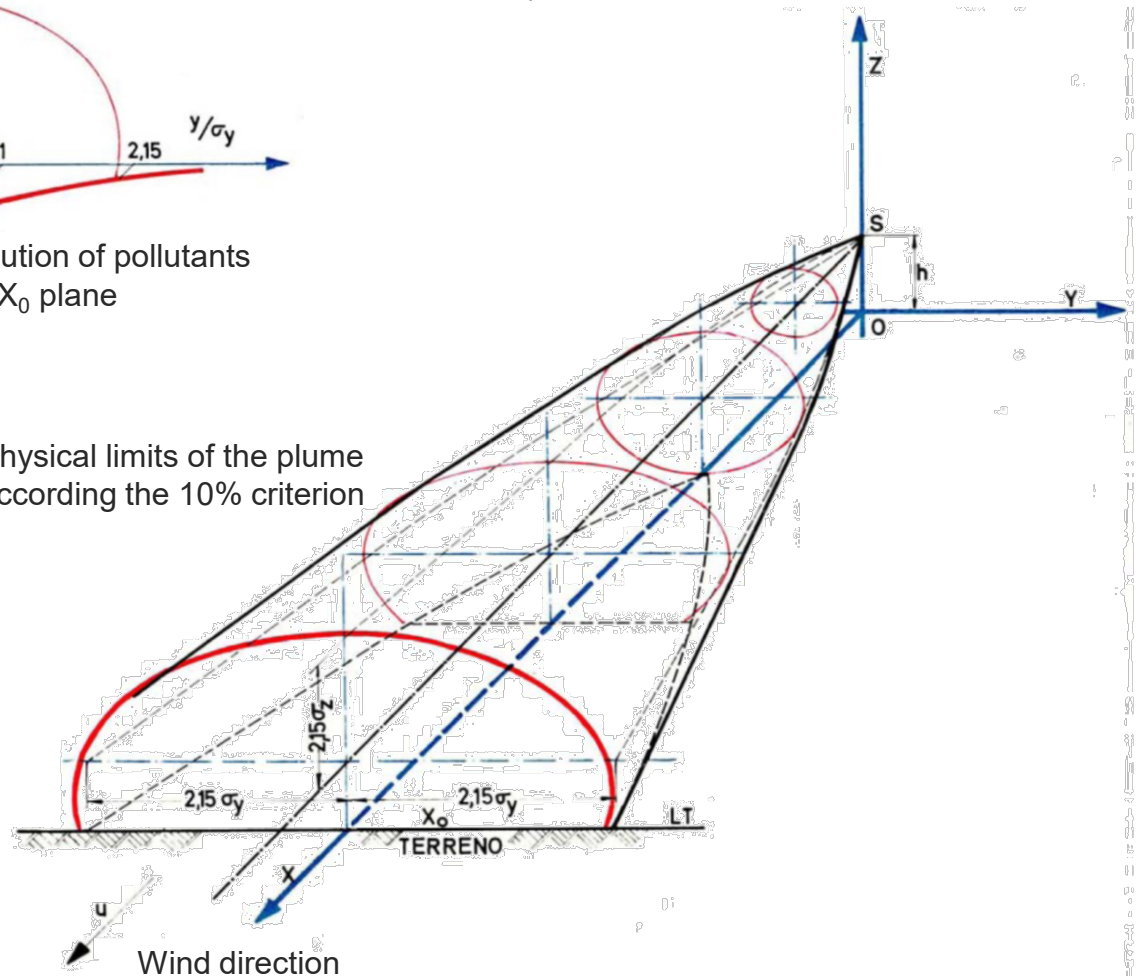
Scheme of a Gaussian cloud released at ground level (Alonso, 1974)

Gaussian plume model. Reflection on the ground

$$\chi = \dot{Q} \frac{e^{-\frac{y^2}{2\sigma_y^2}}}{2\pi u \sigma_y \sigma_z} \cdot \left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] \right\}$$

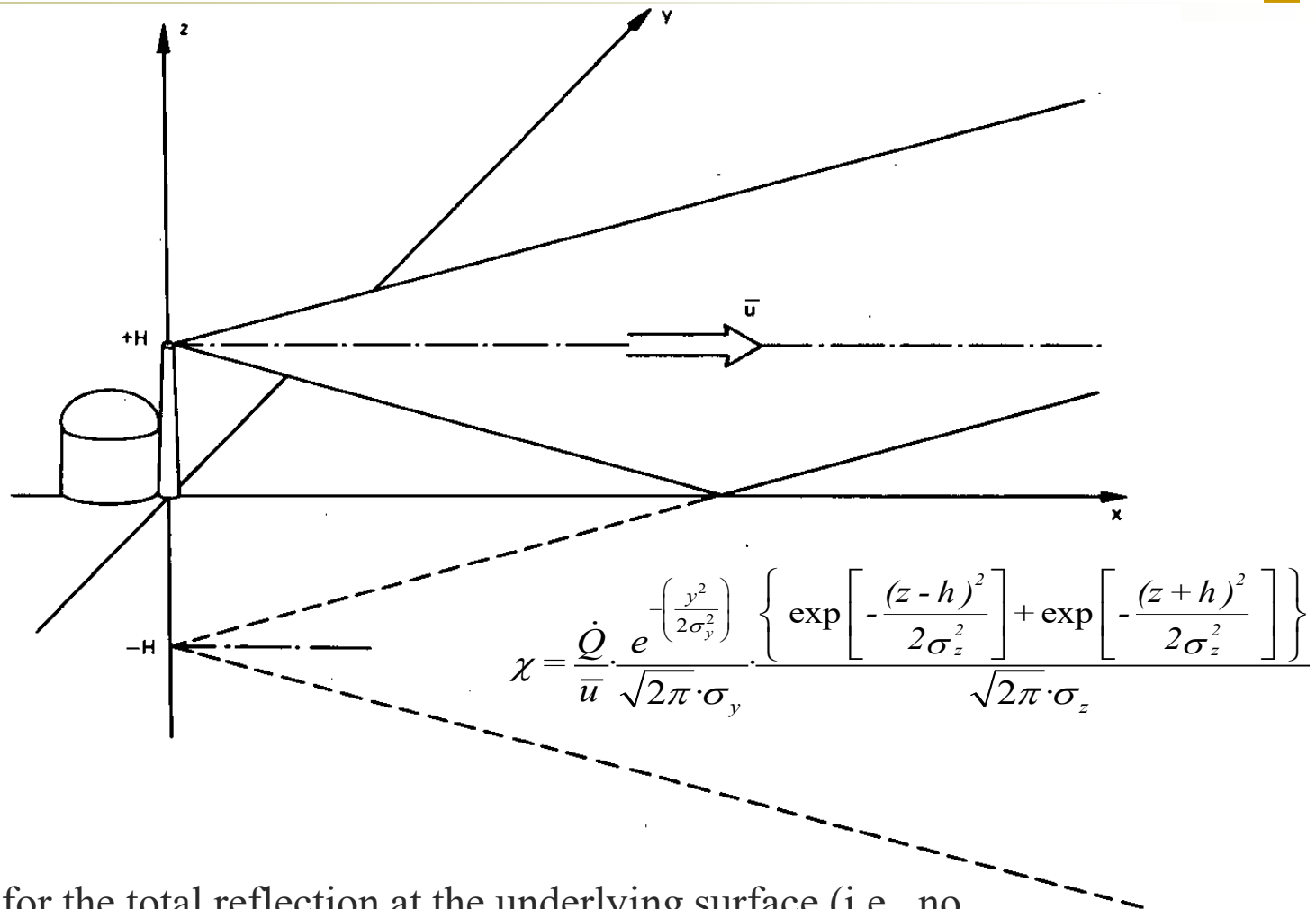


Physical limits of the plume according the 10% criterion



Scheme of a Gaussian cloud released from an elevated point (Alonso, 1974).

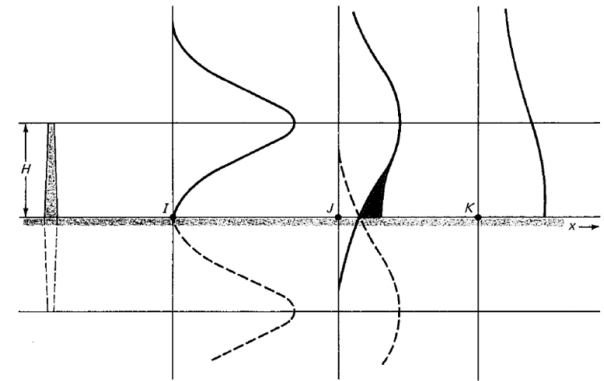
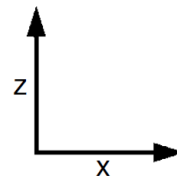
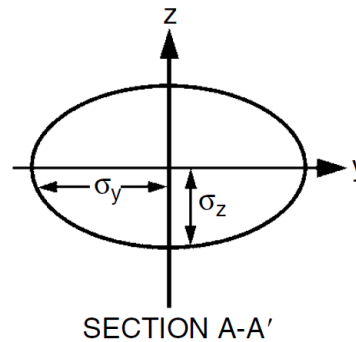
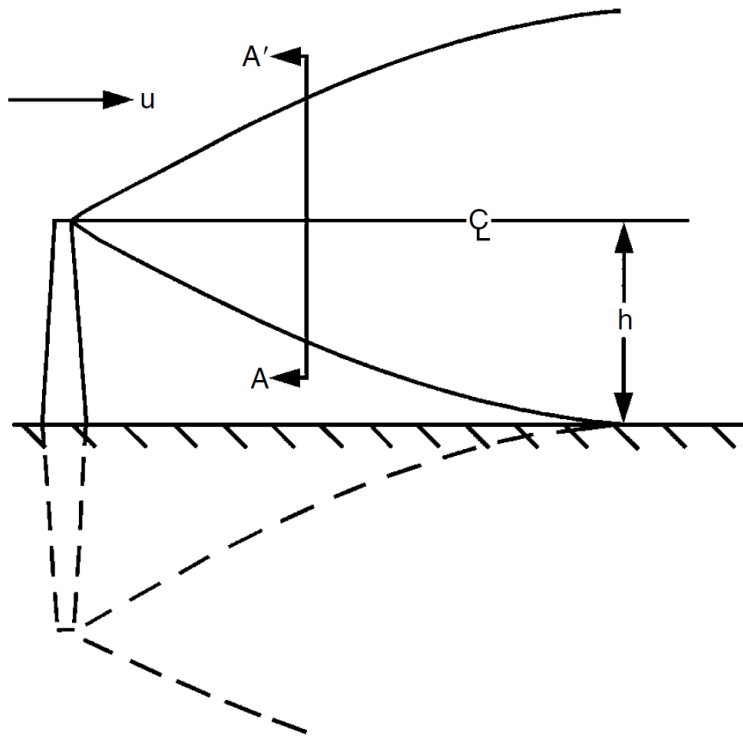
Consideration of full reflection of the plume on the ground



Scheme for the total reflection at the underlying surface (i.e., no ground absorption) (Till & Meyer, 1983).

Gaussian plume model. Reflection on the ground

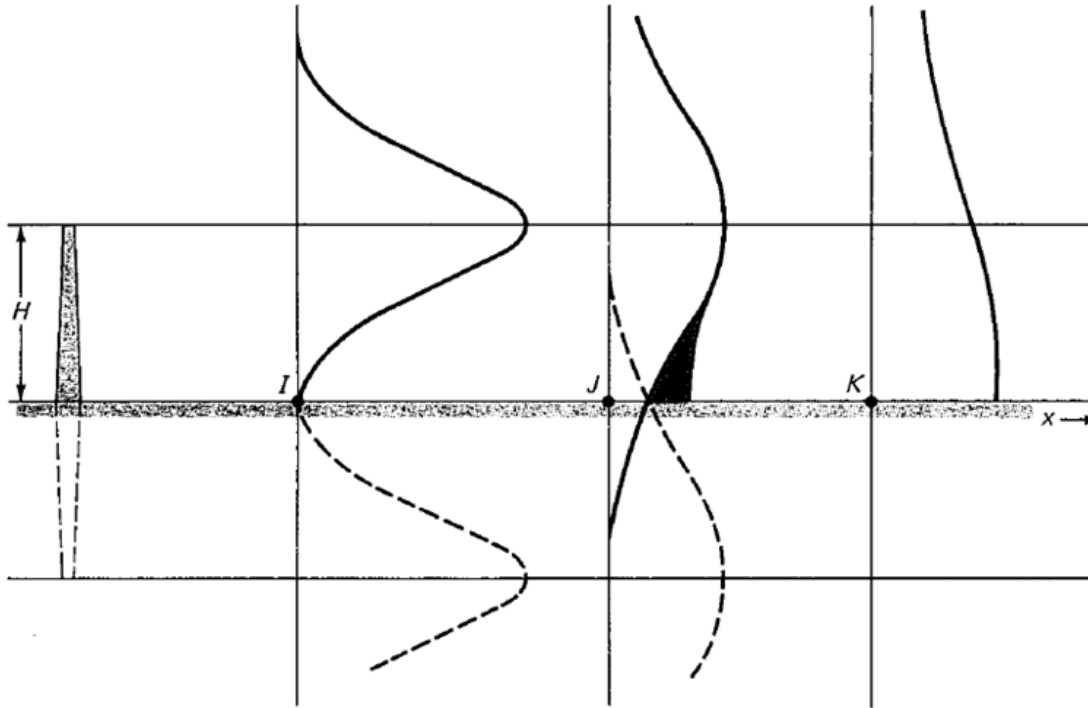
$$\chi = \frac{\dot{Q}}{\bar{u}} \cdot \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi} \cdot \sigma_y} \cdot \frac{\left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] \right\}}{\sqrt{2\pi} \cdot \sigma_z}$$



Coordinate system of the straight-line Gaussian plume model, including representations of the distribution of concentrations within the plume in the horizontal and vertical directions and the location of the **image source**. From Hanna et al. (1982).

(Till & Grogan, 2008)

Ground reflection effect



$$\chi = \frac{\dot{Q}}{\bar{u}} \cdot \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi} \cdot \sigma_y} \cdot \frac{\left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] \right\}}{\sqrt{2\pi} \cdot \sigma_z}$$

At ground level, $z=0$

$$\rightarrow \chi = \frac{\dot{Q}}{\bar{u}} \cdot \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)} \cdot e^{-\left(\frac{h^2}{2\sigma_z^2}\right)}}{\pi \cdot \sigma_y \cdot \sigma_z}$$

In summary, influence of the ground on air concentration from continuous point source...

Elevated point source; no ground effect:

$$\chi(x, y, z; t) = \frac{\dot{Q}}{\bar{u}} \cdot \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi} \cdot \sigma_y} \cdot \frac{e^{-\left(\frac{(z-h)^2}{2\sigma_z^2}\right)}}{\sqrt{2\pi} \cdot \sigma_z}$$

Point source at ground level; full ground reflection:

$$\chi(x, y, z; t) = \frac{\dot{Q}}{\pi u \sigma_y \sigma_z} \cdot \exp \left[-\frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2} \right]$$

Elevated point source; full ground reflection:

$$\chi(x, y, z; t) = \frac{\dot{Q}}{\bar{u}} \cdot \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi} \cdot \sigma_y} \cdot \frac{\left\{ \exp \left[-\frac{(z-h)^2}{2\sigma_z^2} \right] + \exp \left[-\frac{(z+h)^2}{2\sigma_z^2} \right] \right\}}{\sqrt{2\pi} \cdot \sigma_z}$$

Instantaneous air concentration:

$$\chi(x, y, z; t) = \frac{\frac{Bq}{m^3}}{\frac{s}{\frac{m}{s}}} \frac{e^{-\frac{y^2}{2\sigma_y^2}}}{2\pi \frac{m}{s} \sigma_y \sigma_z} \cdot \left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] \right\}$$

Integrated air concentration:

Q is the total released activity in Bq $Q = \int_0^T \dot{Q} \cdot dt$

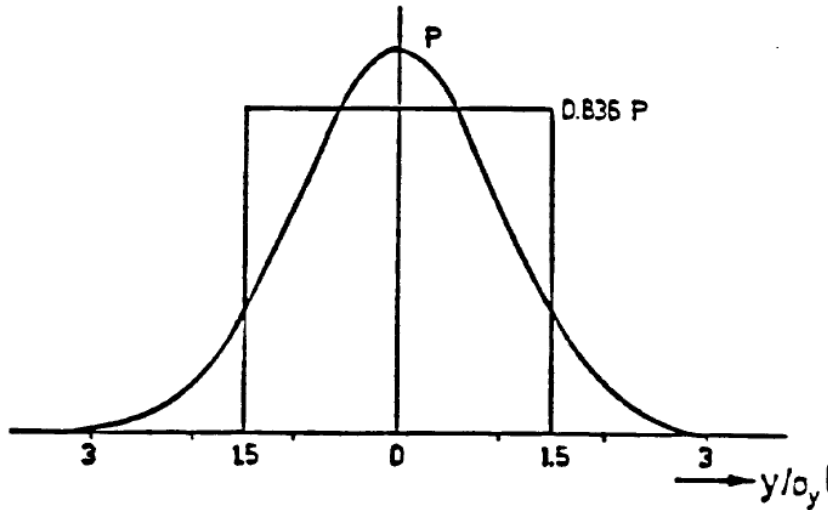
$$\bar{\chi}(x, y, z) = \frac{\frac{Bq \cdot s}{m^3}}{2\pi \frac{m}{s} \sigma_y \sigma_z} \cdot \left\{ \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] \right\}$$

Dispersion Factor:

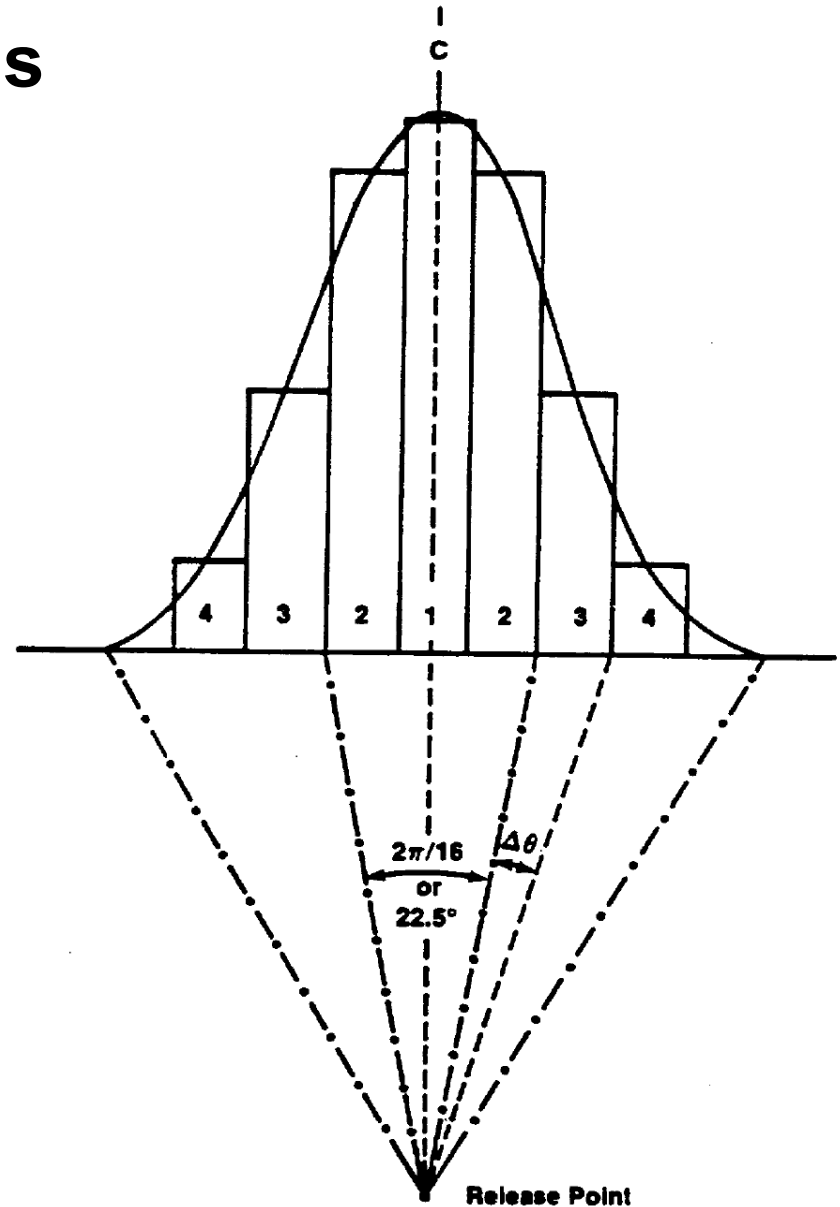
$$\chi/Q \quad (s \cdot m^{-3})$$

Isopleths: lines connecting points with equal values of χ or of χ/Q

Frequent simplifications

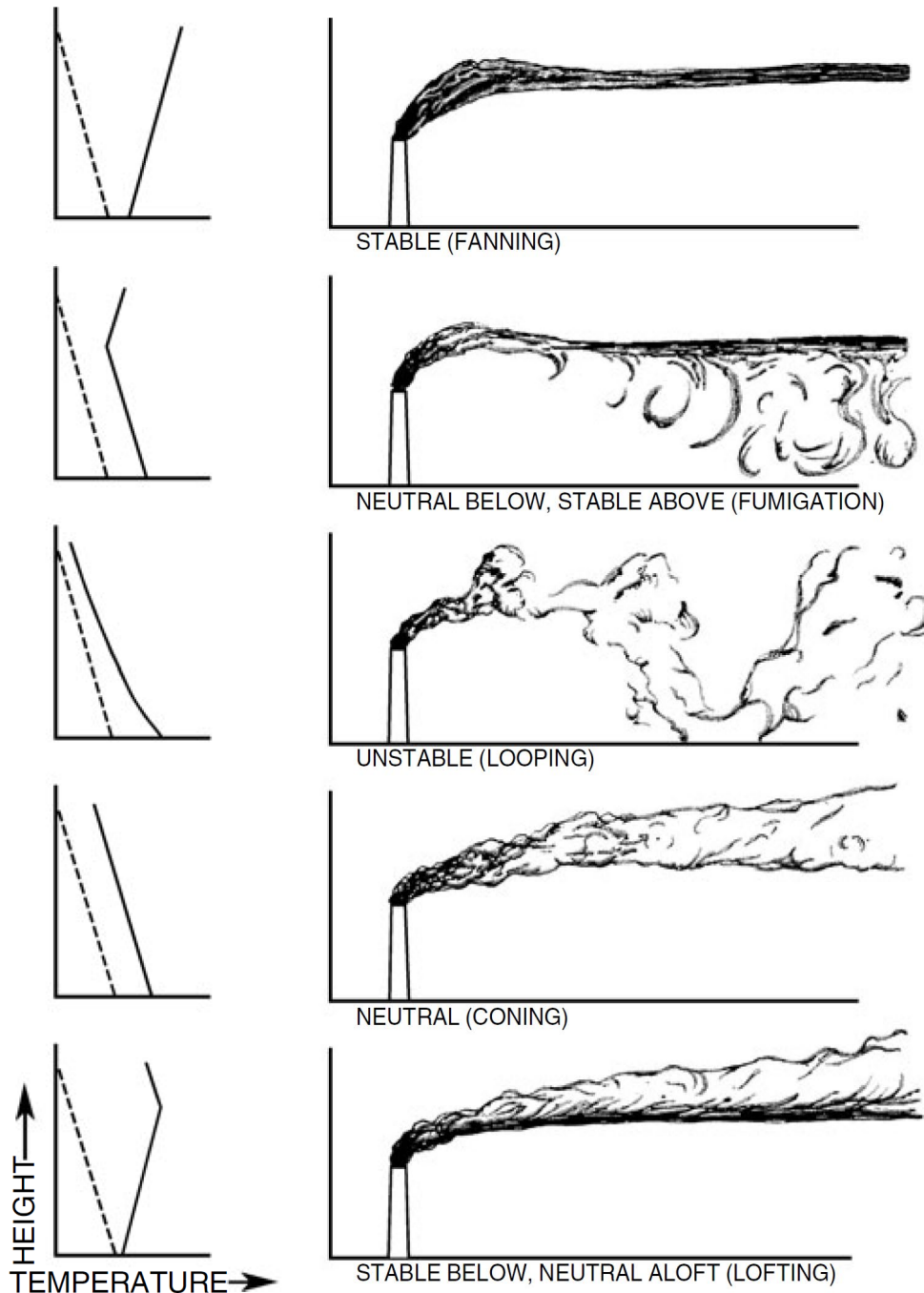


$$\frac{e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi}\cdot\sigma_y} \langle \rangle \frac{1}{3\sigma_y}$$



Approximation of the normal distribution by a uniform (one step) and multi-step for the lateral distribution function

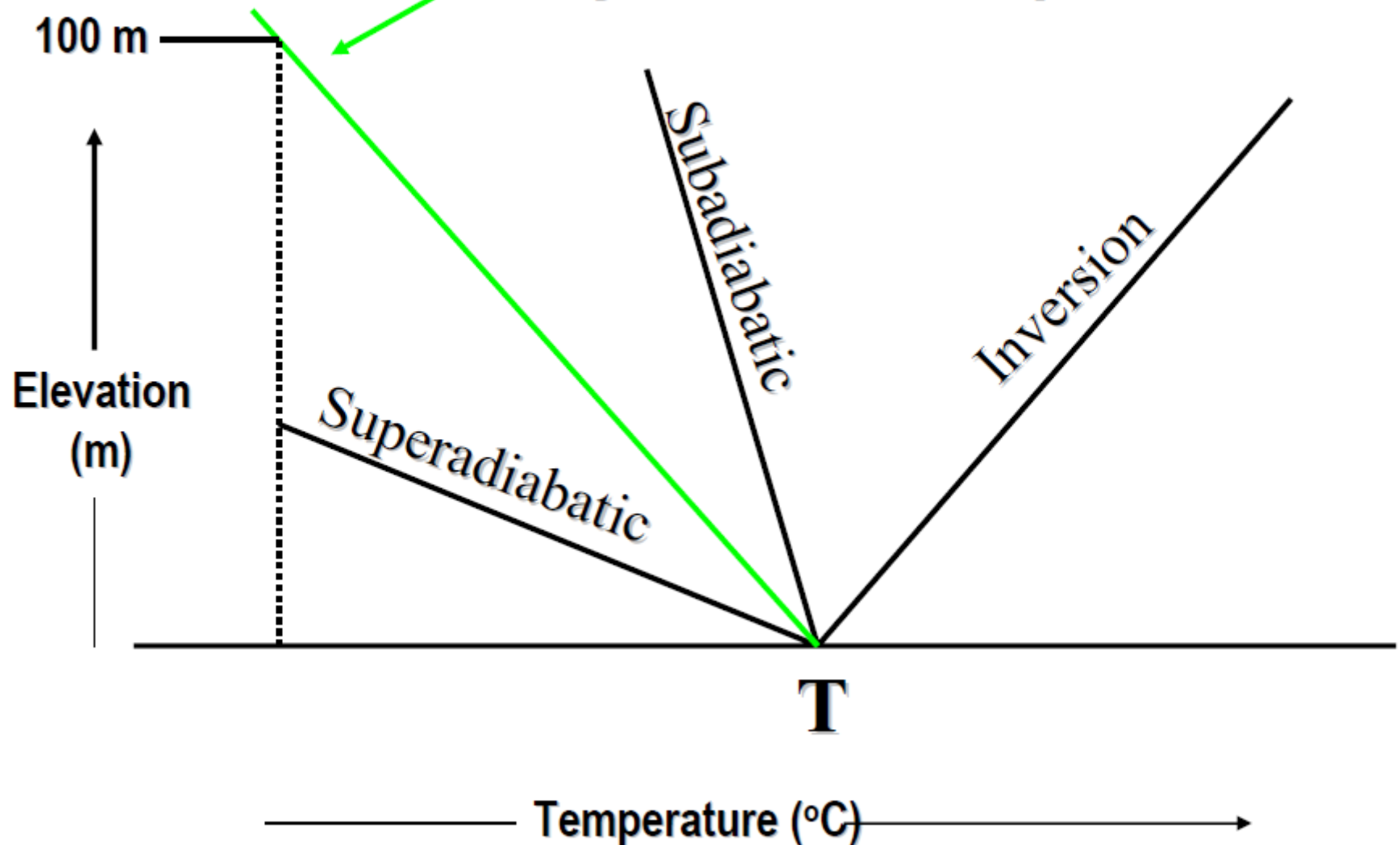
Atmospheric stability



Effect of air temperature variation with altitude and atmospheric stability, on the type of cloud resulting. The dashed line represents the dry adiabatic gradient (Slade, 1968)

$$\left[\frac{dT}{dZ} = -\frac{g}{C_p} \right] = 0.976 \text{ } ^\circ\text{C}/100 \text{ m} \sim 1 \text{ } ^\circ\text{C}/100 \text{ m}$$

Dry Adiabatic Lapse Rate



Diurnal cycle and effect of daytime sunshine on atmospheric temperature gradients

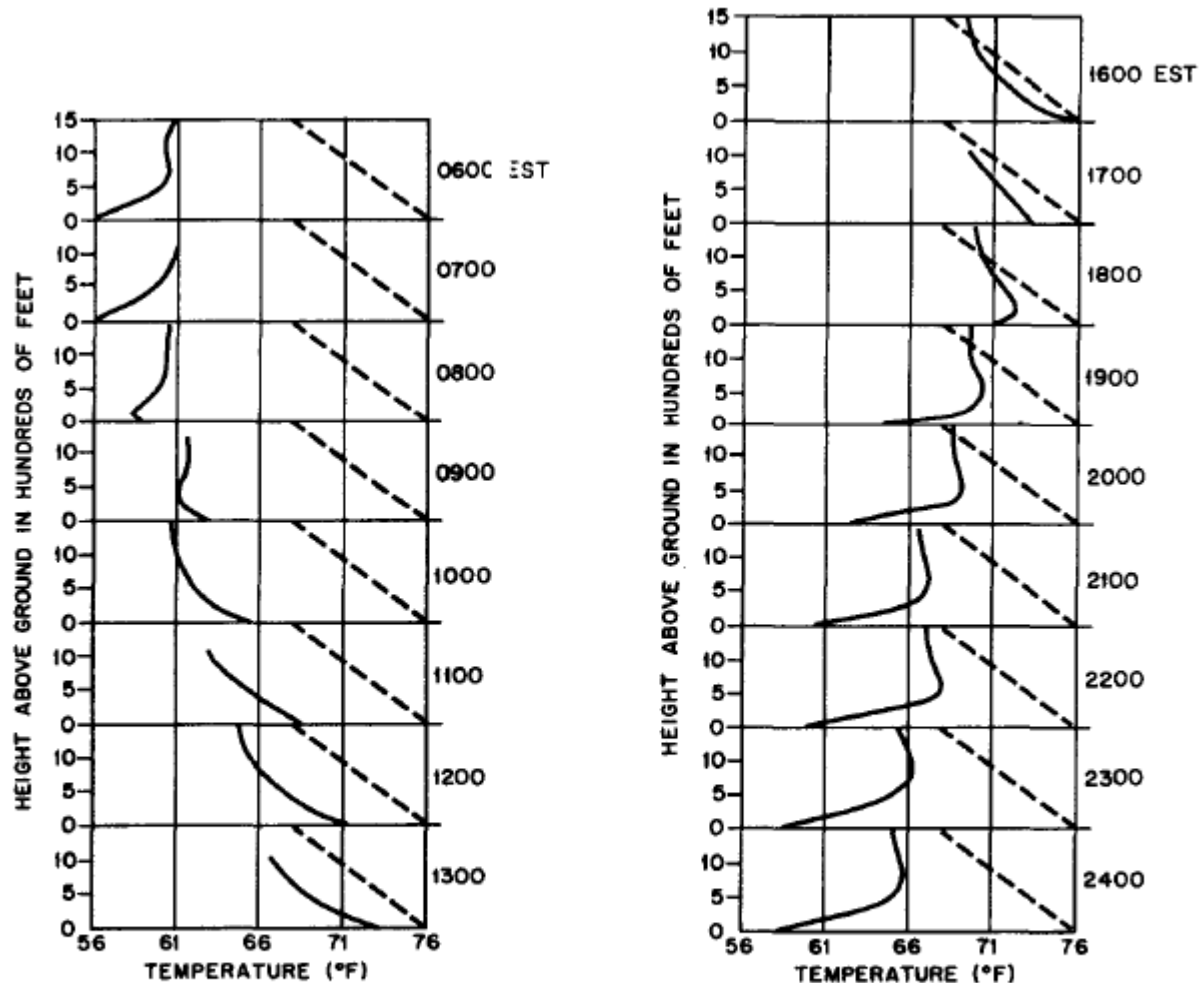
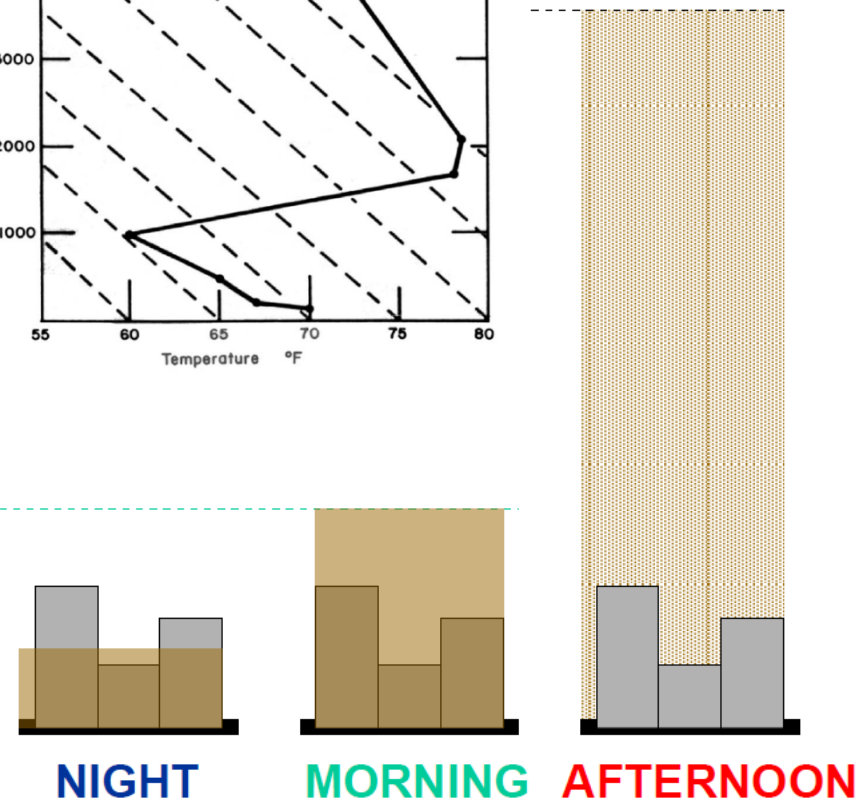
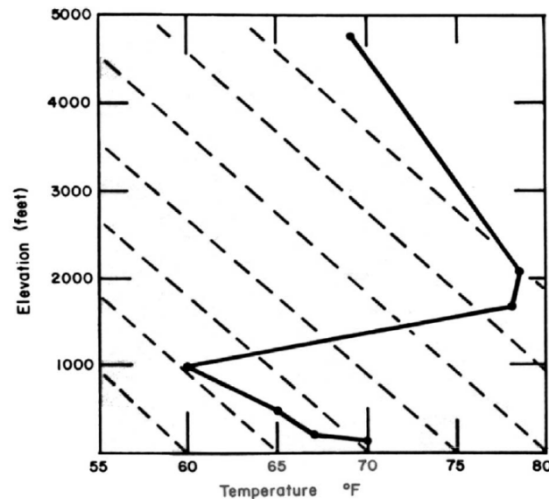
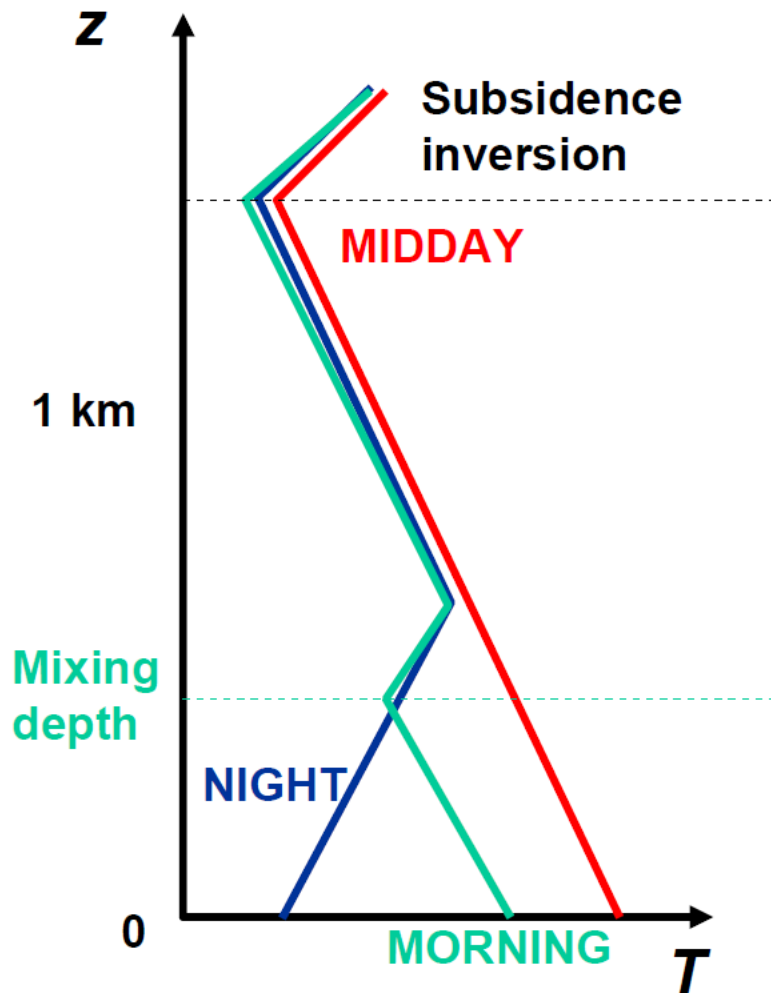
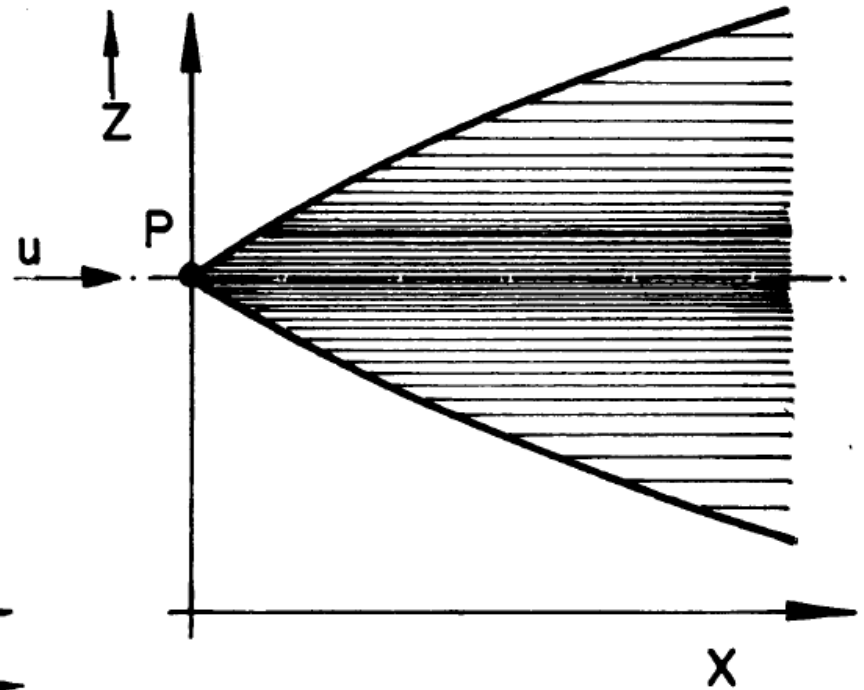
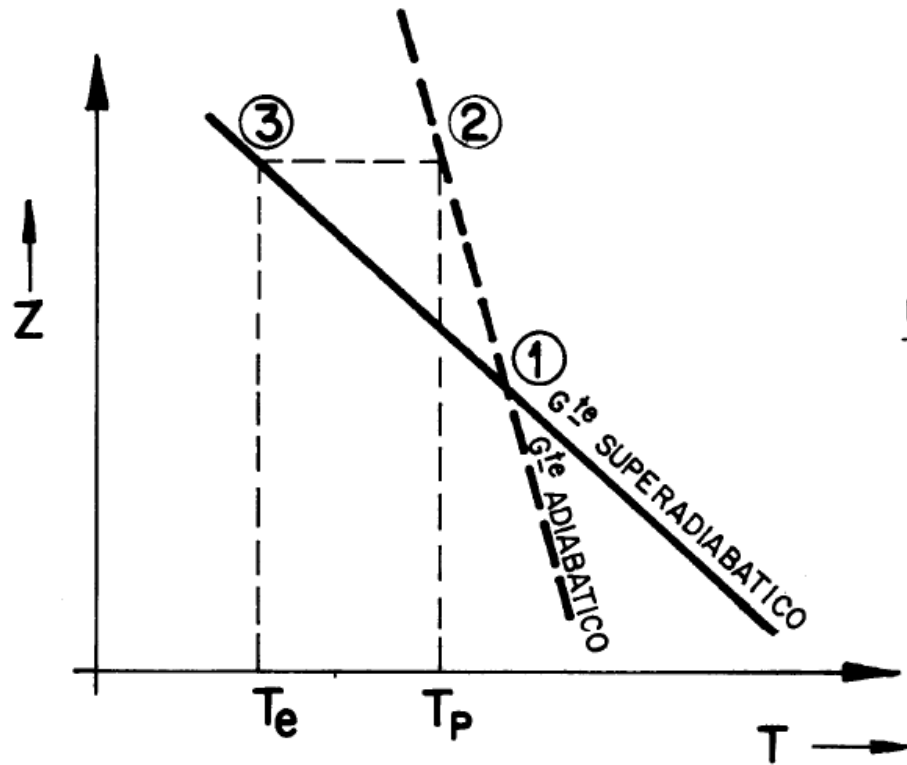


Fig. 2.19—The average diurnal variation of the vertical temperature structure at the Oak Ridge National Laboratory during the period September–October, 1950. The data were obtained from captive-balloon temperature soundings. The dashed line in each panel represents the adiabatic lapse rate. (Holland, 1953).

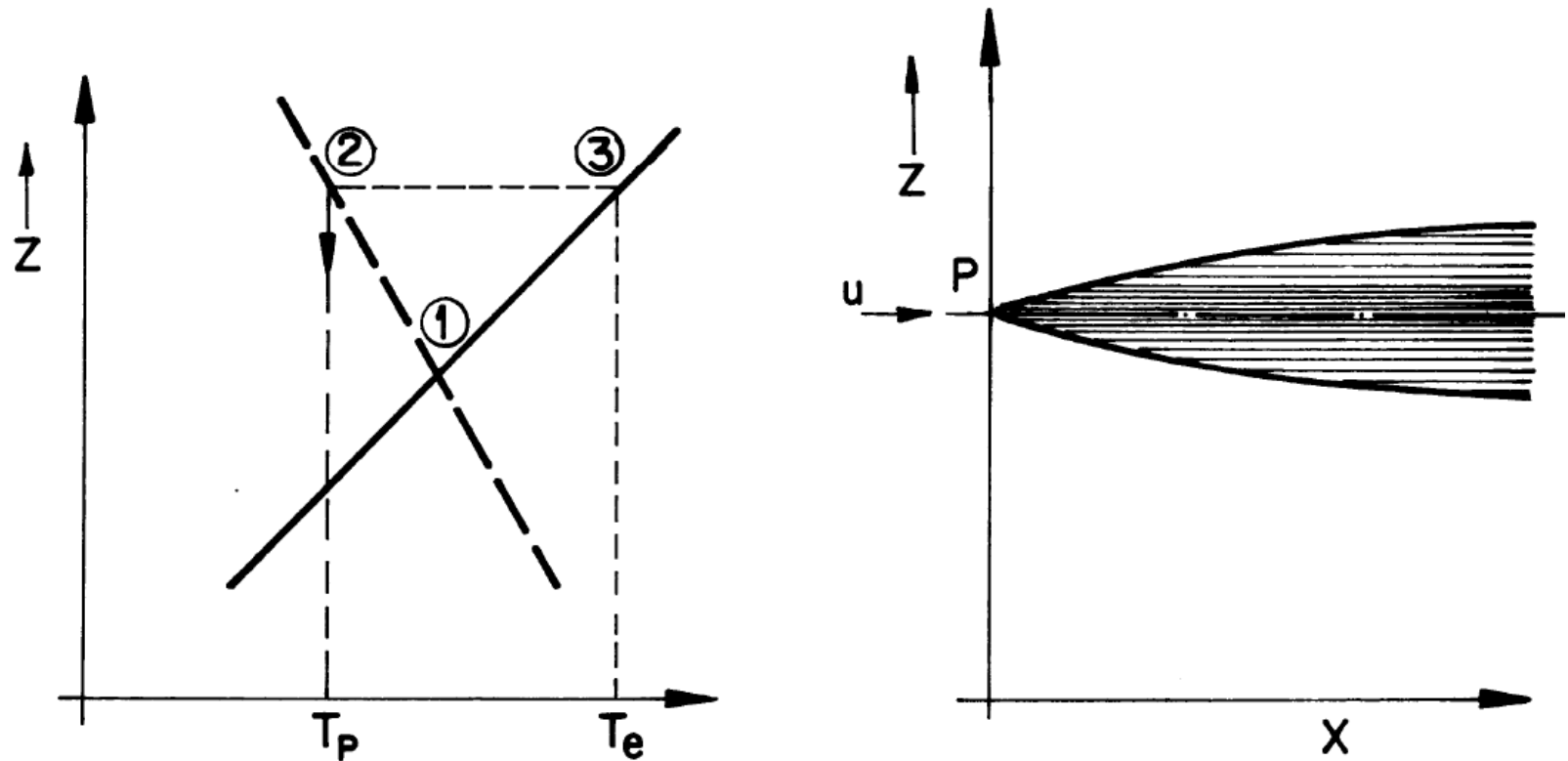
(From Slade, 1968)

Diurnal Cycle of Surface Heating /Cooling





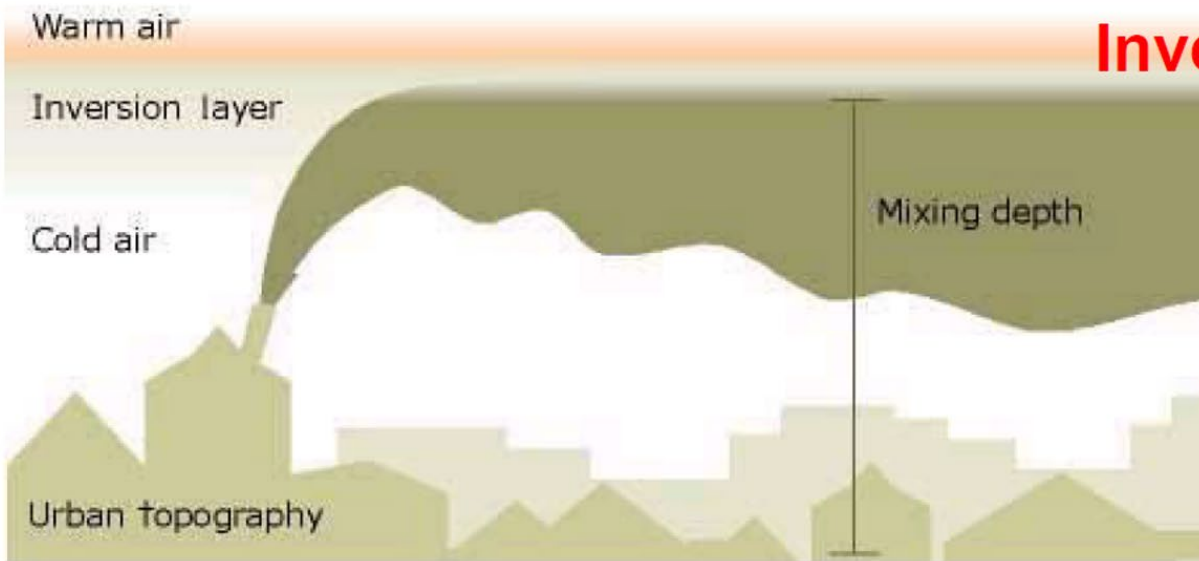
Atmospheric diffusion with a superadiabatic temperature gradient (Alonso 1978)



Atmospheric diffusion with an inversion of the temperature gradient (Alonso 1978)

Thermal inversion

- Typically occurs on cloudless nights and clear sky
- Intensified in valleys (heavier air descends to valley floor at sunset – night)
- It causes air pollutants to be “trapped” within the “**mixing layer**”



Winter inversion layer trapping smoke from home fires

www.ew.govt.nz/enviroinfo/air/weather.htm

www.co.mendocino.ca.us/aqmd/Inversions.htm

- | | | | |
|---|---------------------|---|-------------------|
| A | Extremely unstable | D | Neutral |
| B | Moderately unstable | E | Slightly stable |
| C | Slightly unstable | F | Moderately stable |

Wind speed $U(\text{m} \cdot \text{s}^{-1})$ at 10 m	Stability class, day, with insolation:			Stability class, night, with sky conditions:	
	strong	moderate	slight	thinly overcast or $\geq 4/8$ cloud cover	$\leq 3/8$ cloud cover
$U < 2$	A	A – B	B	*	*
$2 \leq U < 3$	A – B	B	C	E	F
$3 \leq U < 5$	B	B – C	C	D	E
$5 \leq U < 6$	C	C – D	D	D	D
$6 \leq U$	C	D	D	D	D

* In some Member States stability class F is extended to night time conditions with wind speed less than $2 \text{ m} \cdot \text{s}^{-1}$.

Notes: (1) 'Moderate' insolation implies the amount of incoming solar radiation when the sky is clear and the solar elevation is between 35° and 60° . The terms 'strong' and 'slight' insolation refer to solar elevations of more than 60° and less than 35° respectively.

(2) Solar elevation may be obtained for a given date, time and latitude from astronomical tables. Since cloudiness reduces insolation, it should be considered along with solar elevation in determining the Pasquill stability class. Insolation that would be 'strong' may be expected to be reduced to 'moderate' with broken middle clouds (cloud cover $5/8$ to $7/8$) and to 'slight' with broken low cloud cover.

(3) Where data from solar radiation measuring instruments are available, the values of insolation corresponding to 35° and 60° on clear days may be obtained and used as a limit in classification irrespective of cloudiness data.

(4) Neutral class D should be assumed for overcast conditions during day or night. 'Night' refers to a period from 1 hour before sunset to 1 hour after sunrise.

(5) To obtain σ_y and σ_z for (A – B), etc. use is made of the average of those for A and B, etc.

Atmospheric stability classes according to Pasquill-Gifford scheme (from IAEA, 1980)

Neutral conditions



From T. Mikkelsen, Risø

Unstable conditions



From T. Mikkelsen, Risø

Stable conditions



From T. Mikkelsen, Risø



A Extremely unstable
B Moderately unstable
C Slightly unstable

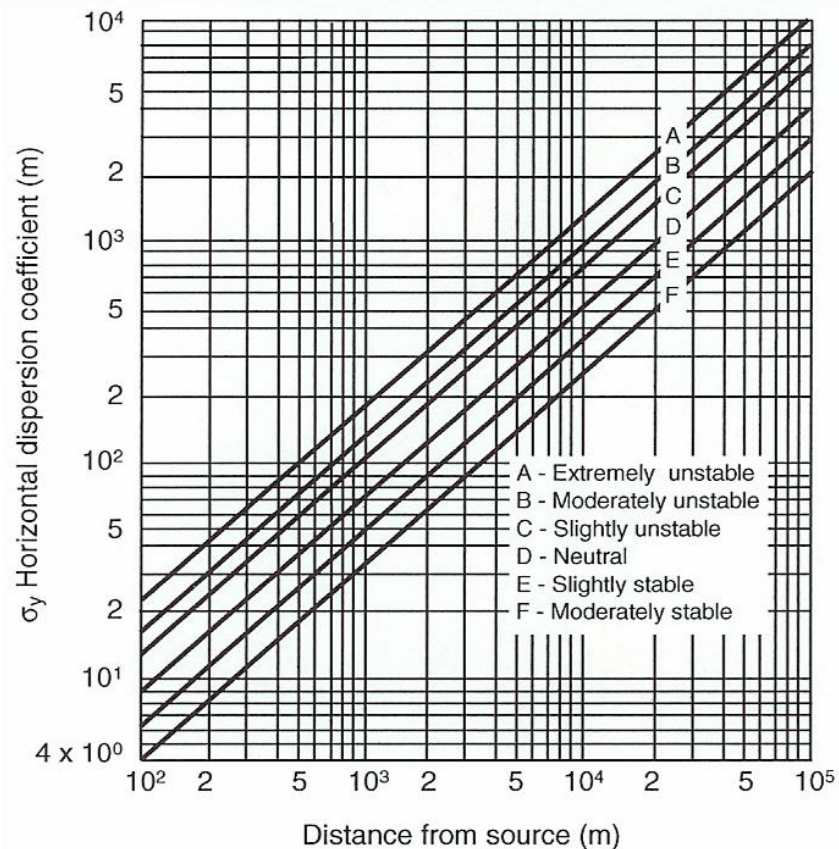
D Neutral
E Slightly stable
F Moderately stable

$\Delta T/\Delta Z$ (K/100 m)	<-1.9	-1.9 to -1.7	-1.7 to -1.5	-1.5 to -0.5	-0.5 to 1.5	>1.5
Pasquill class	A	B	C	D	E	F

Relationship between Pasquill stability class and temperature lapse rate (from IAEA, 1980)

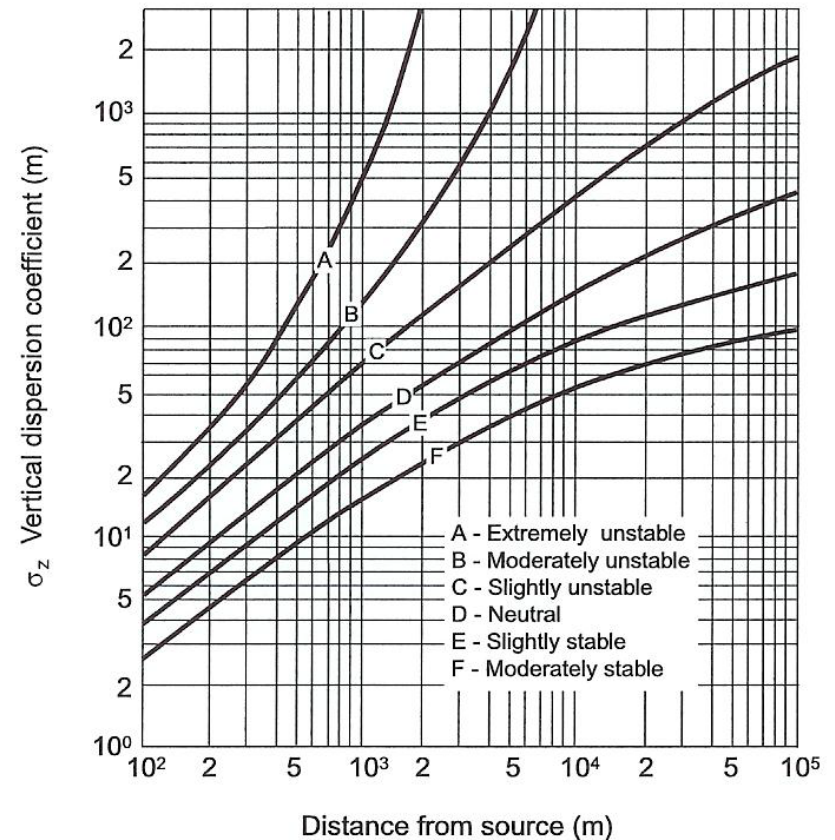
Wind speed U ($\text{m}\cdot\text{s}^{-1}$)	Stability class with $\Delta T/\Delta Z$ (K/100 m), measured between 20 m and 120 m height, of:						
	$\frac{\Delta T}{\Delta Z} \leq -1.5$	$-1.4 < \frac{\Delta T}{\Delta Z} < -1.2$	$-1.1 < \frac{\Delta T}{\Delta Z} < -0.9$	$-0.8 < \frac{\Delta T}{\Delta Z} < -0.7$	$-0.6 < \frac{\Delta T}{\Delta Z} < 0.0$	$0.1 < \frac{\Delta T}{\Delta Z} < 2.0$	$\frac{\Delta T}{\Delta Z} > 2.0$
$U < 1$	A	A	B	C	D	F	F
$1 \leq U < 2$	A	B	B	C	D	F	F
$2 \leq U < 3$	A	B	C	D	D	E	F
$3 \leq U < 5$	B	B	C	D	D	D	E
$5 \leq U < 7$	C	C	D	D	D	D	E
$7 \leq U$	D	D	D	D	D	D	D

Relationship of Pasquill stability class with temperature lapse rate and wind speed (from IAEA, 1980)



Smooth terrain
Sampling time: 3 min

Horizontal dispersion coefficient, σ_y , depending on the distance to the source, for different atmospheric stability categories (adapted from Slade, 1968).



Smooth terrain
Sampling time: 10 min

Vertical dispersion coefficient, σ_z , depending on the distance to the source, for different atmospheric stability categories (adapted from Slade, 1968).

Limitations of the ideal Gaussian atmospheric dispersion model

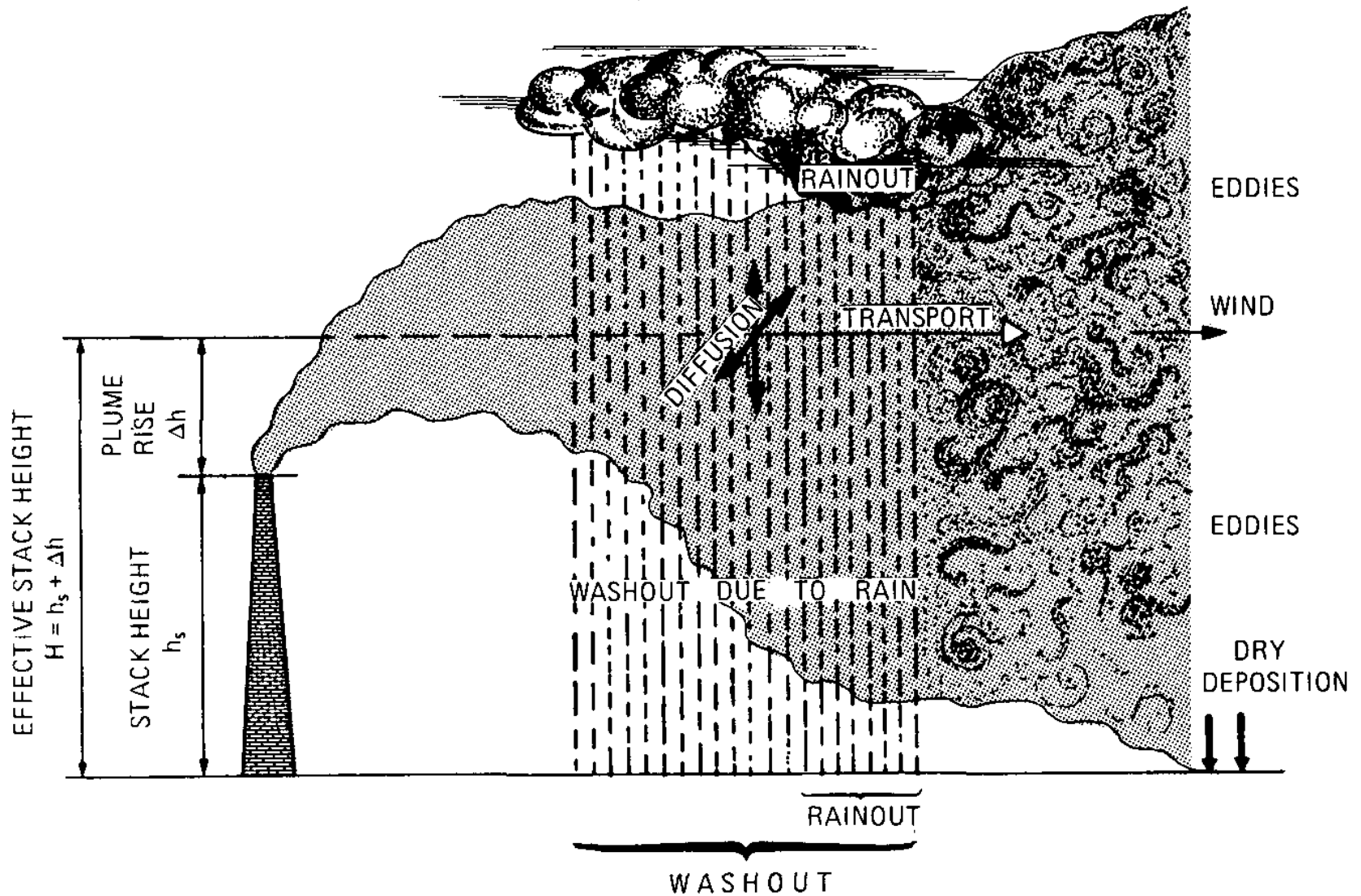
In the real atmosphere, some of the basic assumptions are never met, such as...

- the assumption of constant eddy diffusivity in time and space implicit in the derivation of the equations.
- the Pasquill-Gifford curves were really only determined for distances out to about 1 km, yet they are commonly extrapolated to 100 km.
- In practical terms, the Gaussian plume model should not be applied under conditions of
 - a) low wind speeds,
 - b) complex terrain,
 - c) spatial and temporal changes in wind velocity, or
 - d) deposition and transformation (e.g., radiological decay) within the plume during travel.

However, empirically based adjustments to the basic Gaussian plume formulation allow it to be applied in many situations in which it theoretically should not apply.

But be aware of generalizations that may be applied to conditions not specifically measured.

(Till and Grogan, 2008)



Behaviour of effluents released to the atmosphere (IAEA, 1980).

Modifications to the ideal Gaussian atmospheric dispersion model.

Situations and conditions for which modification/correction to ideal equations are needed (if possible)

1. Depletion processes

- Radioactive decay
- Dry deposition
- Washout and rainout

$$Q'(x) = Q(0) \cdot f_{\lambda} \cdot f_d \cdot f_{\Lambda}$$

2. Source

- Finite size of the source (volume sources)
- Time dependent source strength
- Plume rise (including time dependence)

3. Sampling time

4. Atmosphere

- Changing atmospheric conditions, with time (changes in wind direction speed and stability)
- Differing atmospheric conditions at different heights (fumigation, inversion cap)

5. Terrain

- Wake effects of buildings, etc.
- Effects of rough terrain
- Dispersion over water
- Complex topography
- Coastal sites

Radioactive decay (in route)

In the case of two nuclides, father and son, with decay constants λ_1 and λ_2 respectively, the correction factors to be applied to the source terms Q_1 , Q_2 , would be the following:

$$f_1\left(\frac{x}{u}\right) = \exp\left(-\lambda_1 \cdot \frac{x}{u}\right)$$

$$f_2\left(\frac{x}{u}\right) = \exp\left(-\lambda_2 \cdot \frac{x}{u}\right) + \frac{Q_1(0)}{Q_2(0)} \cdot \frac{\lambda_2}{\lambda_2 - \lambda_1} \left[\exp\left(-\lambda_1 \cdot \frac{x}{u}\right) - \exp\left(-\lambda_2 \cdot \frac{x}{u}\right) \right]$$

x is the distance travelled and $\bar{u}$ the average wind speed

$Q_1(0)$ y $Q_2(0)$ are the initial amounts released of each isotope (activity in Bq)

Depletion of the plume and contamination of ground by dry deposition of aerosols

Chamberlain (1953)

The ground contamination due to dry deposition (fallout processes) is nearly proportional to the activity concentration in air near ground, where the proportionality constant is the so-called deposition velocity, v_d

The material flow to the surface, or precipitation rate $\bar{F}(x,y)$, is assumed to be proportional to the concentration in air at a certain reference height, z_d , above the point,

$$\bar{F}(x, y) = v_d \cdot \chi(x, y, z_d) ,$$

Normally, the concentration at ground level is considered ($z_d=0$).

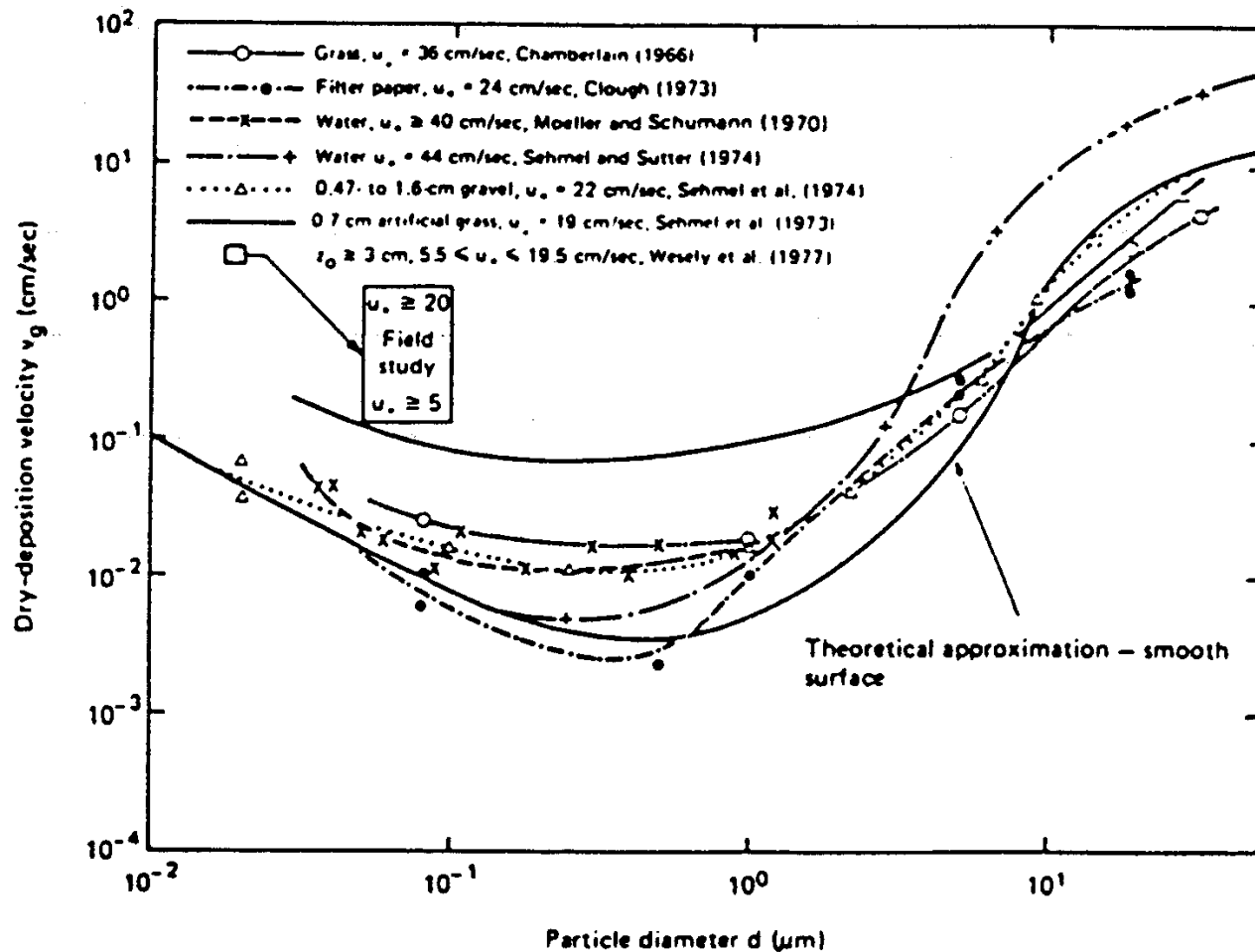
Then, the amount deposited at the point will be $w_d(x,y)$

$$\omega_d(x, y) = v_d \cdot \bar{\chi}(x, y, 0) ,$$

For effluents from nuclear facilities, the following best estimates of the **deposition velocity**, based on experimental data may be adequate (Brenk et al, 1983):

- 10^{-2} m/s for reactive gases such as elemental molecular iodine,
- 10^{-4} m/s for relatively unreactive gases such as organic iodine
- 10^{-3} m/s for aerosols ($\approx 1 \mu\text{m}$ in diameter).

The proportionality constant, v_d , has the dimensions of a velocity and is called the *precipitation rate or deposition velocity*. It is determined experimentally by measuring the integrated concentration χ , and the ground contamination after the passage of a contaminating cloud



Dry deposition velocity based on particle size for different surfaces, obtained experimentally by various authors (NRC, 1983).

Using the expression of the Gaussian plume model for concentration at ground level, when emitted through an elevated point, the amount deposited will be given by

$$\omega_d(x, y) = \frac{v_d \cdot Q'(x)}{\pi \sigma_y \sigma_z u} \exp\left(\frac{-y^2}{2\sigma_y^2} - \frac{h^2}{2\sigma_z^2}\right)$$

The depletion rate per unit distance travelled is obtained by integrating the previous equation along y :

$$\frac{\partial Q'(x)}{\partial x} = -\left(\frac{2}{\pi}\right)^{1/2} \frac{v_d Q'(x)}{u \sigma_z} \cdot \exp\left(-\frac{h^2}{2\sigma_z^2}\right) ;$$

Reordering and integrating with respect to x :

$$\int_0^x \frac{dQ'(x)}{Q'(x)} = -\left(\frac{2}{\pi}\right)^{1/2} \cdot \frac{v_d}{u} \cdot \int_0^x \frac{dx'}{\sigma_z(x') \cdot \exp\left[\frac{h^2}{2\sigma_z^2(x')}\right]}$$

Correction factor to be applied to the source term, to assess its depletion by dry precipitation

$$f_d = \frac{Q'(x)}{Q(0)} = \exp\left\{-\left(\frac{2}{\pi}\right)^{1/2} \frac{v_d}{u} \int_0^x \frac{dx'}{\sigma_z(x')} \exp\left(-\frac{h^2}{2\sigma_z^2(x')}\right)\right\}$$

Depletion of the plume and contamination of ground by wet deposition

The washout rate is a function of rain drop size, rain drop-size distribution, and the physico-chemical attributes of the plume.

Particle drag rate per unit volume → proportional to its concentration
Chamberlain (1953)

$$\frac{d\chi}{dt} = -\Lambda \chi$$

Washout coefficient, Λ (s^{-1})

Depletion ratio by wet deposition: $\frac{\chi}{\chi_0} = \exp(-\Lambda t)$

$$f_{\Lambda} = \frac{\chi}{\chi_0} = \exp\left(-\Lambda \frac{(x - x_1)}{u}\right)$$

Ground contamination due to the washout caused by precipitations :

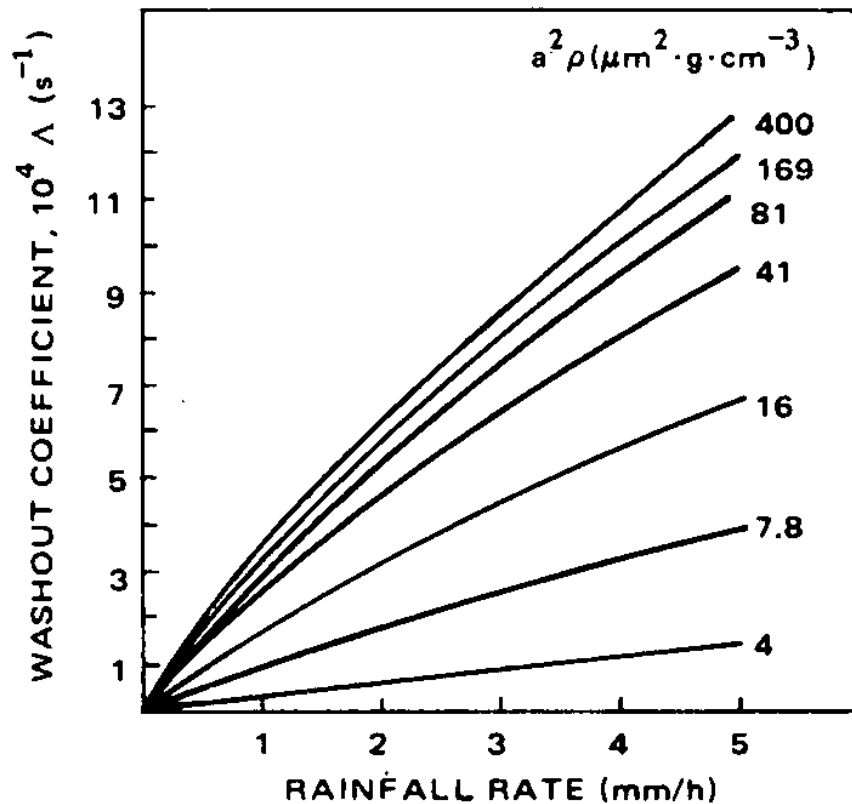
$$\omega_p(x, y) = \Lambda \int_0^z \chi(x, y, z) dz$$

Washout coefficient, Λ (s^{-1})
(Brenk and Vogt, 1983)

$$\Lambda = 8 \cdot 10^{-5} J^{0.6} \text{ for } I_2,$$

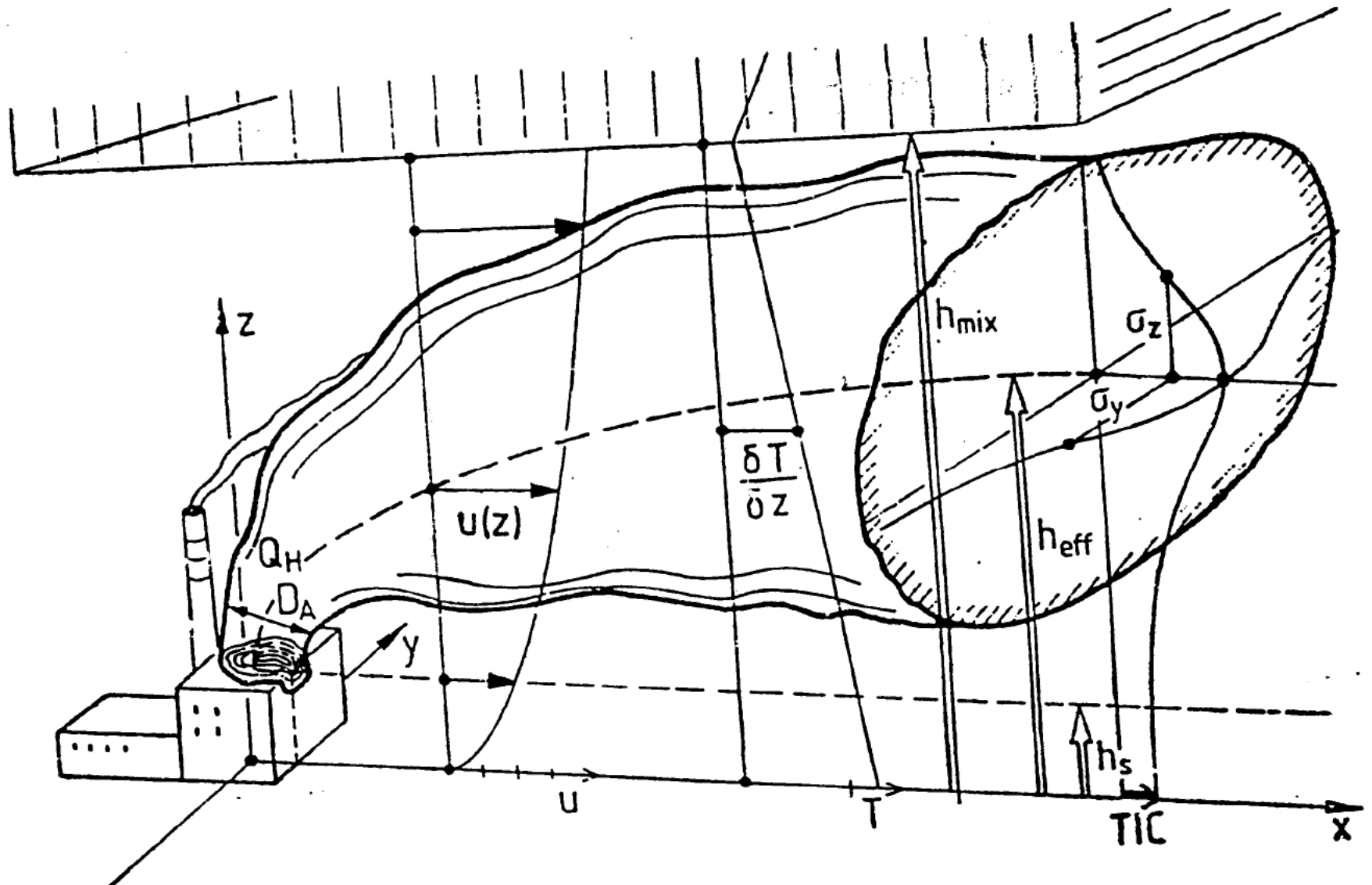
$$\Lambda = 1,2 \cdot 10^{-4} J^{0.5} \text{ for aerosols,}$$

J, rainfall rate in mm/h



Washout coefficients for unit density particles versus rainfall rate and $a^2 p$, where a is the particle radius and p is the density of particle material. (IAEA, 1980)

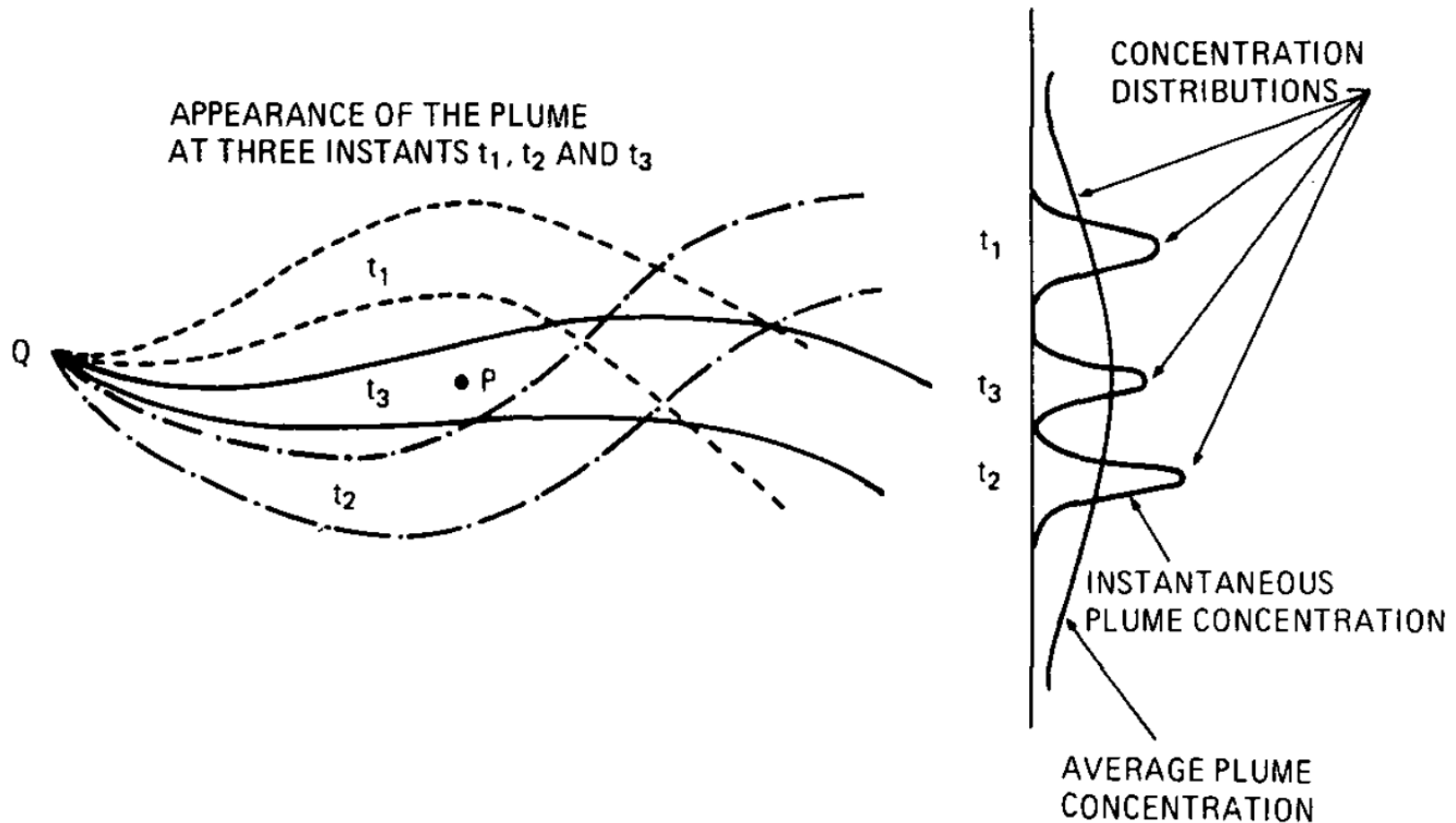
Effects that affect atmospheric dispersion



Calm (very small wind speed) situations

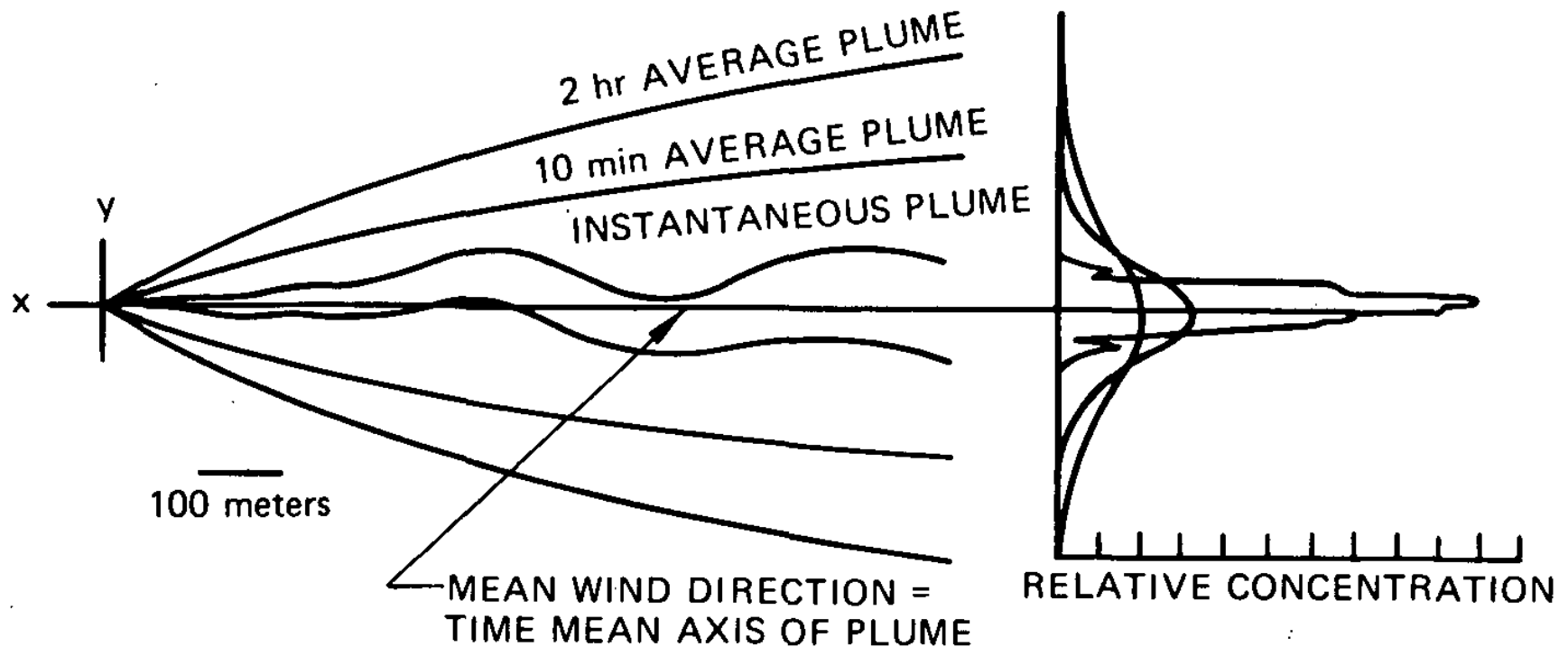
- ❑ The direct application of the Gaussian model for very small values of u would lead to predicting very high concentration values, since the wind speed is in the denominator of the model equations.
- ❑ However, reality indicates that the existing dispersion is much greater, and that the concentration does not grow so much.
- ❑ A simple recommendation [IAEA guide, 1980]: **to multiply the original value of σ_y by a factor 4**, as long as the observed wind speed is less than 2 m/s.
- ❑ If the release is of long duration, it is preferable **to assume a uniform dispersion** within the sector covered by the observed wind directions.

Release duration & sampling time vs. Instantaneous sampling



Instantaneous and average plumes. The figure shows the effect of sampling time on concentration. Note: for short sampling times the resulting concentrations are similar to the instantaneous values; for larger sampling times they are similar to the average values. Q is the source; P is the receptor point. (IAEA, 1980).

Release duration vs. Instantaneous plume



Instantaneous and average plumes. The diagram on the left represents the approximate outlines of a smoke plume observed instantaneously and of plumes averaged over 10 min and 2 h. The diagram on the right shows the corresponding cross-plume distribution patterns (Slade, 1968).

Dispersion sampling time examples

Sample time =
1/50 sec.

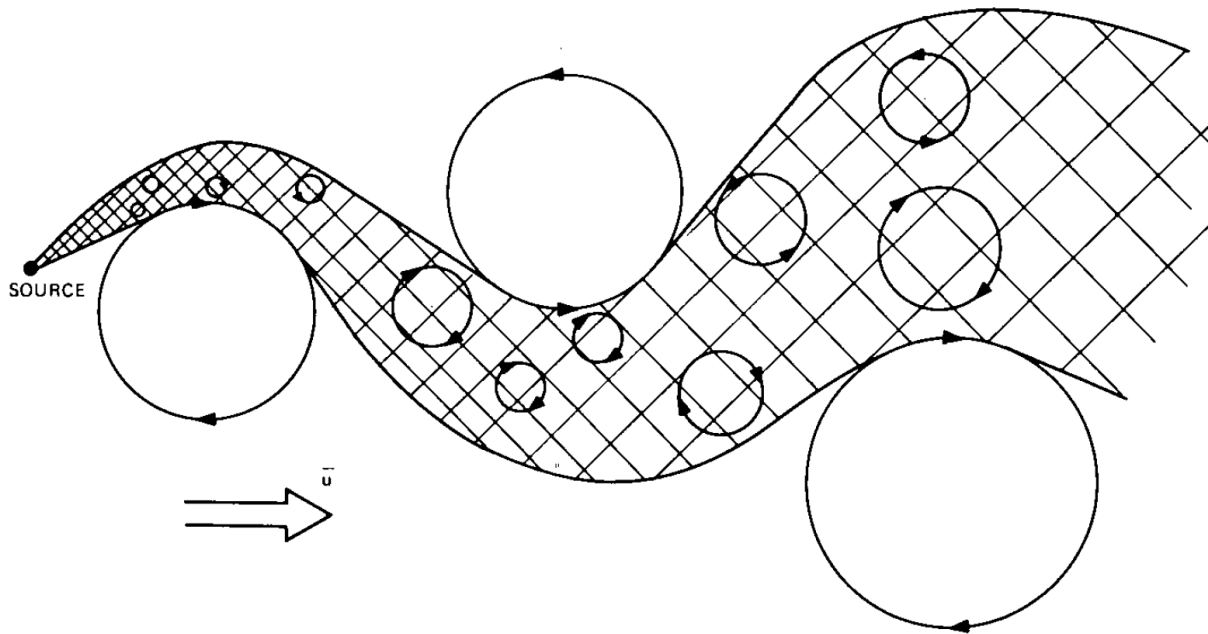


Sample time =
5 min.



From Culkowski W.M., 1961,
Time Exposure Photography
of Smoke Plumes
USAEC Report ORO-359,
Oak Ridge

(From Slade, 1968)



Eddies that are larger than the plume tend to cause the plume to meander, whereas those that are smaller tend to tear it apart (Till & Meyer, 1983).

$$\sigma_{yd} = \sigma_{yr} \left(\frac{T_d}{T_r} \right)^b$$

$b = 0,2$ for
 $b = 0,25$ for
 $T_r = 3 \text{ min.}$

$3 \text{ min.} < T_d < 1 \text{ h}$
 $1 \text{ h} < T_d < 10 \text{ h}$

Alternative: puffs of fixed duration, superimposed (see next slide)

Sequential Gaussian puff trajectory model

Fundamental assumptions:

- (1) a plume may be represented by a sequence of puffs and
- (2) puff movement can be considered separately from puff diffusion.

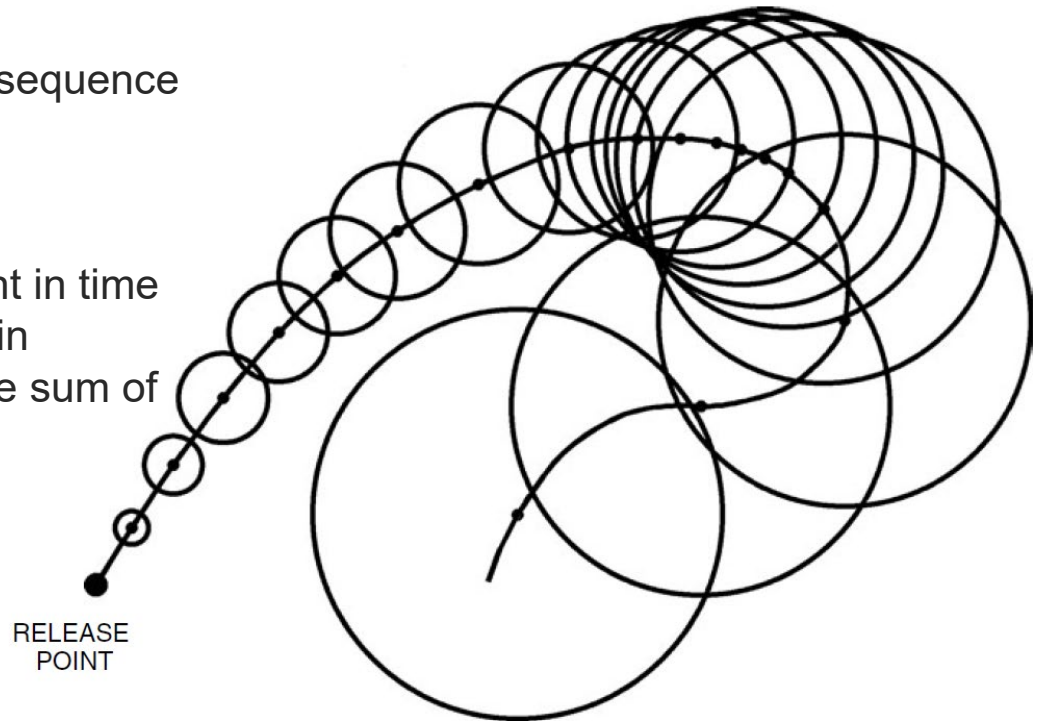
The air concentration at any given point in time and space over the assessment domain (x, y, z, t) is assumed to be equal to the sum of the concentrations from all of the puffs at that location.

$$\chi(x, y, z, t) = \sum_{i=1}^N \chi_i(x, y, z, t),$$

where

i = puff number

N = total number of puffs



Simulation of a plume composed of a series of puffs released at equal time intervals and $\sigma \propto t$ (Hanna et al. 1982).

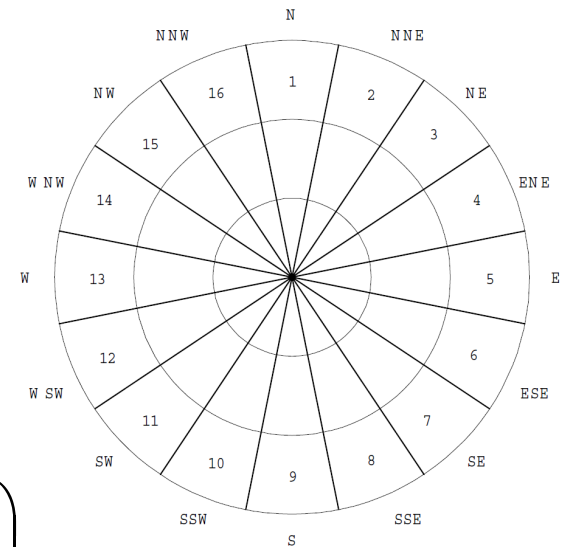
Long-term (or chronic) releases

Averaging lateral dispersion within each sector of the polar grid:

$$\left(\frac{\bar{\chi}}{\bar{\dot{Q}}} \right) = \frac{1}{\frac{2\pi}{n} x} \int_{-\infty}^{\infty} \left(\frac{\chi}{\dot{Q}} \right) \cdot dy = \frac{n}{\sqrt{2\pi} \pi x \bar{u} \sigma_z} \exp \left(-\frac{h^2}{2\sigma_z^2} \right).$$

If n equals 16, which corresponds to an angle of variability of 22.5° , which is considered acceptable for many practical applications, then the above expression becomes:

$$\left(\frac{\bar{\chi}}{\bar{\dot{Q}}} \right) = \frac{2,032}{x \bar{u} \sigma_z} \exp \left(-\frac{h^2}{2\sigma_z^2} \right),$$



Long-term (or chronic) releases

$$\left(\frac{\bar{\chi}}{\bar{Q}} \right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left(\frac{\chi}{Q} \right) \cdot dy = \frac{n}{\sqrt{2\pi} \pi x \bar{u} \sigma_z} \exp \left(-\frac{h^2}{2\sigma_z^2} \right).$$

- The previous models for atmospheric dispersion and deposition are applicable when the atmospheric stability, wind speed and direction and rain condition can be assumed to remain constant during the release period.
- This assumption is not applicable when calculating annual average concentrations, and then it is necessary to perform an averaging of the resulting dispersion factors or concentrations taking into account the frequencies of each atmospheric condition.

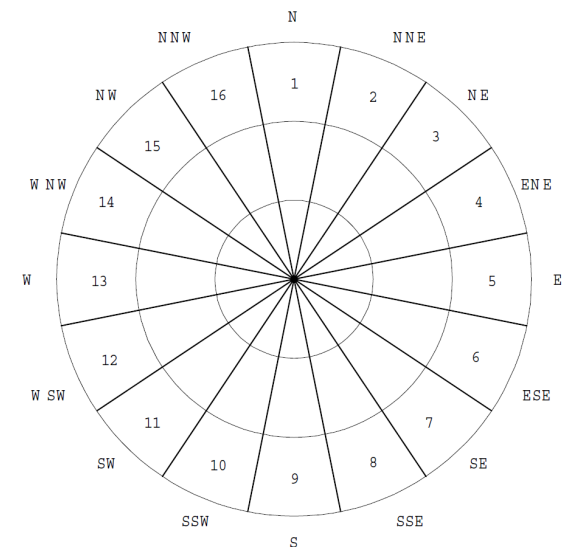
$$\left(\frac{\chi}{Q} \right)_j (x, z) = \sum_j f_{j,s,w,r} \cdot \left(\frac{\chi}{Q} \right)_{j,s,w,r} (x, z)$$

j is the sector of the polar grid

s is the stability class

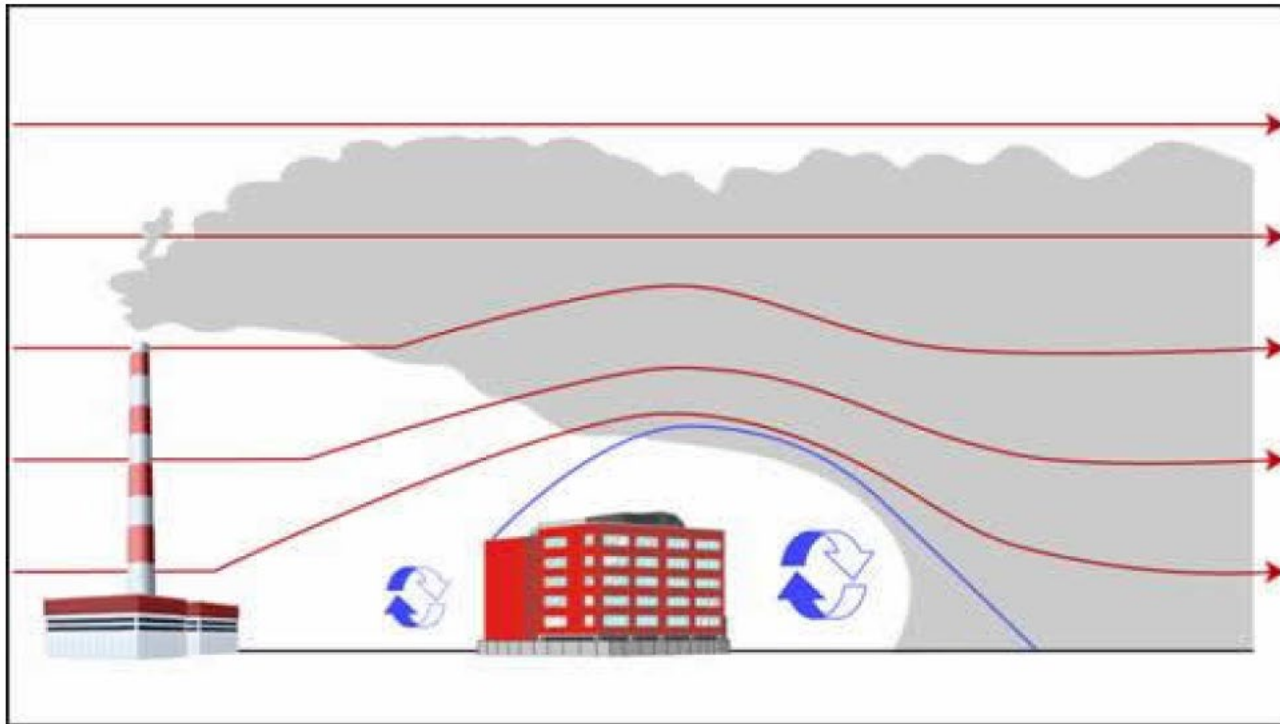
w is the wind speed class

r is the rain condition



Building wake effects

Plume Air Pollutant Building Downwash



Building wake effects

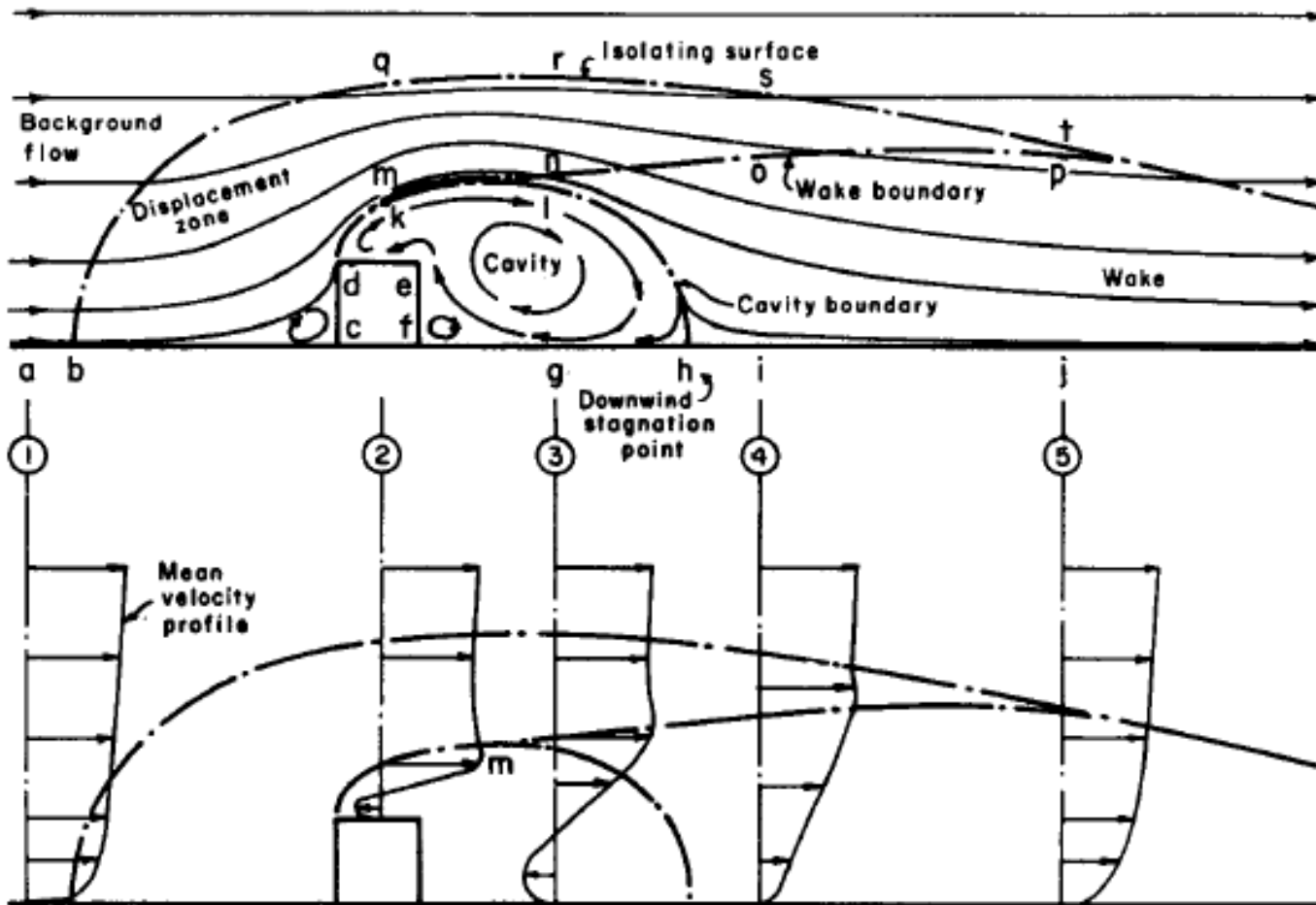


Fig. 5.17 — General arrangement of flow zones near a sharp-edged building.

Building wake effects

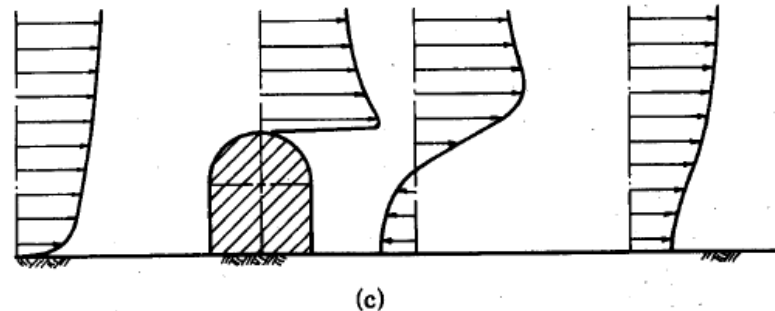
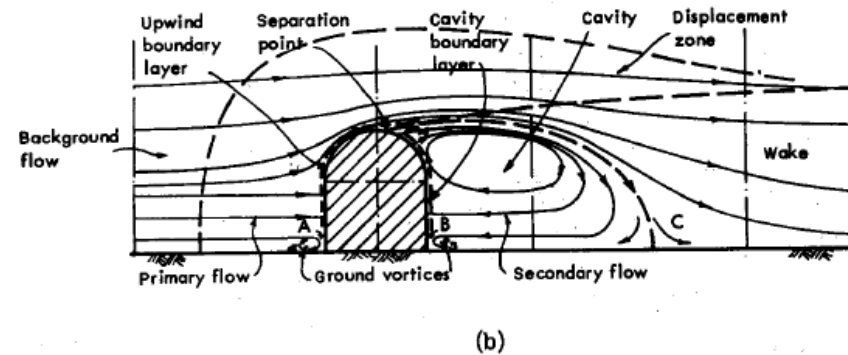
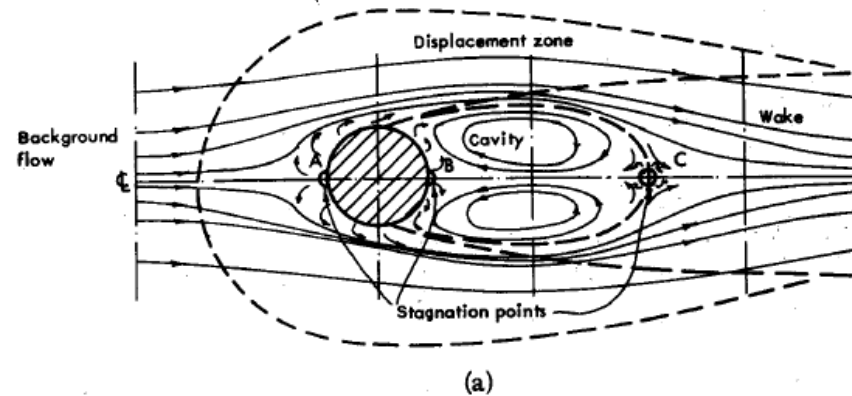
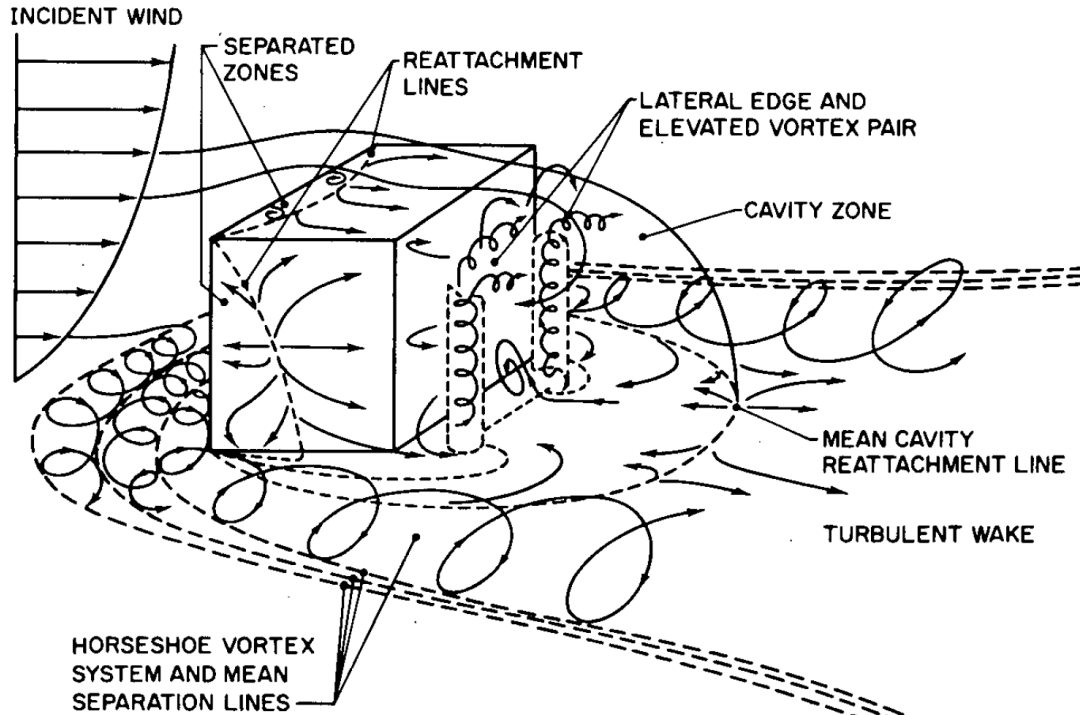


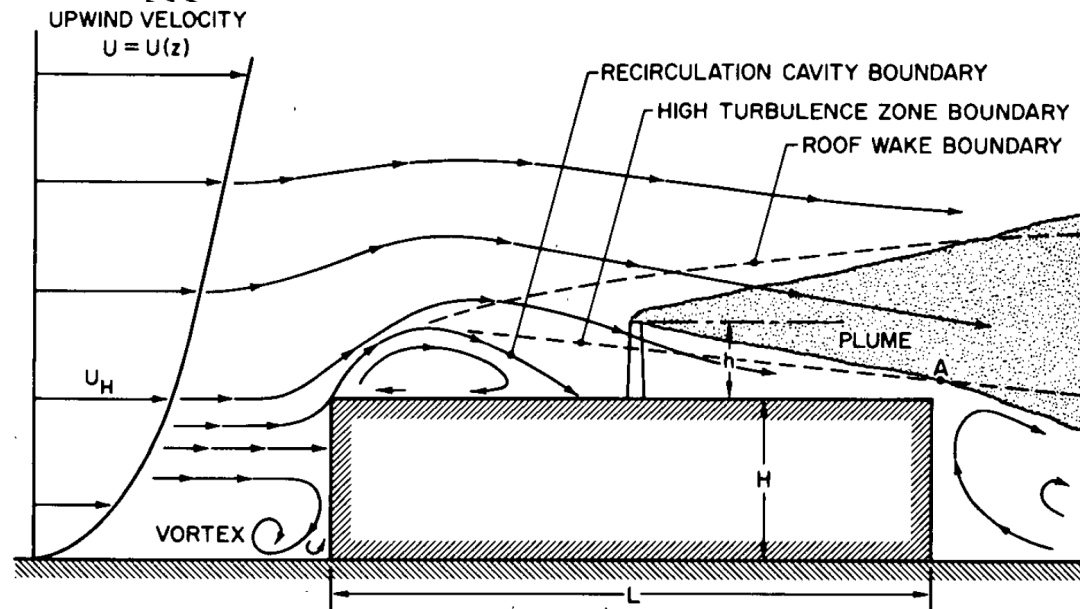
Fig. 5.22 — Flow around a rounded building. (a) Flow in a horizontal plane near the ground. (b) Flow in the longitudinal center plane. (c) Velocity profiles in the longitudinal center plane. (From Halitsky, Golden, Halpern, and Wu, 1963.)

Building wake effects



Model of flow near a sharp-edged building normal to a deep boundary layer wind (Hosker 1979)

Flow over center of a long, flat building roof for wind upwind face. (Wilson 1979).



(From Till and Meyer, 1983)

[Building wake effect (volume source)]

The most common form of the Gaussian model to consider the effect of building wakes for short-term plume centerline calculations is to replace the denominator of the Gaussian model by

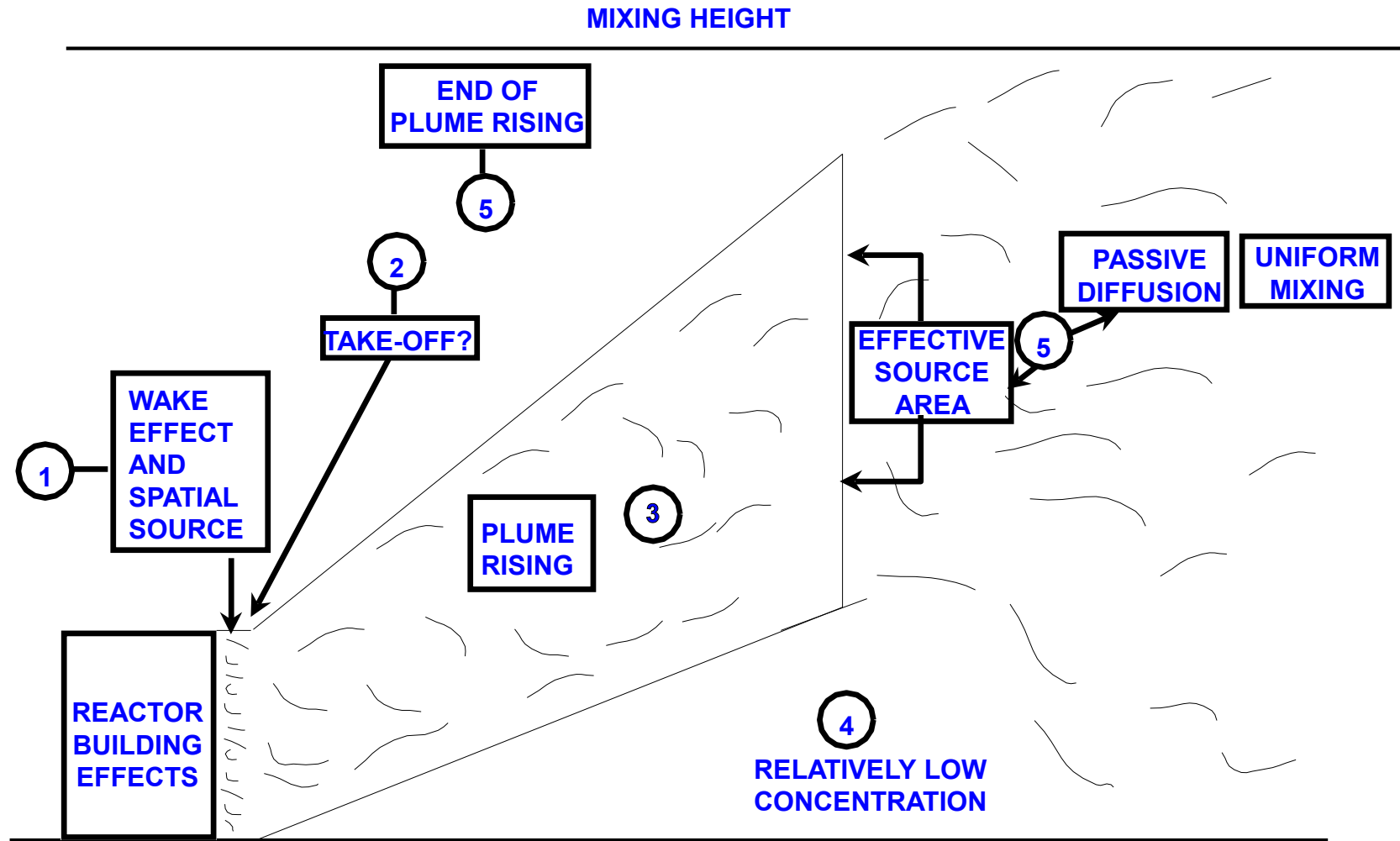
$$[\pi \sigma_y(x) \sigma_z(x) + C \cdot A] \bar{u}$$

where

A = cross-sectional area of the building normal to the flow, and
 C = "shape factor" to represent the fraction of A over which the plume is dispersed; $C = 0.5$ is a conservative value which is commonly used.

(IAEA, 1980)

Plume rise effects



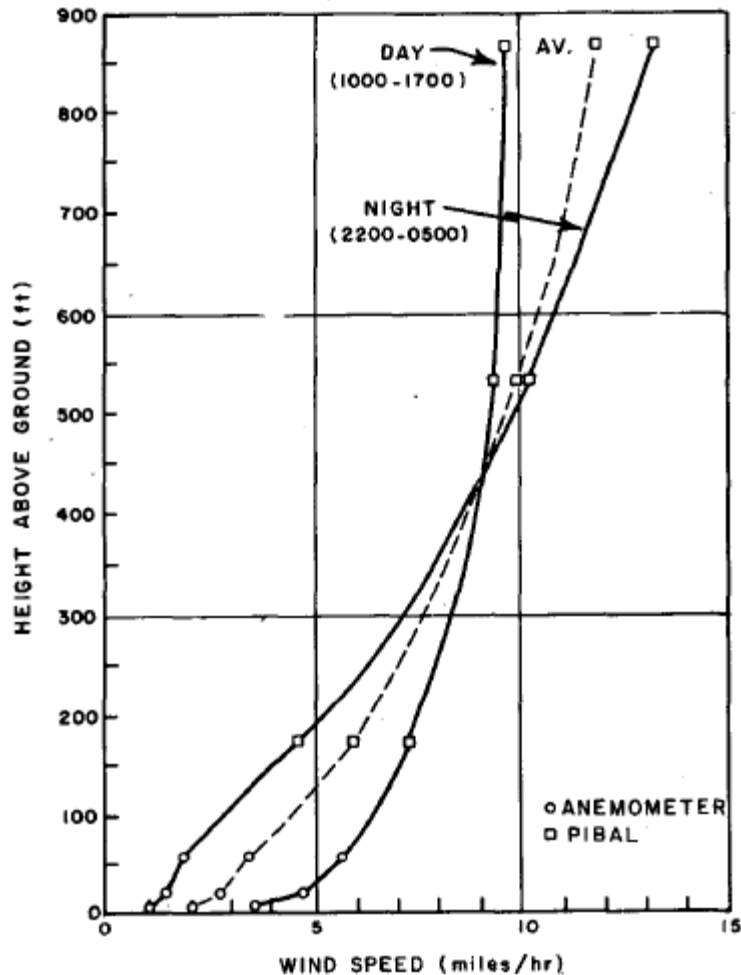
Rise effects of a hot plume (CSNI, 1983).

Plume rise

- Briggs models^(*):
 - Take-off Criteria
 - Trajectory
 - Maximum height of the plume axis

^(*)Briggs, G.A. 1984. "Plume Rise and Buoyancy Effects." In *Atmospheric Science and Power Production*, ed. D. Randerson. DOE/TIC-27601. U.S. Department of Energy, Office of Scientific and Technical Information, Technical Information Center, Oak Ridge, TN. Pages 327–3

Plume rise and wind speed increase



- Increase in wind speed with height.

$$\bar{u} = \bar{u}_{10} \cdot \left(\frac{h}{10} \right)^{P(i)}$$

For example, for rural land, the values of $P(i)$ would be, for each stability category:

- A- 0,07;
- B- 0,07;
- C- 0,10;
- D- 0,15;
- E-0,35;
- F- 0,55

Fig. 2.24—Average wind-speed profiles constructed from measurements made during a 1-year period at the Oak Ridge National Laboratory. (Holland, 1953)

]

Mixing heights change diurnally and seasonally, generally being largest on summer afternoons and least on autumn mornings.

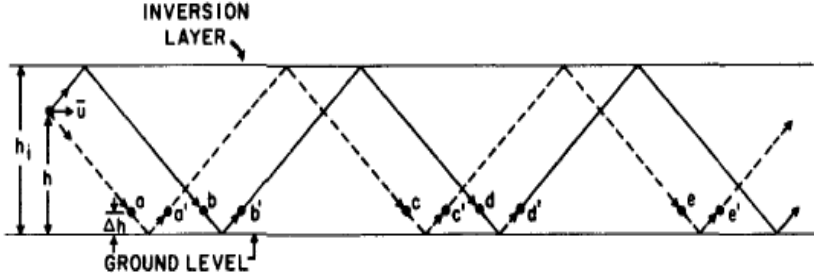


Fig. 7.17—Schematic drawing of the reference system used in the calculational model for the cloud concentration under a capping inversion.

$$\chi(x, y, z) = \frac{Q \cdot \exp(-y^2 / 2 \sigma_y^2)}{2 \pi u \sigma_z \sigma_y} \cdot S(h, z, Hm)$$

$$S(h, z, H_m) = \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+2H_m+h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+2H_m-h)^2}{2\sigma_z^2}\right] + \dots$$

Alternatively:

$$\chi(x, y, z) = \frac{Q \cdot \exp(-y^2 / 2\sigma_y^2)}{\sqrt{2\pi} \sigma_y u H_m}$$

Valid whenever it gives a higher concentration value, or when $\sigma_z = H_m$

Surface roughness

Surface roughness increases turbulence above ground → Pasquill experiments were performed on smooth terrain.

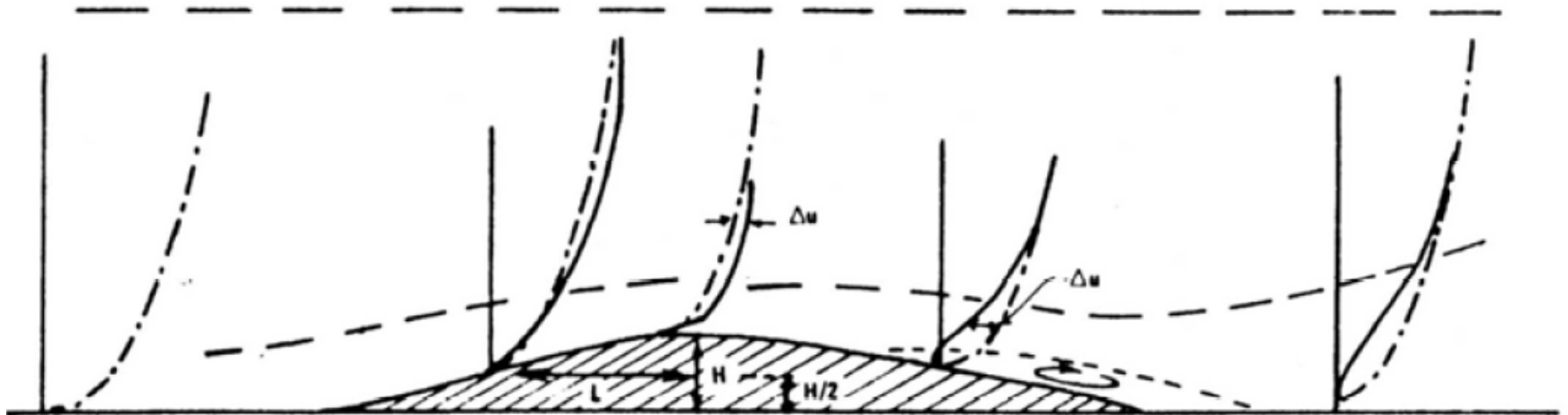
Correction in σ_z values:

$$\sigma_{zr} = \sigma_z \left(\frac{z_0}{z_r} \right)^{0,2}$$

Table 3.1 Representative values of surface roughness length, z_0 , for different types of surfaces (Randerson 1984)

Type of surface	z_0 (cm)
Very smooth (ice, mud flats)	0.001
Smooth sand	0.01
Grass lawn up to 1 cm high	0.1
Grass lawn up to 5 cm high	1.0
Thin grass up to 50 cm high	5.0
Thick grass up to 50 cm high	10.0
Woodland forest	20.0
Urban areas	100–300

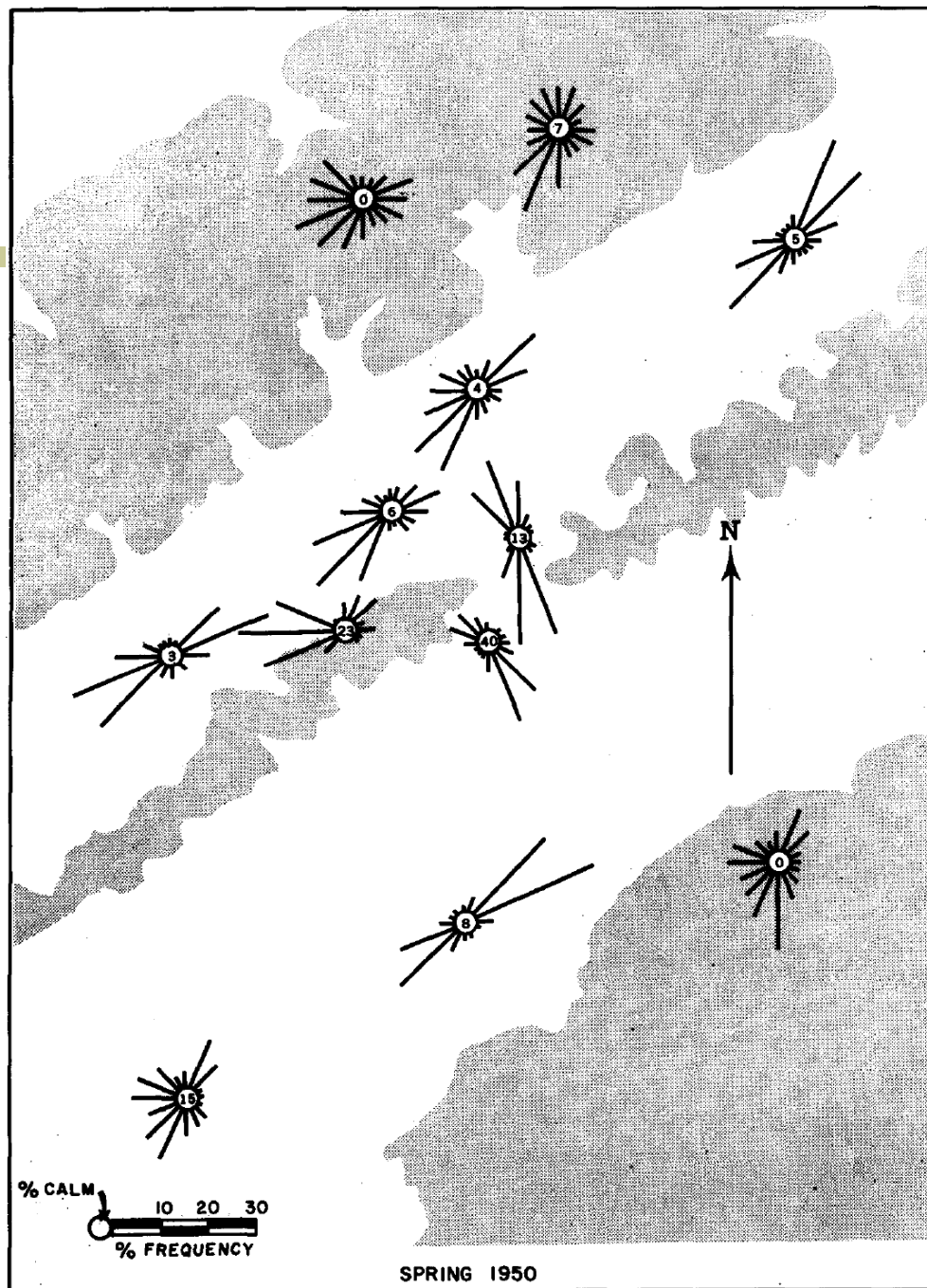
Effects of orography



*Example of acceleration and slowdown of wind speed when passing a soft hill
(Witteck, 1985)*

$$\frac{\Delta u}{u} = \frac{2h}{L}$$

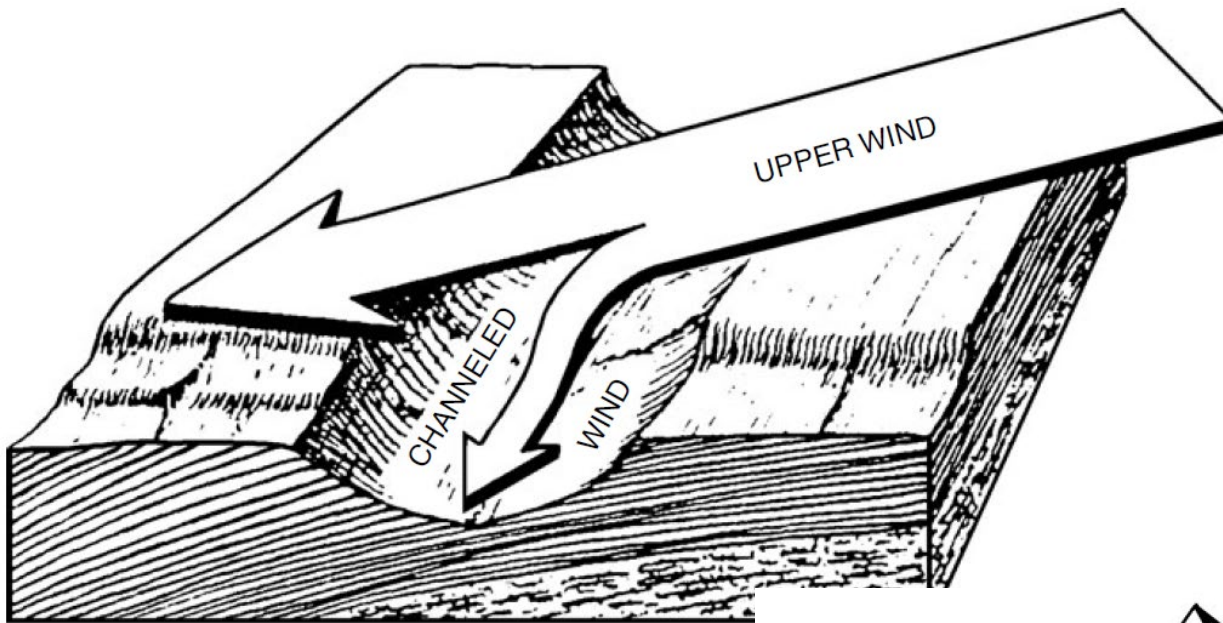
Effects of orography



Map of the hilly area about the Oak Ridge National Laboratory showing the wind flow in this region by means of massed wind roses. The shaded areas represent elevated terrain.

(Slade, 1968).

Effects of orography

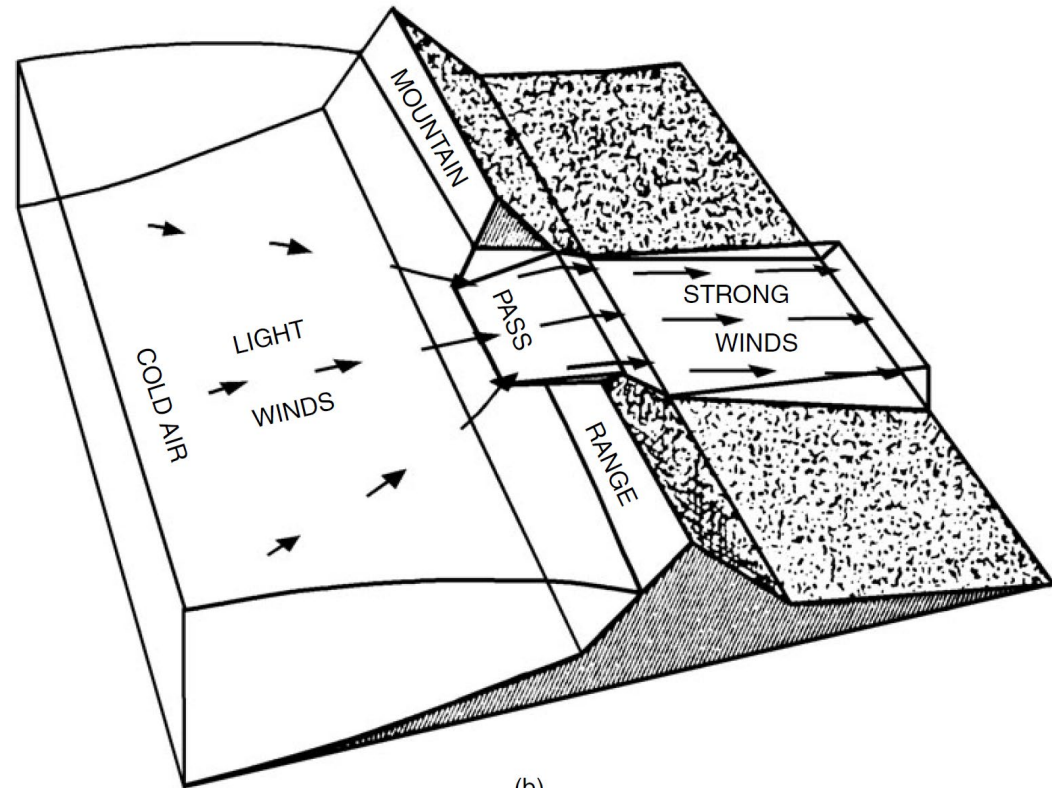


(a)

Distortion of the wind flow by topographic obstacles.

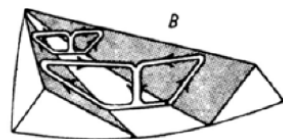
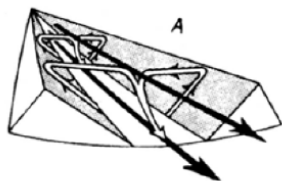
(a) Channeling of the wind by a valley.

(b) The effect of a mountain pass on the wind flow

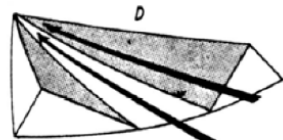
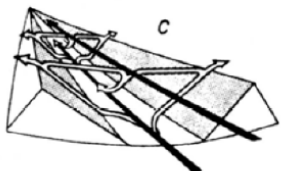


(b)

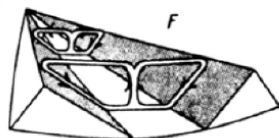
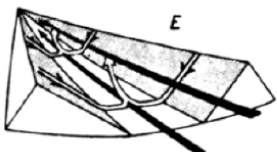
(Slade 1968)



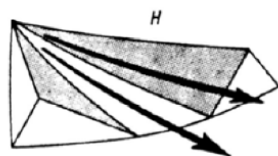
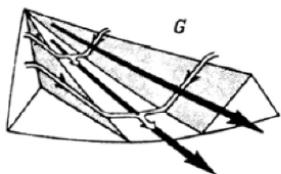
After sunrise



At noon



At sunset



At midnight

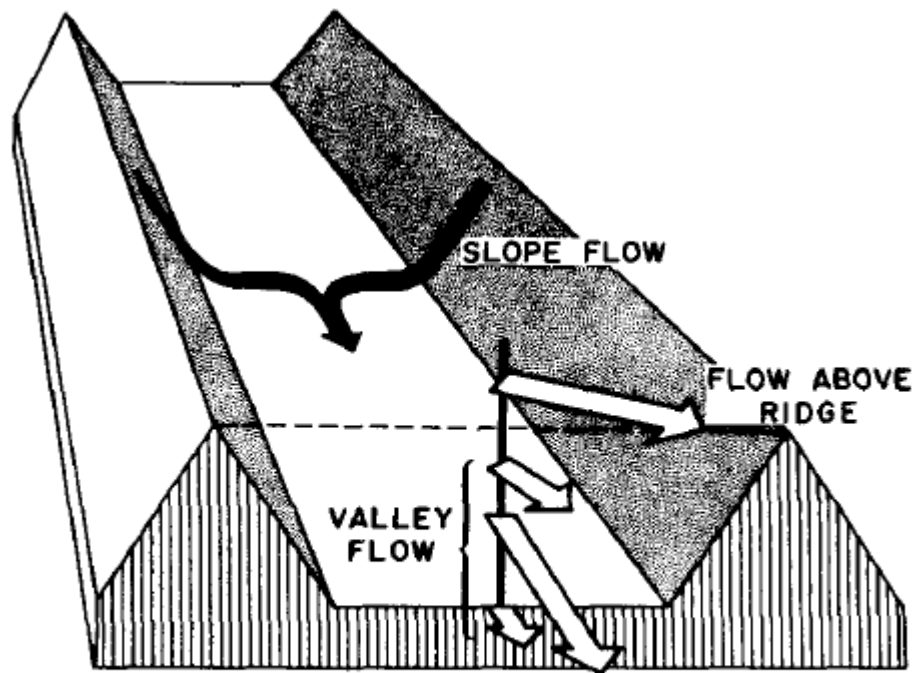
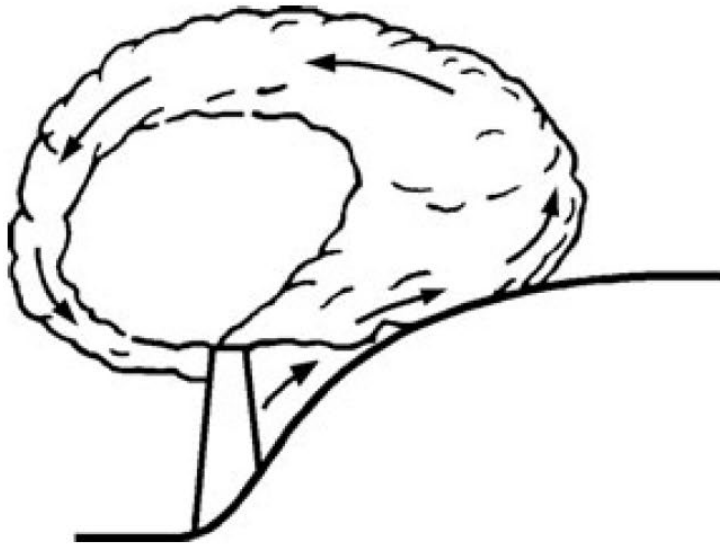


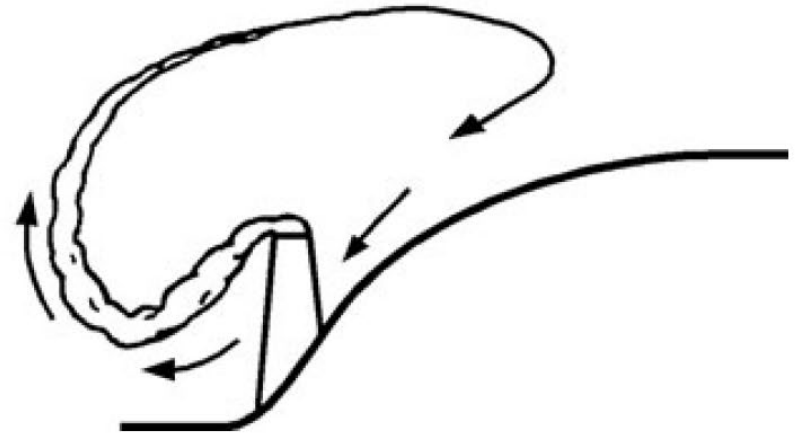
Fig. 2.9 — Idealized representation of the circulation that might be expected in a typical valley on a clear night.

Air currents on the slopes and bottom of a valley during daytime periods (Witteck, 1985).

Effects of orography



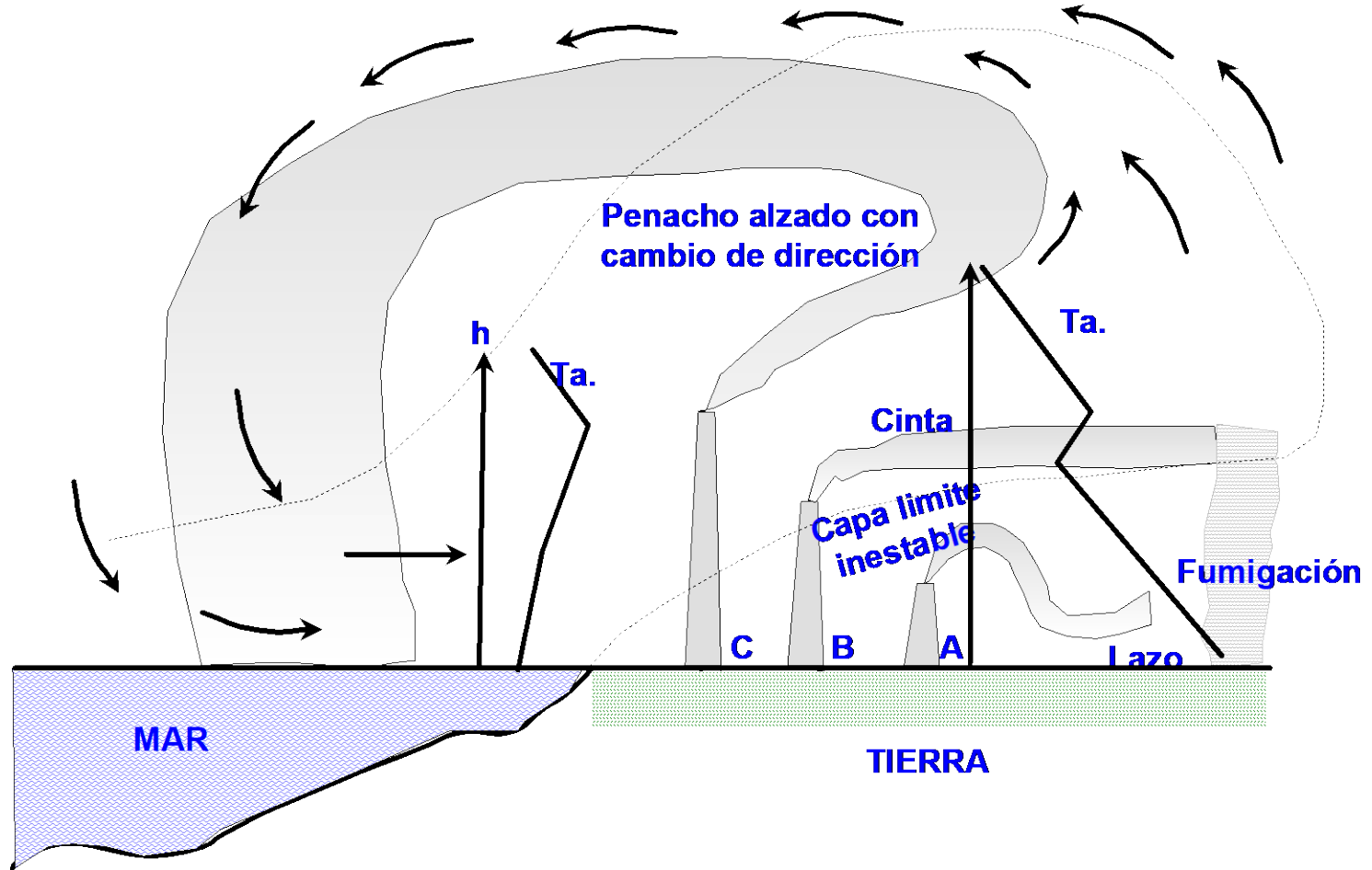
VALLEY BREEZE (daytime)



MOUNTAIN BREEZE (nighttime)

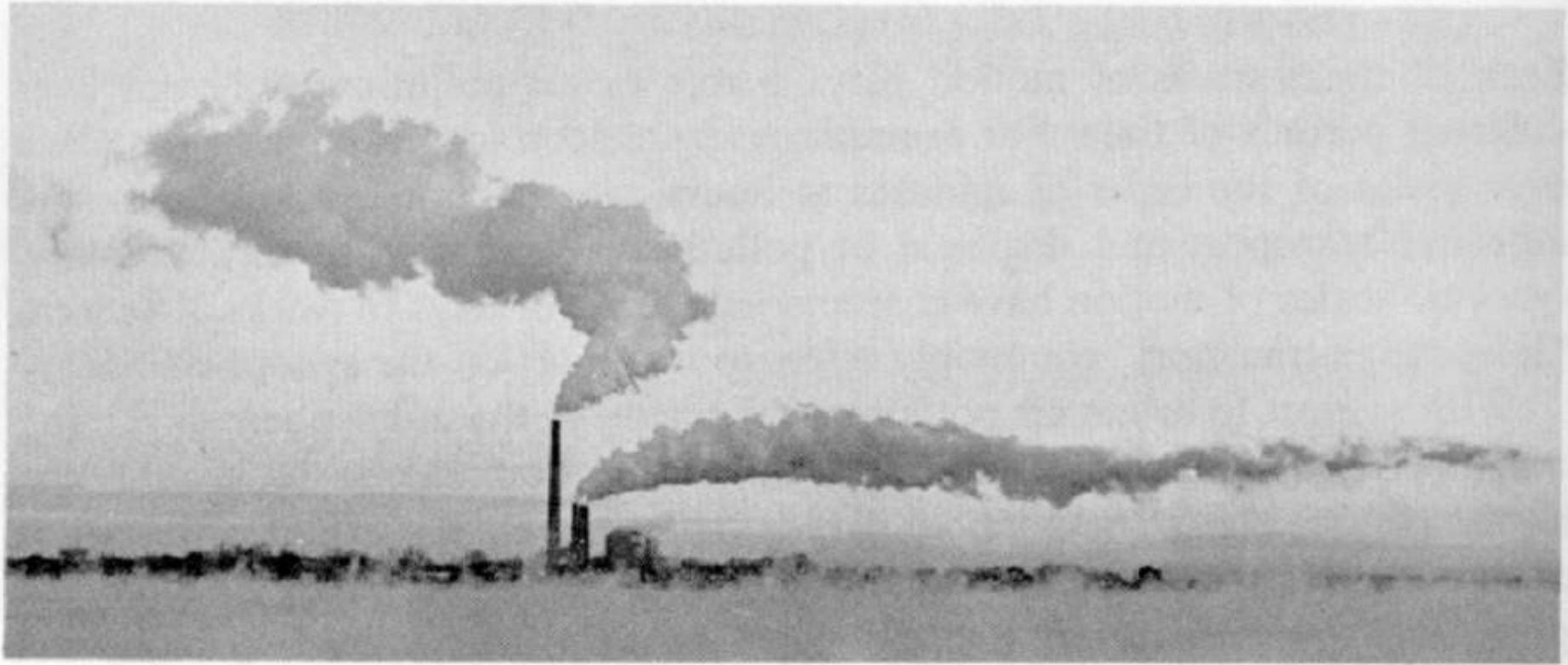
Effect of mountain valley breezes. From Pendergast (1984)

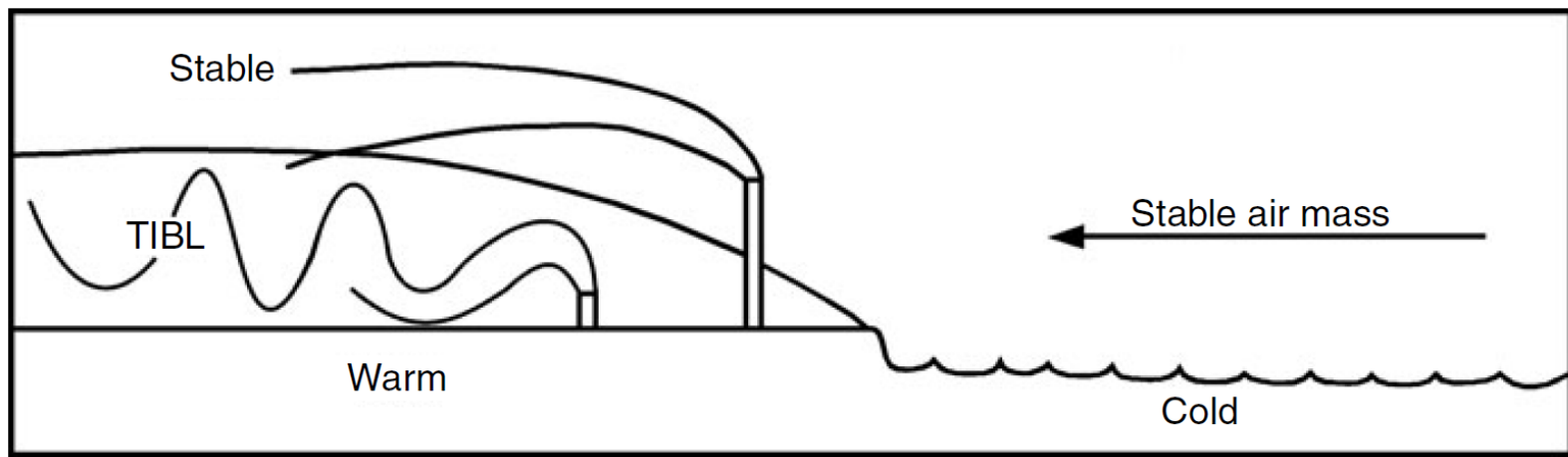
Coastal sites



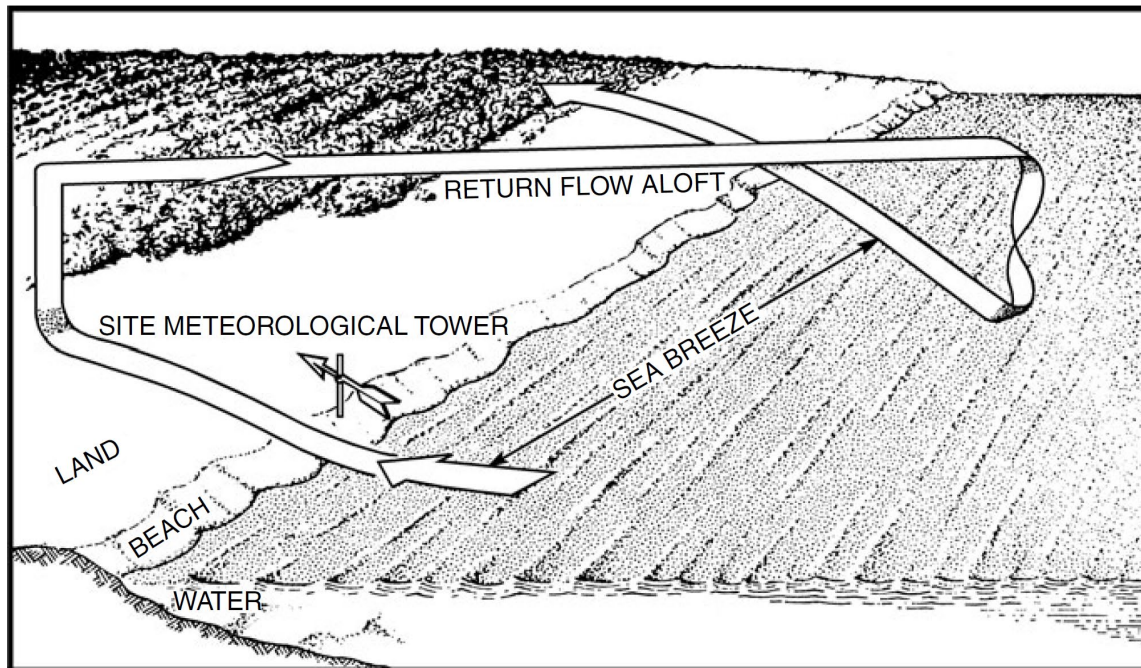
Sea-land daytime breeze circulation. Typical behavior of different plumes emitted in coastal locations.

[Coastal sites]





Example of pollutant behavior for emissions within and above the thermal internal boundary layer (TIBL). From Barr and Clements (1984)



Coastal sites

Example of wind flow onshore, return flow aloft, and the returning of the air with the sea breeze at a different location. From McKenna et al. (1987)

References:

- Slade D.H. (Ed.), *Meteorology and Atomic Energy 1968*. U.S. Atomic Energy Commission, Report [TID 24190](#), (1968).
- Till J.E., Meyer H.R. (Ed.), *Radiological Assessment*. Informe [NUREG/CR-3332](#), ORNL-5968, U.S. Nuclear Regulatory Commission (1983).
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