Gaussian Plume Model

AIR QUALITY MODELING

By Hariom Sir

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Air quality models

Air quality models use mathematical and numerical techniques to simulate the physical and chemical processes that affect air pollutants as they disperse and react in the atmosphere.

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Purposes

- Establishing emission control legislation, i.e. determining the maximum allowable emission rates that will meet fixed air quality standards
- Evaluating proposed emission control techniques and strategies i.e. evaluating the impacts of future control
- Selecting locations of future sources of pollutants (e.g. industries), in order to minimize their environmental impacts
- Planning the control of air pollution episodes, ie. Defining immediate intervention strategies.
- Assessing responsibility for existing air pollution levels, ie, evaluating present source-receptor relationships.

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Factors to be considered in modeling

In air pollution dispersion modeling, 5 major physical processes are simulated:

- **i) Pollutant advection**
- **ii) Diffusion**
- **iii) Deposition**
- **iv) Chemical reaction (ie, transformation)**
- **v) Emission**

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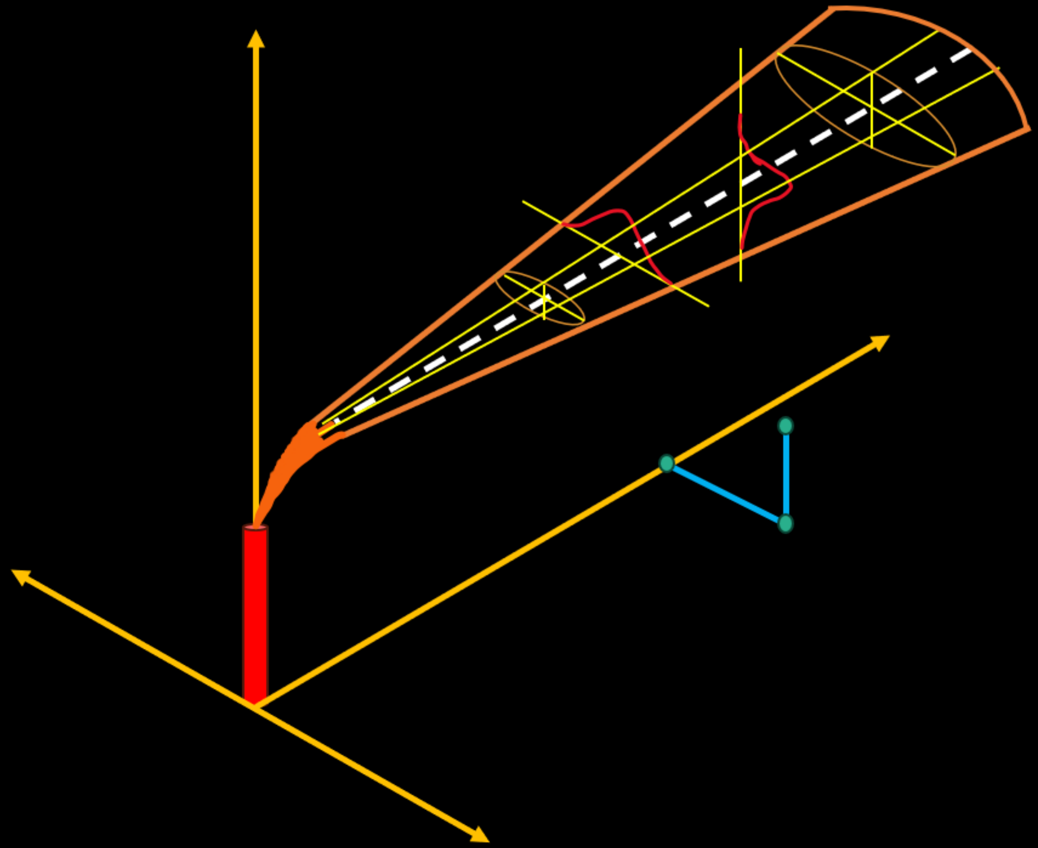
Types of Air Quality Models

i) Dispersion/Diffusion Modeling: uses mathematical formulations to characterize atmospheric processes that disperse a pollutant emitted by a source.

ii) Photochemical Modeling: Long-range air quality models that simulate the changes of pollutant concentrations in the atmosphere due to the chemical and physical processes in the atmosphere.

iii) Receptor Modeling: Mathematical or statistical procedure for identifying and quantifying the source of air pollutants at a receptor location. • Example:- Chemical Mass Balance Method

Point Source Gaussian Plume Model



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Parameters affecting concentration of Air Pollutant from Point Source

Wind Direction:

- Total concentration of air pollutant is inversely proportional to the increase of wind angle direction with respect to receptor. (studied by experiments).

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Wind Speed

- Wind speed generally increases with the height.
- For buoyant sources, plume rise is affected by wind speed; the stronger the wind, the lower the plume rise.
- Wind speed dilutes continuously the released pollutants at the point of emission. Whether a source is at the surface or elevated, this dilution takes place in the direction of plume transport.

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Turbulence

- Turbulence is another factor which affects the wind direction and hence the concentration of air pollutant.
- It is highly irregular motion of the wind.

Assumptions:

- Plume spread results primarily by Molecular Diffusion.
- Time required for the pollutant to travel to the receptor is neglected; Steady state is assumed
- Normal distribution of horizontal and vertical pollutant concentrations in the plume.
- There is No diffusion in x direction.
- Uniform continuous emission rate.
- Wind speed is constant.
- Terrain is flat.
- Pollutant dispersion follows Normal Statical Distribution.
- Shape of plume is conical.
- Pollutant are non reactive

At any point P there is a contribution to the concentration C(x,y,z)

$$C(x,y,z) = \frac{Q}{U}\,\frac{1}{2\pi\sigma_y\sigma_z}\,e^{\left(\frac{-y^2}{2\sigma_y^2}\right)}\left[e^{\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)} + e^{\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)}\right]$$

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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

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

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

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If only concentrations at ground level are required (for example in assessing the exposure of crops or humans to the pollutant) then we can simplify the equation by setting z=0. This gives

$$C(x,y,0) = \frac{Q}{U}\frac{1}{\pi\sigma_y\sigma_z}e^{\left(\frac{-y^2}{2\sigma_y^2}\right)}e^{\left(\frac{-H^2}{2\sigma_z^2}\right)}$$

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It should be noted that the maximum concentration occurs when

$$\sigma_z = \frac{H}{\sqrt{2}}$$

If only concentrations at ground level on the centre-line of the plume (along the x-axis direction) are required then the equation is simplified further since both z=0 and y=0. This gives

$$C(x, 0, 0) = \frac{Q}{U} \frac{1}{\pi \sigma_y \sigma_z} e^{\left(\frac{-H^2}{2 \sigma_z^2}\right)}$$

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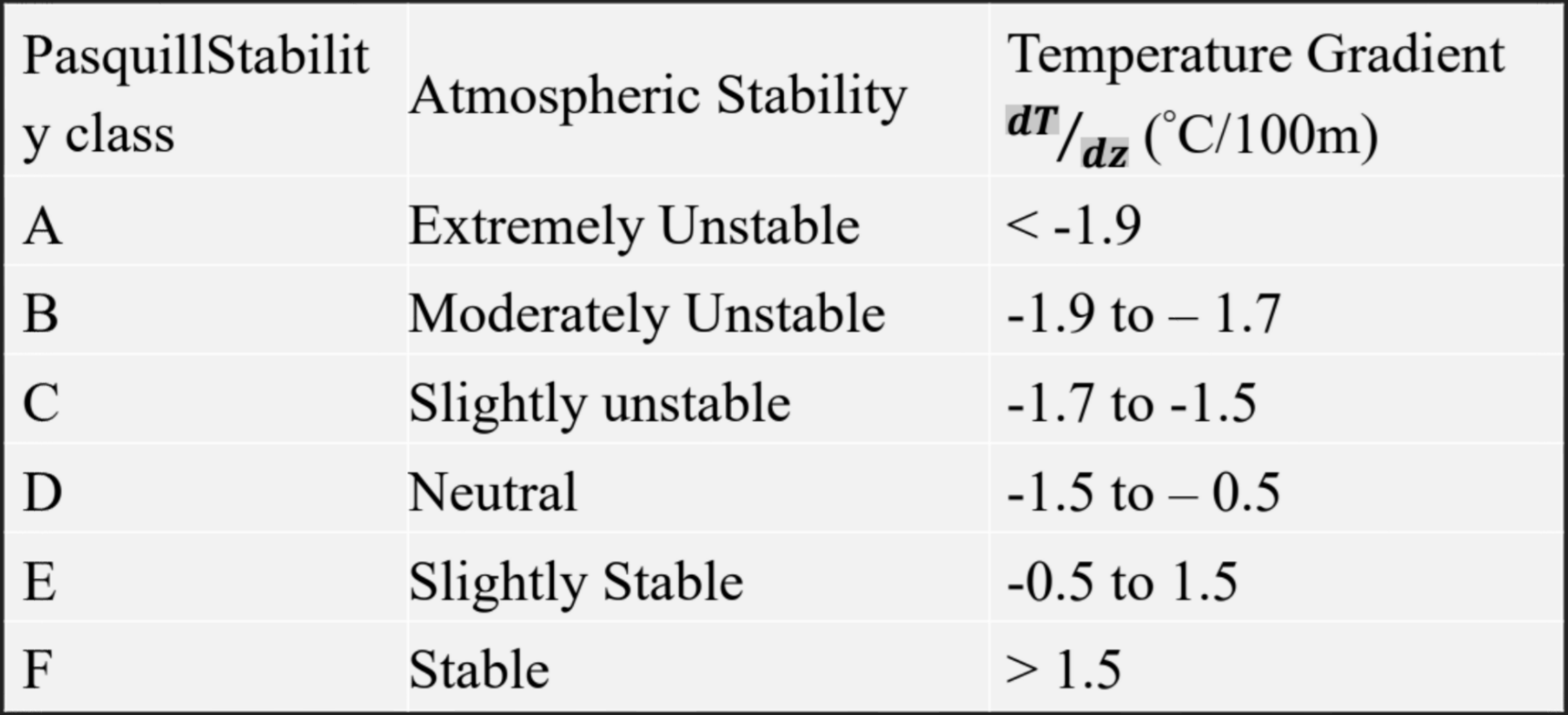
Pasquill Stability classes



PasquillStability class	Atmospheric Stability	Temperature Gradient $^{dT}/_{dz}$ (°C/100m)
A	Extremely Unstable	< -1.9
B	Moderately Unstable	-1.9 to – 1.7
C	Slightly unstable	-1.7 to -1.5
D	Neutral	-1.5 to – 0.5
E	Slightly Stable	-0.5 to 1.5
F	Stable	> 1.5

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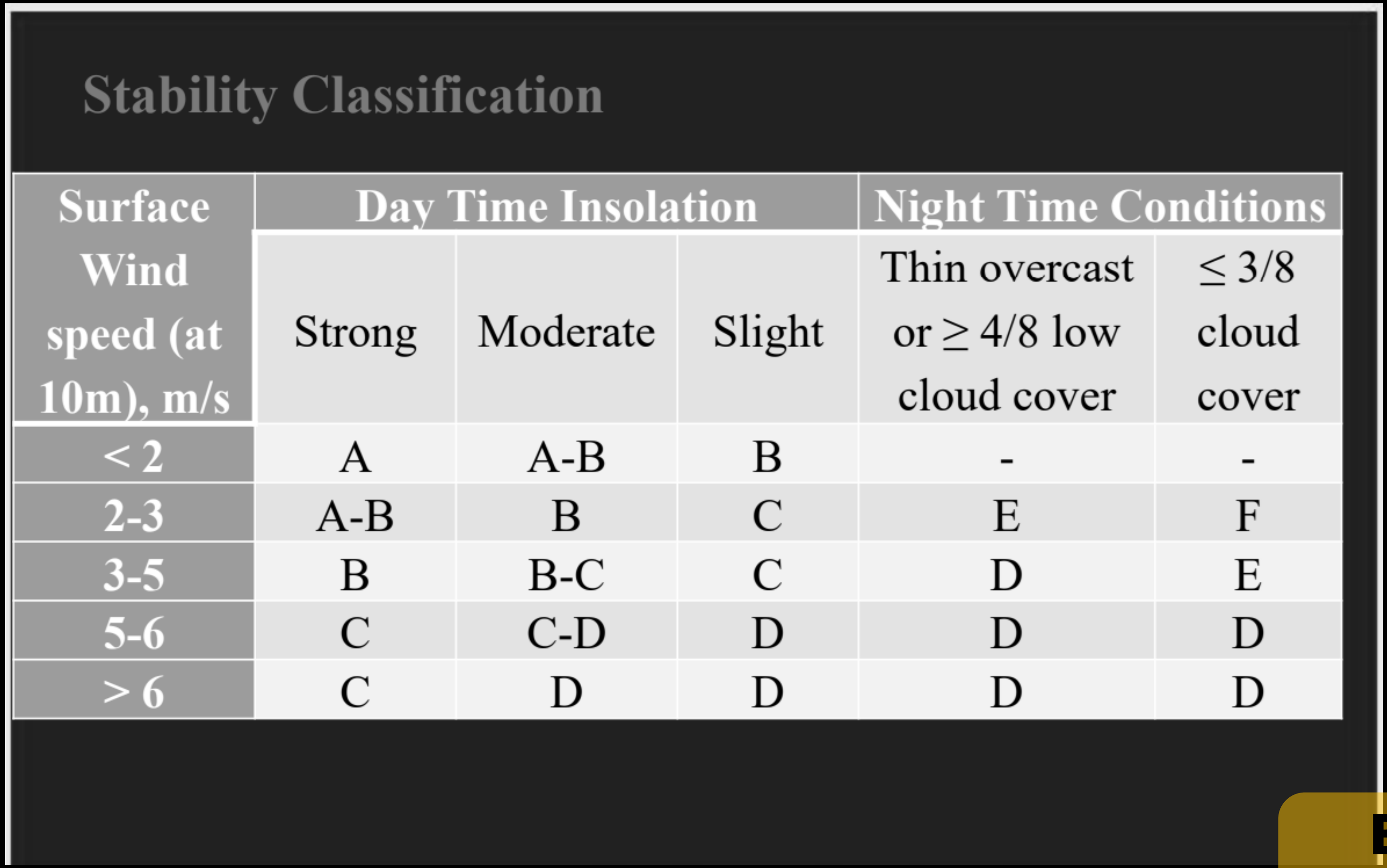

Stability Classification

Surface Wind speed (at 10m), m/s	Day Time Insolation			Night Time Conditions	
	Strong	Moderate	Slight	Thin overcast or ≥ 4/8 low cloud cover	≤ 3/8 cloud cover
< 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

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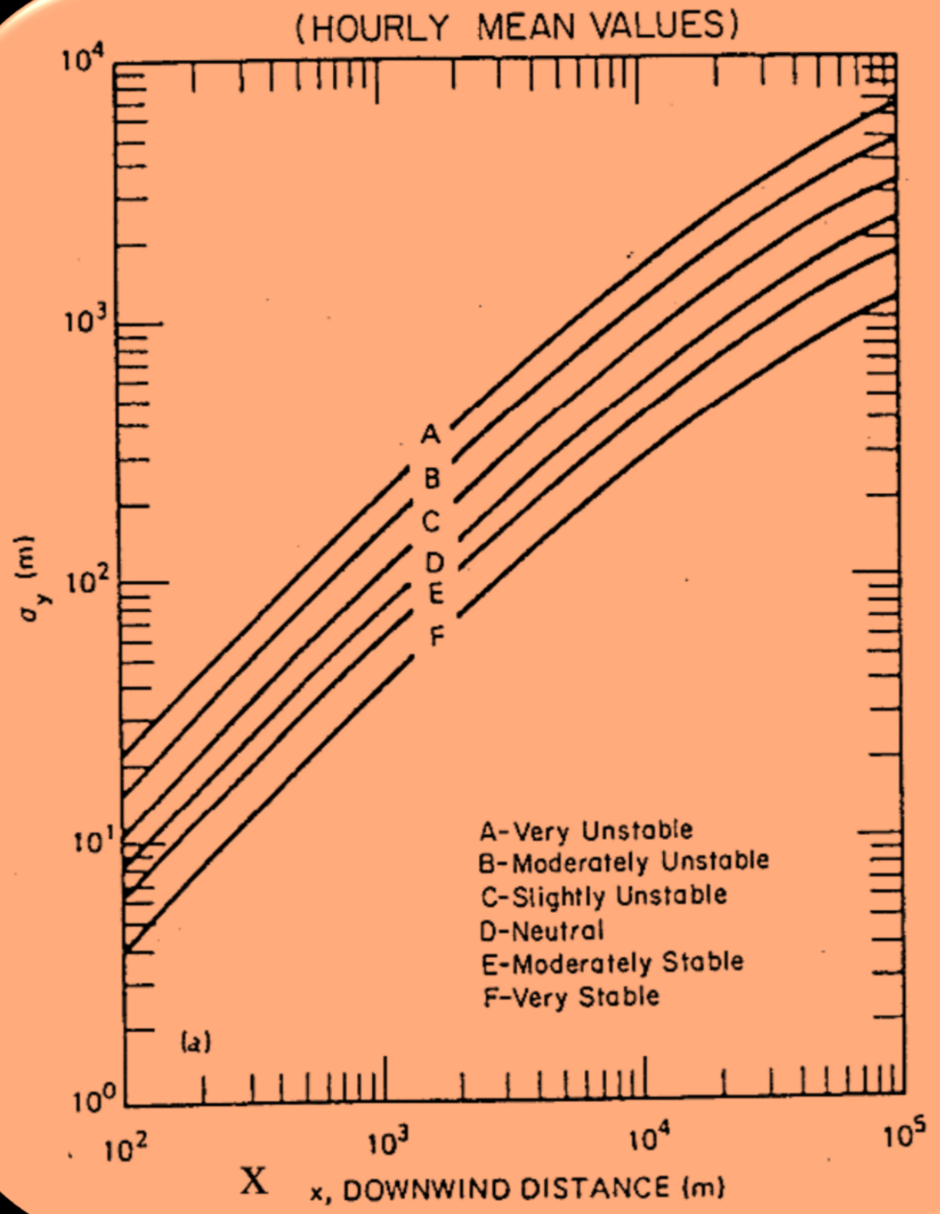
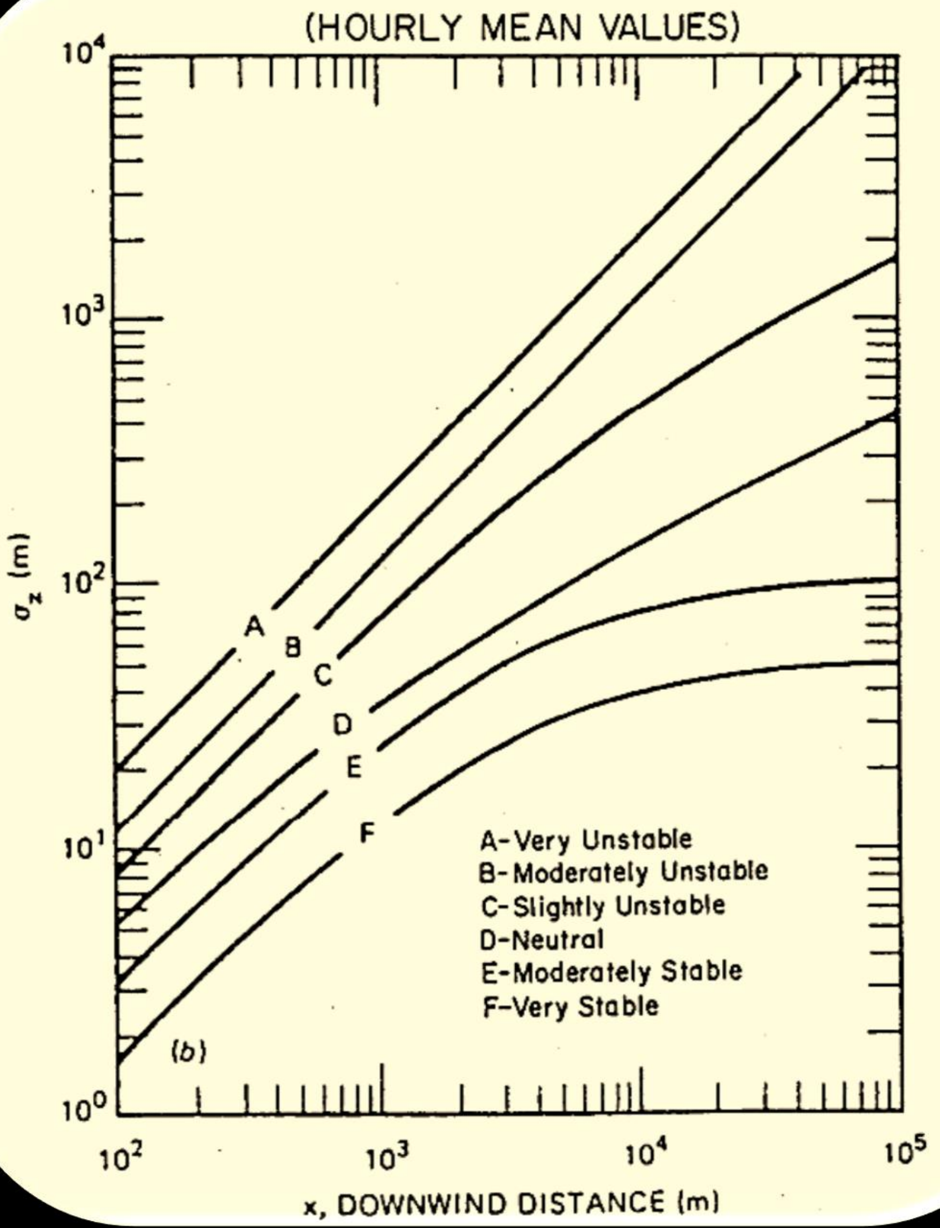
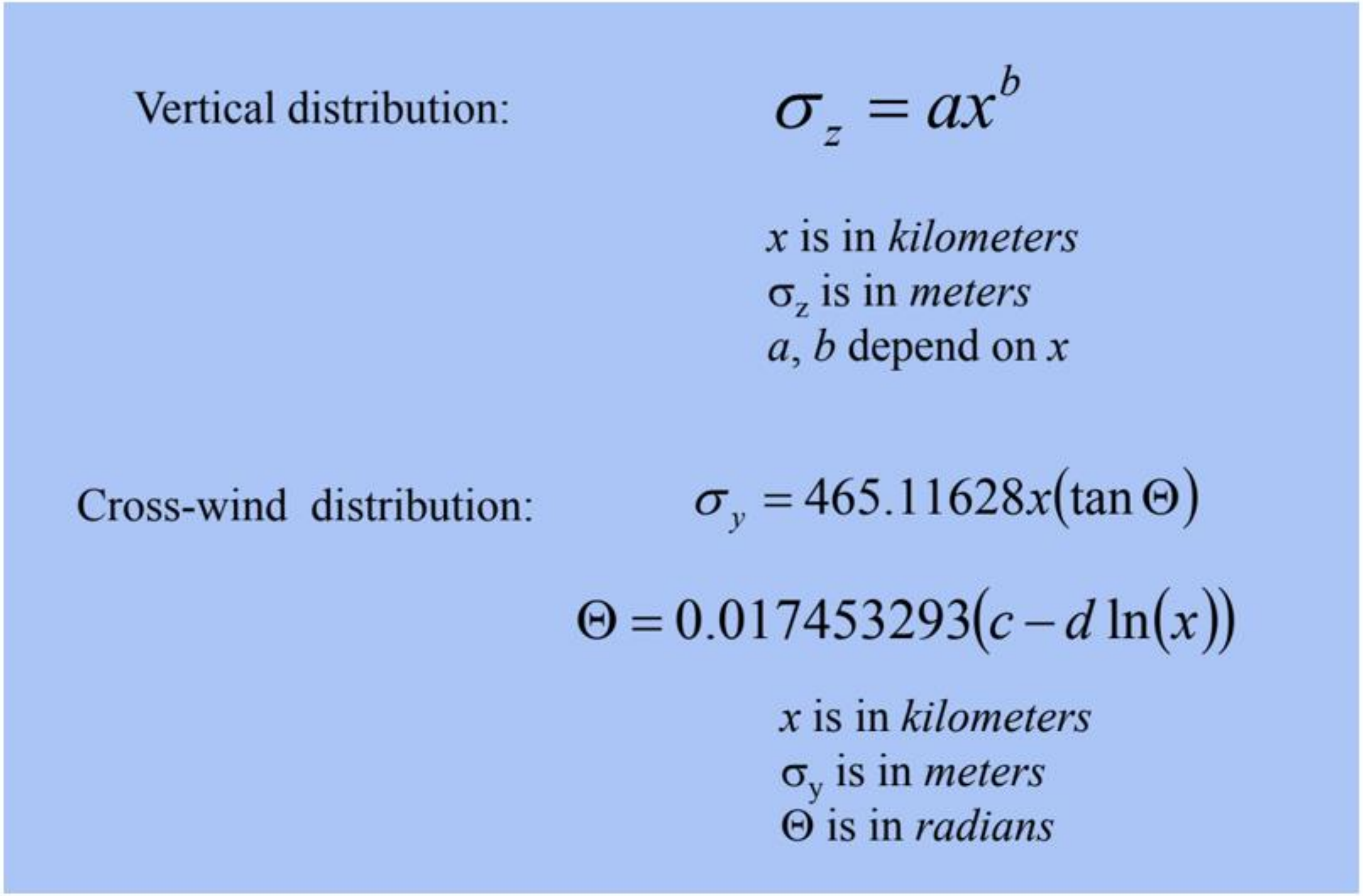

(HOURLY MEAN VALUES)
σ_y (m)
10^0
10^1
10^2
10^3
10^4
A
B
C
D
E
F
A-Very Unstable
B-Moderately Unstable
C-Slightly Unstable
D-Neutral
E-Moderately Stable
F-Very Stable
(a)
10^2
10^3
10^4
10^5
X
x, DOWNWIND DISTANCE (m)


(HOURLY MEAN VALUES)
σ_z (m)
10^0
10^1
10^2
10^3
10^4
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)

σ_z / σ_x



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*

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

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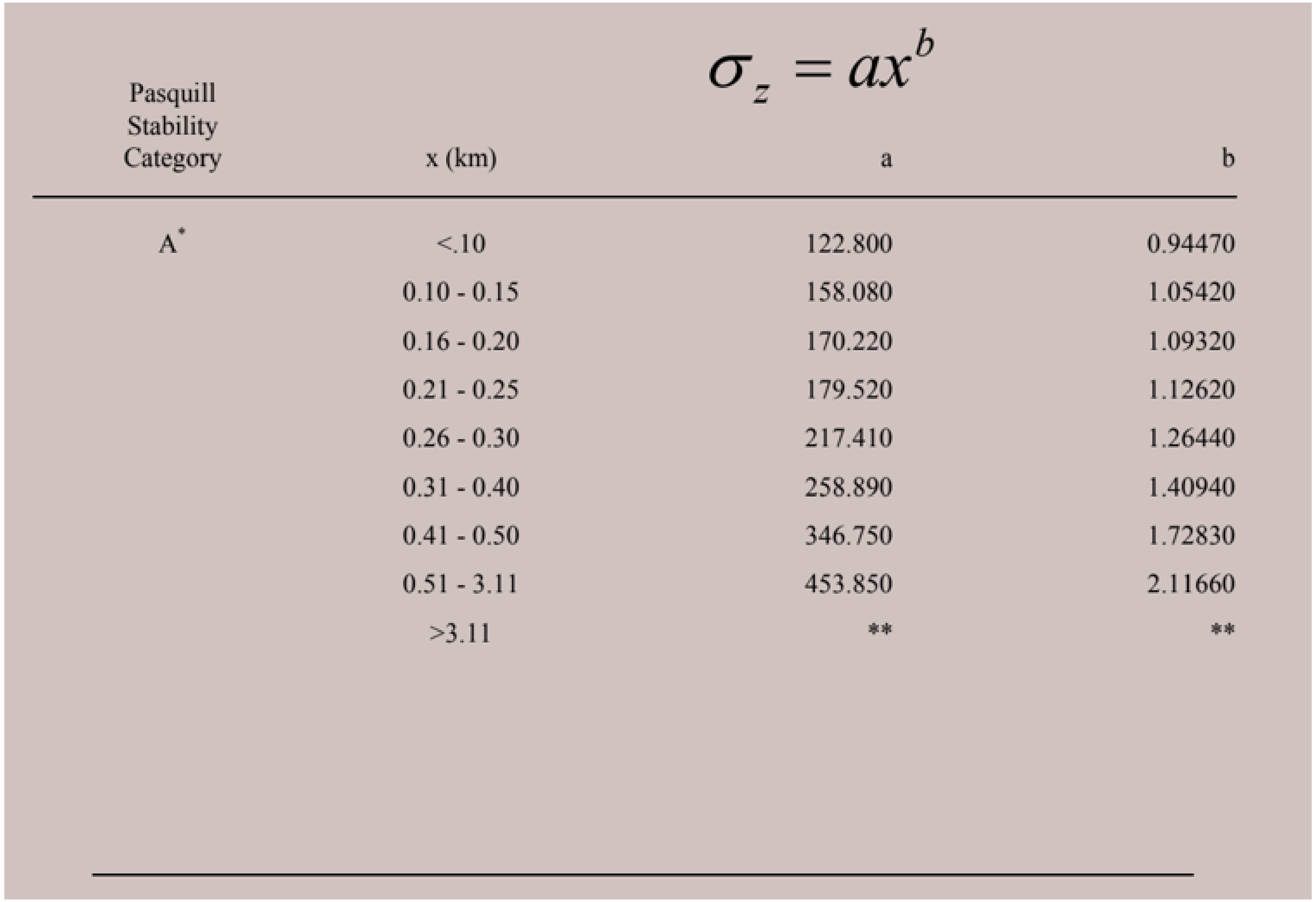
σ_z

(a,b)



$$\sigma_z = ax^b$$

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.

** $\sigma_z = 5000$

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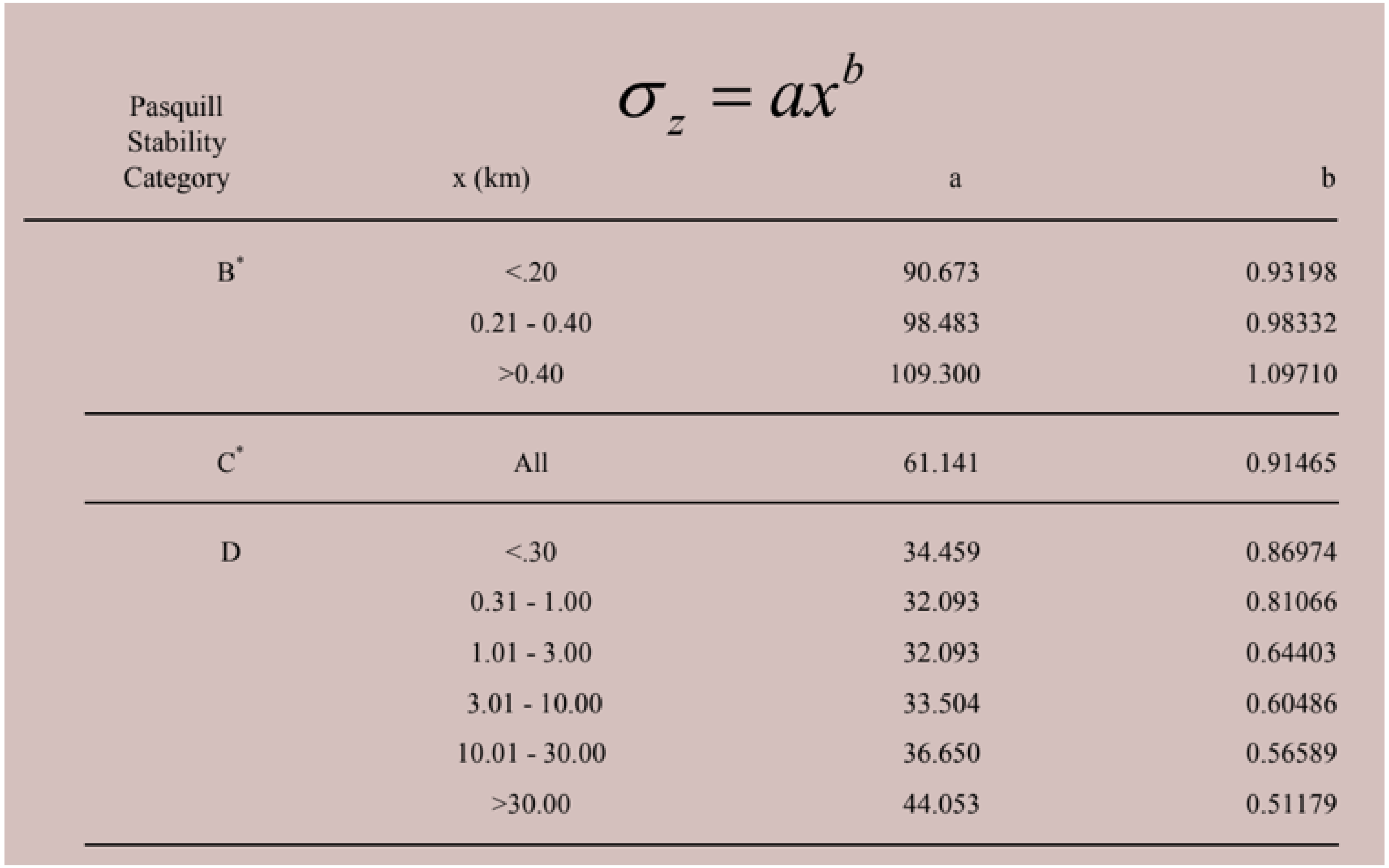
σ_z

(a,b)



$$\sigma_z = ax^b$$

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

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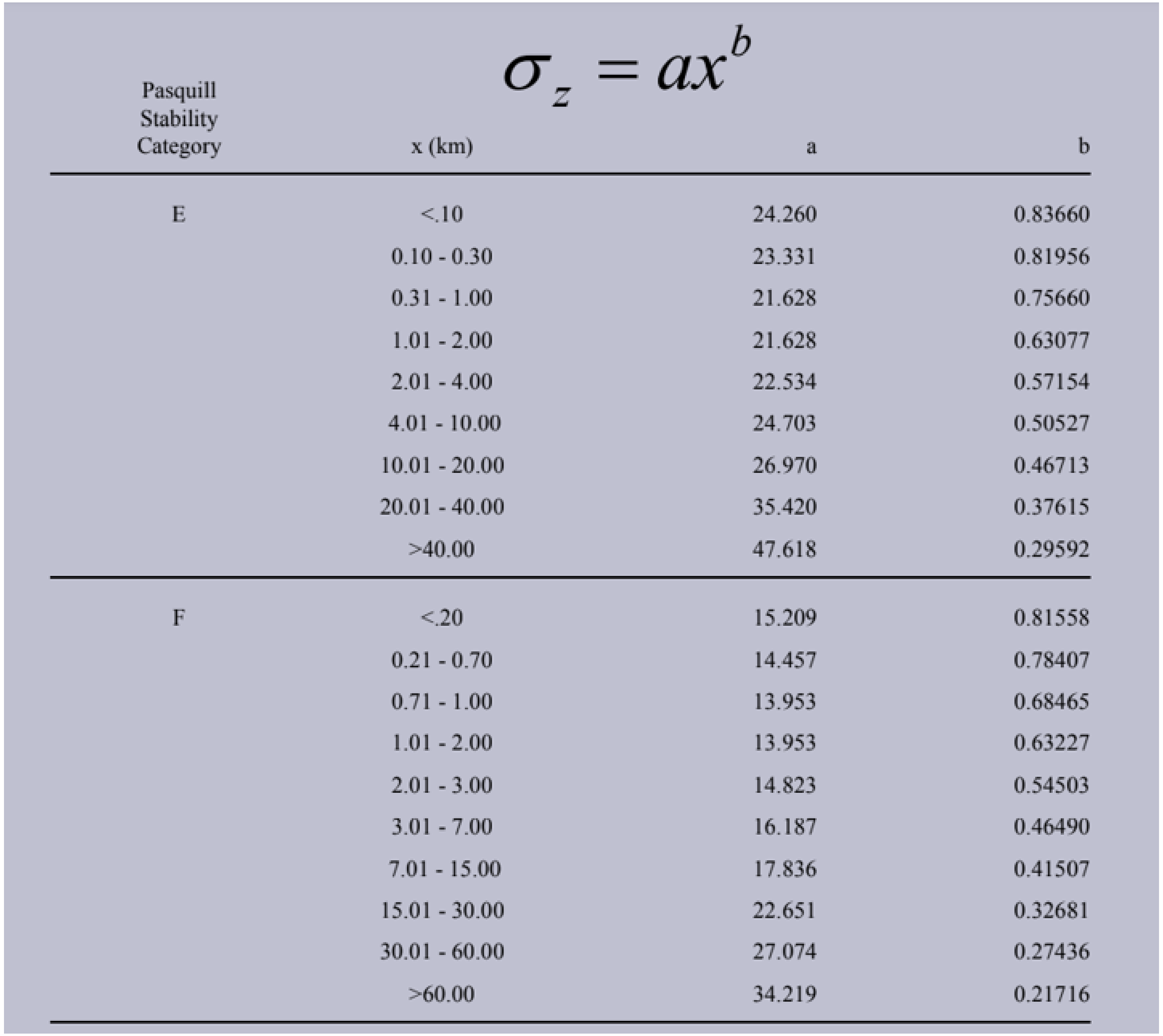
σ_z

(a,b)



$$\sigma_z = ax^b$$

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

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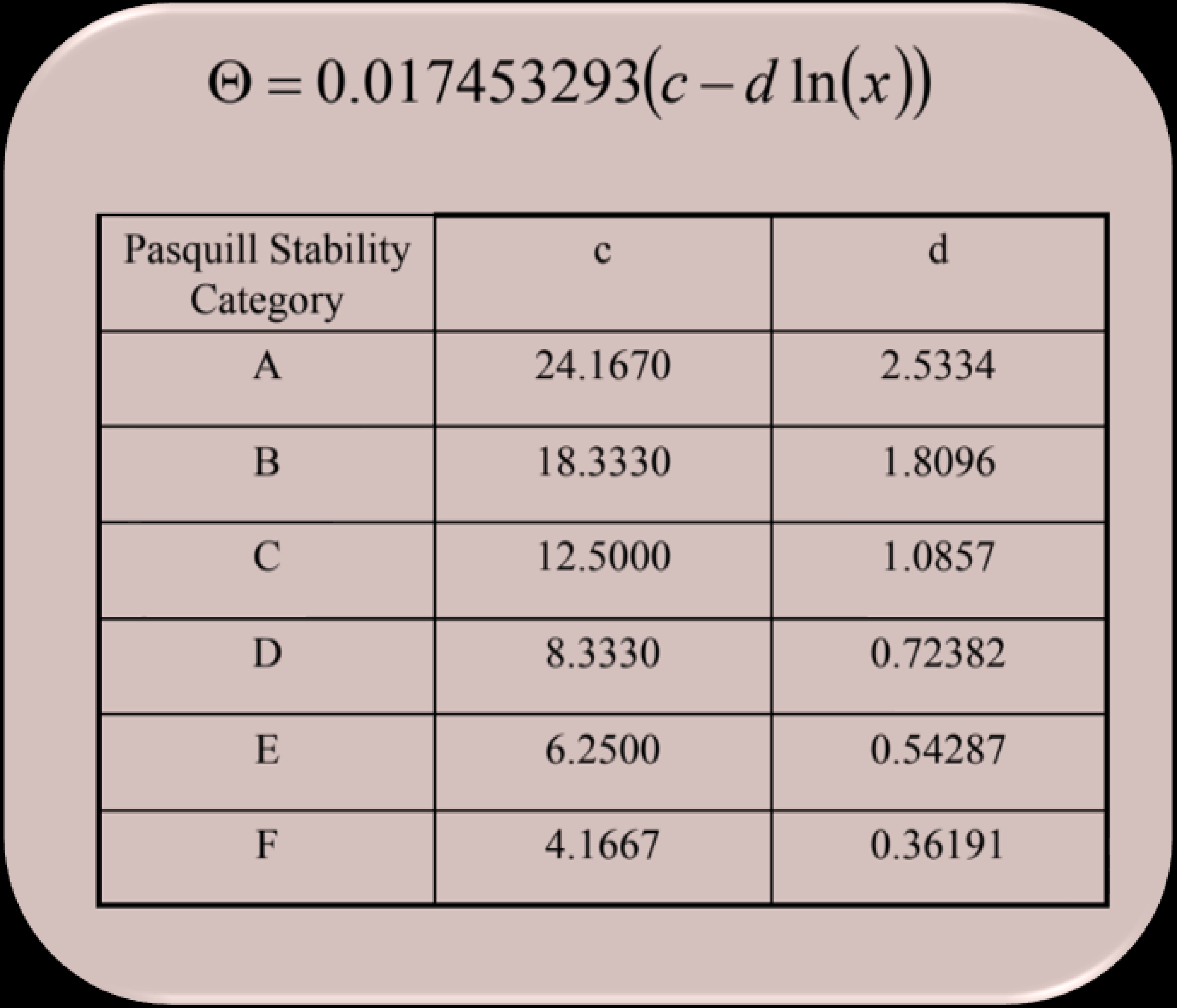
Θ (c,d)



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

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

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Mean wind speed at plume height (u(z))

$$u(z)=u_0\left(\frac{z}{z_0}\right)^p$$

where

- $u(z)$ = wind speed at plume height, z
- u_0 = wind speed at instrument height
- z = effective stack height (m)
- z_0 = instrument height (m)
- p = A factor which depends on stability condition of atmosphere

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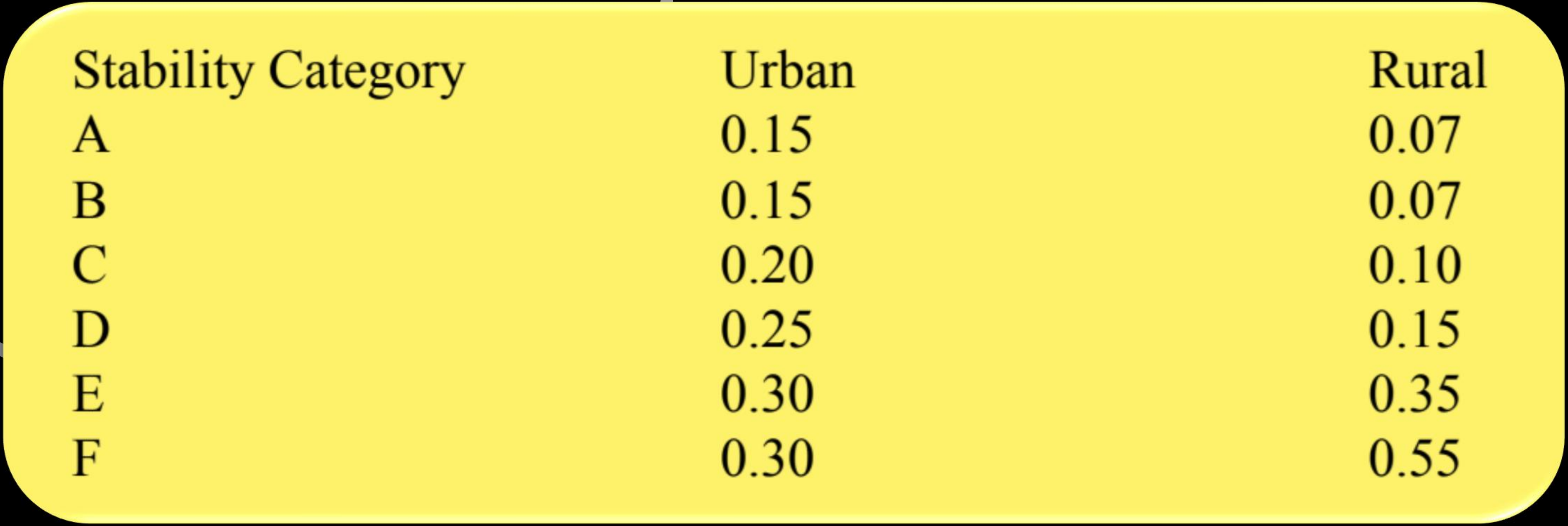
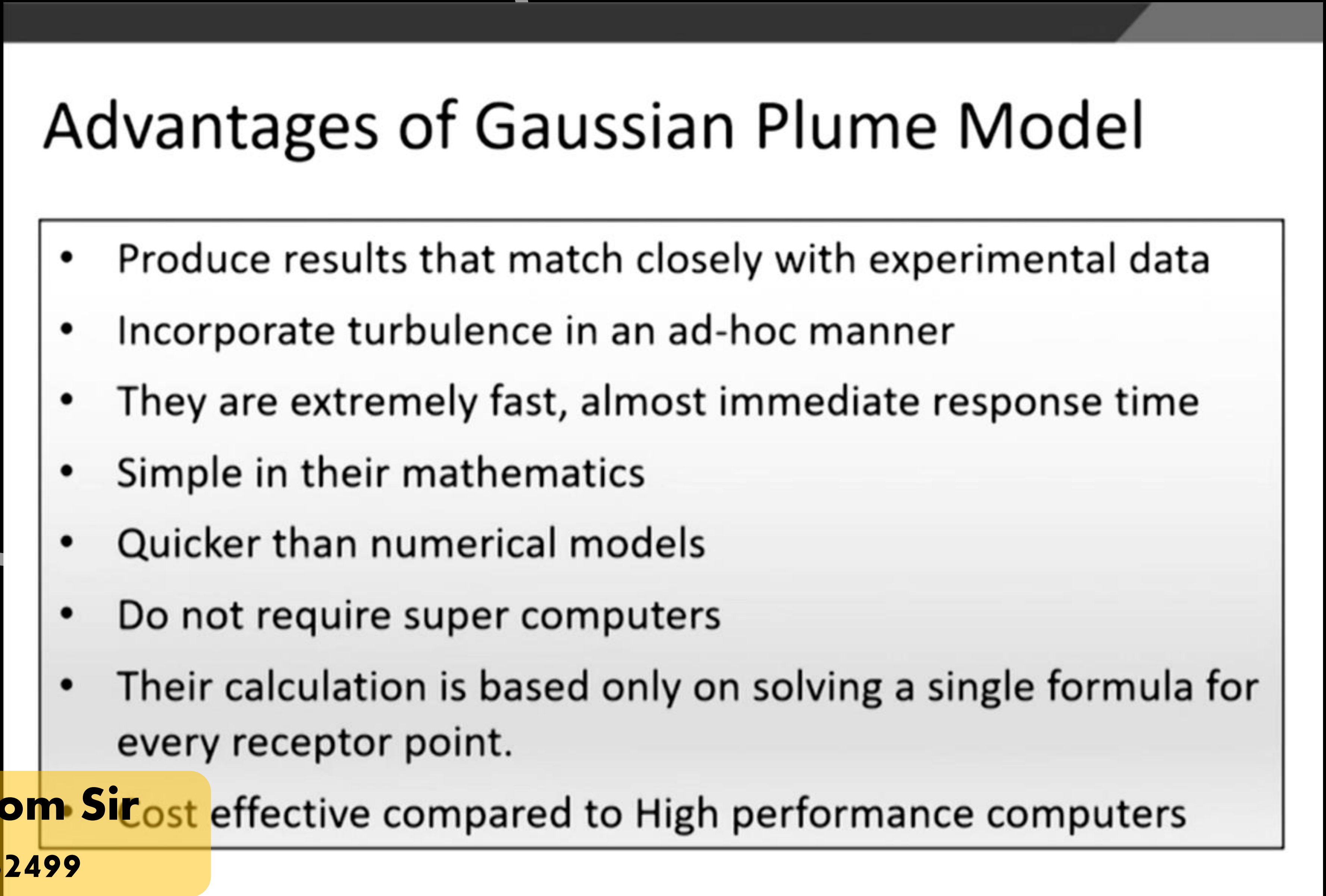


Stability Category	Urban	Rural
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.30	0.35
F	0.30	0.55



Advantages of Gaussian Plume Model

- Produce results that match closely with experimental data
- Incorporate turbulence in an ad-hoc manner
- They are extremely fast, almost immediate response time
- Simple in their mathematics
- Quicker than numerical models
- Do not require super computers
- Their calculation is based only on solving a single formula for every receptor point.
- Cost effective compared to High performance computers

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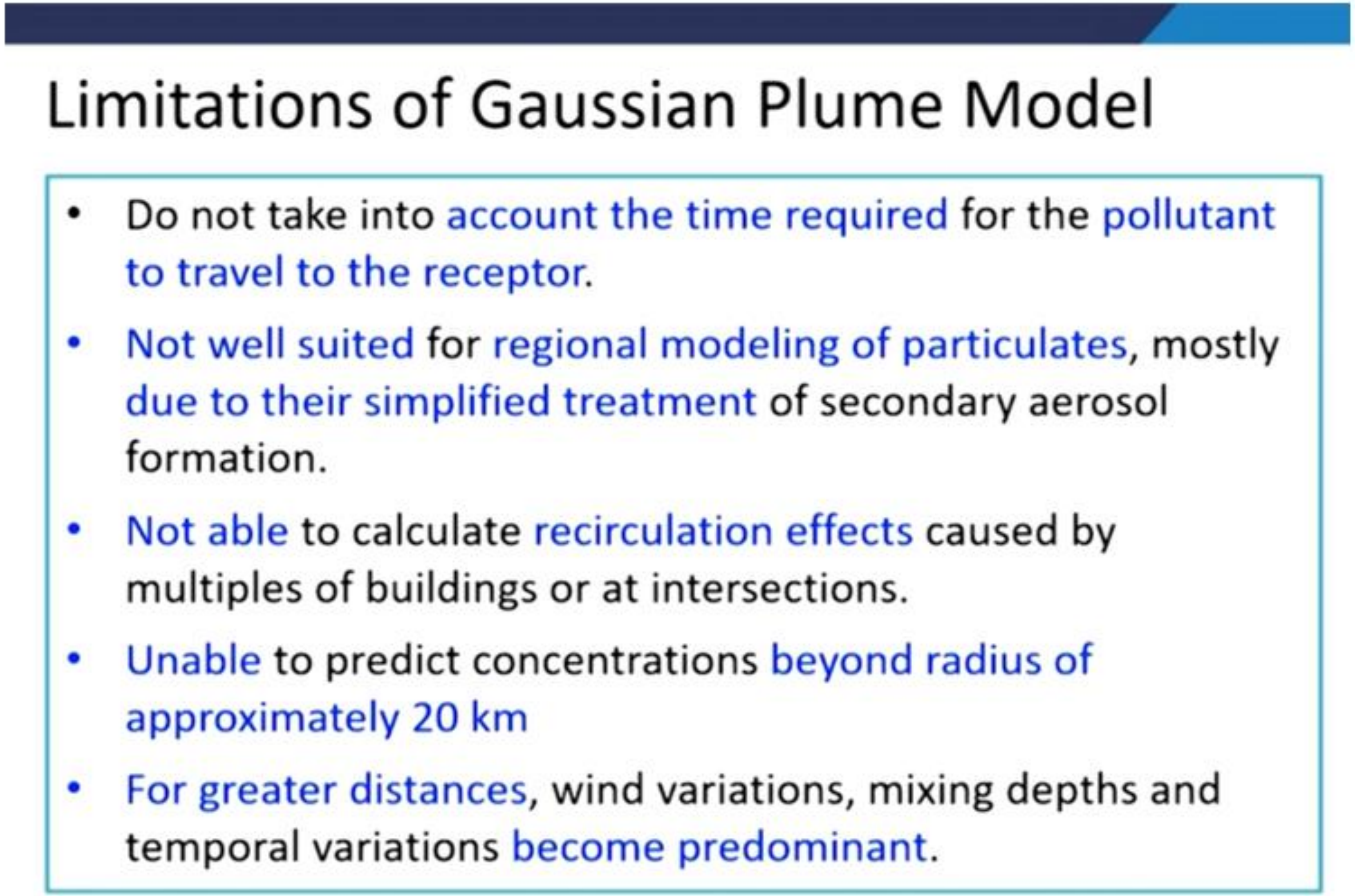
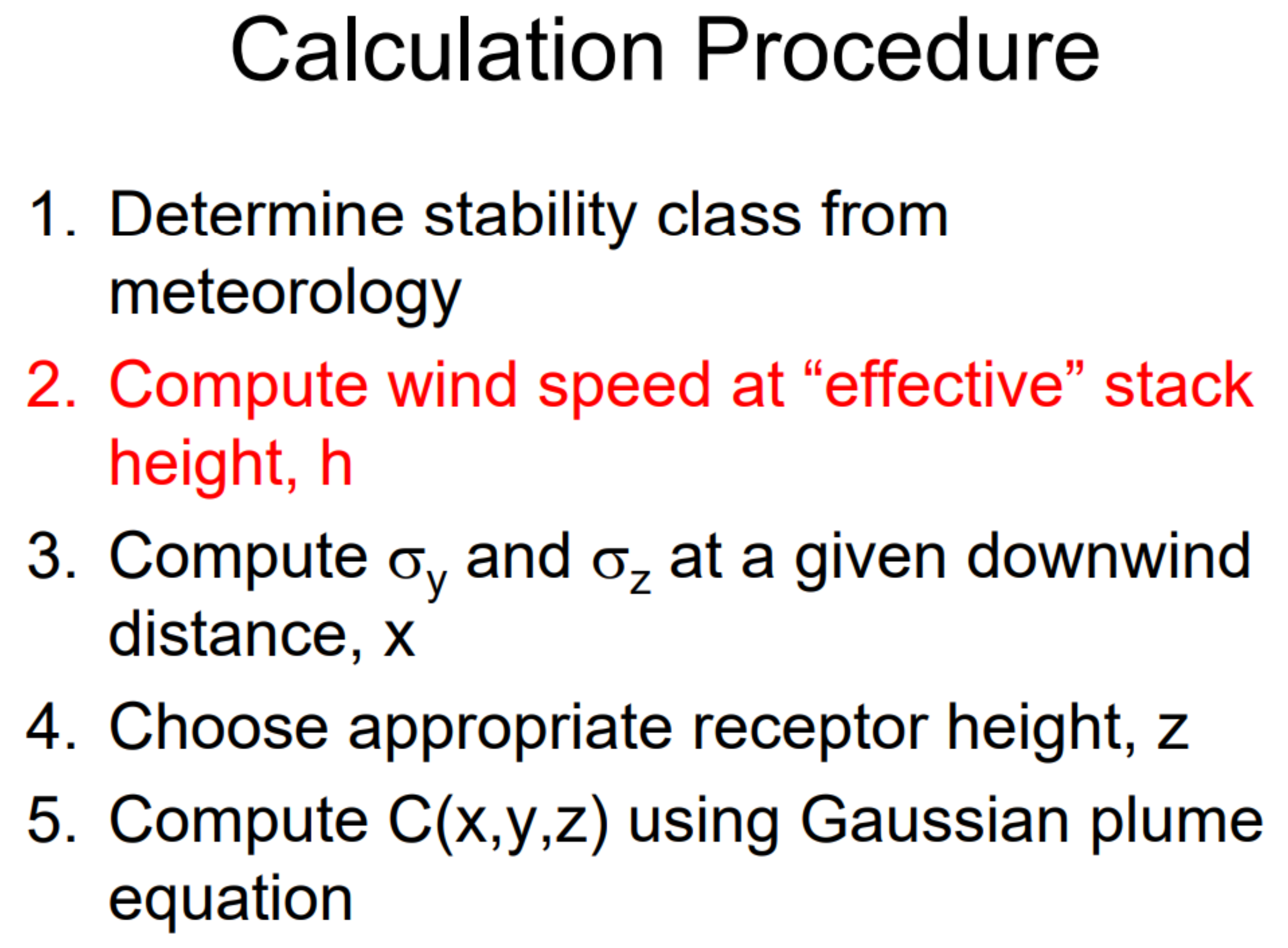
Limitations



Limitations of Gaussian Plume Model

- Do not take into account the time required for the pollutant to travel to the receptor.
- Not well suited for regional modeling of particulates, mostly due to their simplified treatment of secondary aerosol formation.
- Not able to calculate recirculation effects caused by multiples of buildings or at intersections.
- Unable to predict concentrations beyond radius of approximately 20 km
- For greater distances, wind variations, mixing depths and temporal variations become predominant.



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

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