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Study of the Vertical Dispersion Coefficient of Air Pollution Under Different Atmospheric Stability Conditions over Baghdad

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Abstract: The city of Baghdad is facing a real crisis of increasing air pollution due to increasing population density and industrial areas. This study aims to construct the specialized six curves for calculating vertical dispersion coefficients at different stabilities and distances from the measurement point, which can be represented by the urban atmosphere of Baghdad. This was also achieved in conjunction with the integrated Lagrangian time scale (T_L). The observed data were obtained through a three-dimensional ultrasonic anemometer for instantaneous velocity components and air temperature, as the study was from January to July of the year (2016). The vertical wind speed and the height dispersion coefficient were also calculated in the context of Lagrangian coordinates and related to the dimensionless atmospheric stability. The results show that T_L has the unity value at neutral, behaves in the linear increase at stable, and is non-linear under unstable conditions. Most of the stability is found in the slightly unstable segment range (–0.1 to –1) and it was found that the vertical dispersion coefficient plays an important role in measuring the dispersion of pollutants causing instability in the atmosphere. The dispersion coefficient is mainly produced by atmospheric turbulence, which is of great importance in mixing pollutants and spreading them horizontally or vertically.

Key words: Vertical dispersion, Lagrangian time scale, atmospheric stability, Baghdad vertical wind standard deviation.

Introduction

In urban atmospheric environmental issues, man-made sources of pollutants, such as vehicle exhaust and industrial waste gases, have become major contributors to air pollution. Therefore, understanding the dispersion of pollutants in the air in urban areas is of great importance for human health (Shen et al., 2017). Dispersion models are crucial for predicting pollutant concentrations. Dispersion refers to the movement of pollutants through the air, resulting in the spread of plumes over a large area both horizontally and vertically, primarily due to atmospheric turbulence. The theory of dispersion offers various methods for estimating the concentration of substances and providing specialised data on atmospheric factors, as well as the geometry and strength of the source (Peirce et al., 1989). Air pollution is an important environmental issue around the world, including the city of Baghdad in Iraq, because Baghdad is a densely populated urban area and various sources of air pollution contribute to the emission of pollutants that negatively affect air quality. Turbulent diffusion plays a crucial role in estimating peak human exposure to air pollutants and aquatic life to water pollutants and dominates most dispersion issues. This is because it has a specific role in environmental dispersion and

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provides simple mathematical models of dispersion phenomena that are useful in understanding the more complex turbulent dispersion process (Su et al., 2021). Air pollution has been the subject of many studies. The shape of the plume undergoing dispersion depends on the vertical wind speed, vertical temperature, and atmospheric stability (Wyngaard, 2010). It is very important in the dispersion of pollutants, as stability is the tendency of the atmosphere to either resist or promote air and control the vertical movement of airborne pollutants.

There were several previous studies carried out about the connection of stability with pollutant transportation. The stability is a powerful tool to characterize pollution events in urban areas (Perrino et al., 2001). Evaluated the standard deviations of the horizontal and vertical direction as a function of downwind distance and atmospheric stability (Na et al., 1986). The estimated ratio between the Lagrangian and Eulerian time scales in an atmospheric boundary layer generated by large eddy simulation through standard deviations of wind velocity, integer time scales, autocorrelation functions, and spectra for the three wind components, both in the Lagrangian and Eulerian frames, have been calculated. However, this task is very challenging as the problem of realistic pollutant dispersion in an urban environment is very demanding (Anfossi et al., 2006), who developed a modelling method to simulate the dispersion of dust in the atmospheric surface layer with an embedded strong flow perturbation using the Monin-Obukhov theory. The dust dispersion is simulated using a new two-layer stabilized Lagrangian stochastic model configured (McAlpine, 2009), which made the experimental and numerical study of the Lagrangian dynamics of high Reynolds turbulence to track the motion of tracer particles in high Reynolds number turbulent flows (Maldaner et al., 2014).

We present a semi-analytical Lagrangian particle model to simulate the pollutant dispersion during low wind speed conditions. The model is based on a methodology that solves the Lagrangian equation through the assumption that the coefficient of the integrating factor is a complex function (Carvalho et al., 2013). The Lagrangian time scale (T_L) in the context of dispersion (particularly in fluid dynamics and atmospheric sciences) refers to the characteristic time over which a fluid parcel or particle retains its velocity or momentum before it becomes decorrelated due to turbulent fluctuations or other dynamic processes (Xin et al., 2002). This concept is critical in turbulent diffusion and particle dispersion modelling, as it helps determine how particles spread in a turbulent medium over time (Xia et al., 2013)

The main aims of this paper focus on (1) the calculation of the stability using Monin-Obukhov (MO) length and then classifying into 6 groups, (2) examining the dimensionless nature of the turbulent quantities, such as the T_L, a ratio of vertical wind standard deviation to mean wind vertical deviation ($\sigma w/U$), and vertical height standard deviation (σz) through the wide different stabilities, and (3) empirical graph including finding the vertical dispersion coefficient under several horizontal distances.

The Site Description and Data Sources

Site Description

The city of Baghdad is located in the central region of the government of Iraq and is bordered by Iraqi cities from all directions as shown in Figure 1. Baghdad is located at 33.14° latitude and 44.20° longitude, and this location is considered great importance to the city, which consists of two main parts, namely: Karkh, which occupies the western side of the Tigris River, while the other part is Rusafa, which occupies the eastern side of the Tigris River, both parts include modern neighbourhoods with wide streets and shops, and the city includes many industrial areas, and the city contains relatively low buildings, which generally do not reach high heights and are surrounded by green gardens with tall trees. The location of Mustansiriya University in the center of the city of Baghdad was chosen to conduct the research. The study site is featured as a mixture of high buildings and trees, which are medium height. The average surface roughness length for this location was found to be about (1.2 m) as reported by Haraj and Al-Jiboori (2019) using the Logarithmic equation for natural cases. There is also a set of parking lots with some open spaces. Last but not least, there is a bridge in section NW-N near the measurement site.

Data Source

In this work, the fast-response ultrasonic anemometer (Wind Master Pro 021-MMG079141189 PK), which is located on the roof of the Atmospheric Science Department Building at Mustansiriyah University (see Figure 2), is 23 meters long and its base is 19 meters above the ground. It can observe and record the wind speed in each of the three components (longitudinal velocity (u), transverse velocity (v), and vertical velocity (w) every second) and the air temperature. The

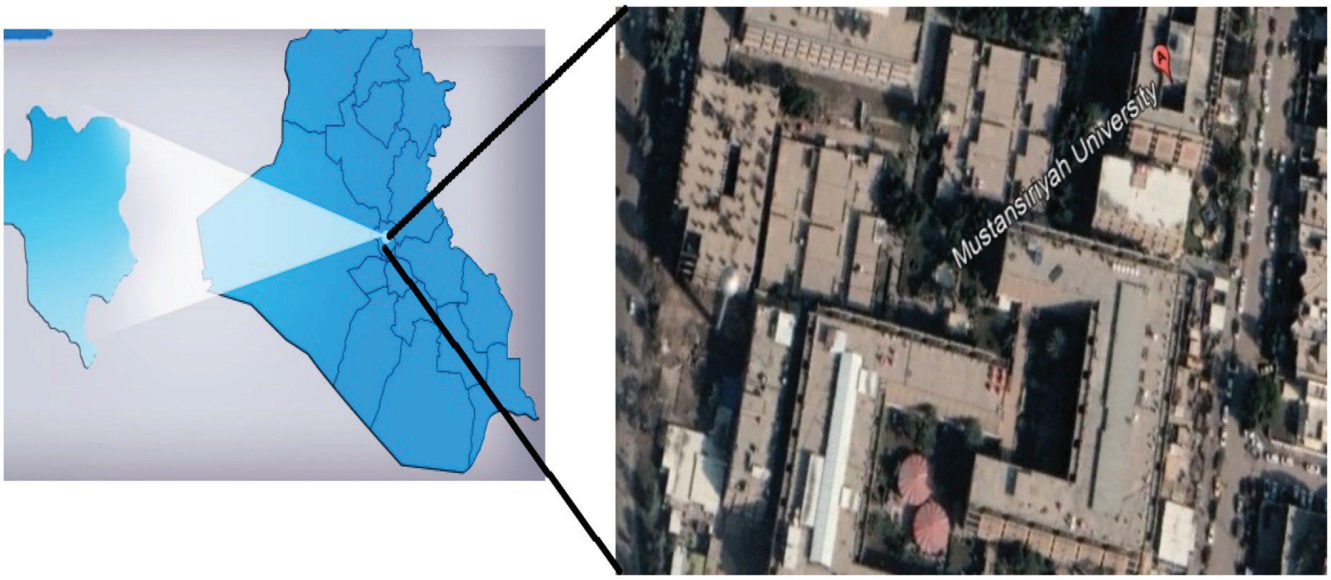

Figure 1: Maps of Iraq, Baghdad City, and the study site (Mustansiriyah University).

Figure 2: Photograph of 3D ultrasonic anemometer used in this paper.

instrument records a large amount of data in a short time. u, v, and w components have been defined as +u in the direction of the North Pole, as shown in the figure below. +v is defined as 90 degrees counterclockwise from the north, the reference bar. +w is defined as vertically up the mounting shaft.

The urban turbulence data measured by the above instrument were collected in this study with a sampling frequency of 1 Hz (i.e., every 1 s) on a CD-ROM. The observation period covered different days for each of the months (January, March, April, May, June, and July) of the year 2016, and for comprehensive analysis, observations were selected during different times of sunrise, morning, sunset, and evening. This provided a wide extent of different atmospheric conditions when calculating atmospheric stabilities, especially for obtaining neutral stratification available in transition times in sunrise and sunset. In addition, we focussed on April month because it is represented as one of the transitional seasons from winter to summer, where the weather is warmer and wetter, the sun is perpendicular to the equator, and the amount of solar energy is balanced in both hemispheres. However, the device read the three components of wind speed and temperature every second, and the length of each sample was a quarter of an hour. This means that 900 readings were taken in the period. This is because the 60 seconds were multiplied by the 15 minutes.The total number of runs was 70 deduced from spared 10 days with their dates displayed in Table 1.

Table 1: Summary of the number of runs with their data for 2016

Date	*27/1*	*15/3*	*11 and 16/4*	*25-26/4*	*4/5*	*28-30/7*	*Total no.*
No. of days	1	1	2	2	1	3	10
No. of runs	8	7	4	36	5	10	70

Methodology

Turbulent Wind Components and Air Temperature

The wind is variable. Distinct values of u(t) can occur at various times. Mean values of wind speed components (u), the turbulent part (or gust component), u', can be calculated by subtracting this mean wind from the instantaneous wind. In other words, the wind is a combination of mean and turbulent portions for all components (u, v, w). The three turbulent wind components (u', v', w') as well as air temperature (T') were captured in the mean value of $\bar{u}$, $\bar{v}$, $\overline{w}$ and $\overline{T}$ as given (Redah et al., 2023):

$$u' = u - \overline{u};\ v' = v - \overline{v};\ w' = w - \overline{w};\ T' = \overline{T} \tag{1}$$

Stability Parameter

Atmospheric stability refers to the tendency of the atmosphere to resist or enhance vertical motion. It determines whether air parcels will rise, fall, or remain at their original levels. In a stable atmosphere, vertical motion is suppressed, and air tends to return to its original position after being displaced. In an unstable atmosphere, vertical motion is enhanced, and displaced air tends to keep moving upward or downward (Stull, 2012). Several different methods are used to calculate atmospheric stability. Here the M-O length (L) is one of these methods that is based on heat flux and friction velocity near the surface. It can be calculated from measurements of wind speed, temperature gradients, and fluxes. The dimensionless stability parameter (ζ) is commonly used in formulating the universal relationships of turbulent quantities (Roth & Oke, 1993):

$$\zeta = \frac{Z}{L} \tag{2}$$

where Z is the height of the device above the earth's surface and L is given by:

$$L = -\frac{u_*^3}{\sim \kappa \frac{g}{T}(\overline{w'T'})} \tag{3}$$

where κ is the von Kármán constant (here taken to be 0.4); g is the acceleration of gravity, and the mean temperature is the kinematic heat flux at the surface value of. The dimensionless stability was obtained from Al-Samarrai and Al-Jiboori (2022) and Garratt (1994). In Eq. (3), the friction velocity (u_*) is given by:

$$u_* = \sqrt{\left|-\overline{u'w'}\right|} \tag{4}$$

Vertical Dispersion Coeffision

The particles will be released one by one from a single source, and the motion of the particles will be independent of the previous motion. In Lagrangian dispersion, one tracks individual particles as they move with the fluid flow. The Lagrangian time scale provides a measure of how long the velocity of the particle remains correlated with its initial velocity, capturing the influence of turbulence on particle movement. In this study, the moving Lagrangian coordinate frame with the center of mass of the blower was used as the coordinate system from which the dispersion coefficients could be determined, and for this purpose, we applied Tayler's theory of steady turbulent diffusion to establish the relationship between the vertical dispersion coefficient (σw) of the turbulent velocity. Since in steady turbulence, the time origin of the statistical properties of the particles does not matter, this means that the autocorrelation between particle velocity (w_L) at the time (t) and that at t + t′ depends only on time difference t′ and not on t or (t + t′).

Mathematically, the T_L is often defined using the autocorrelation function of the particle's velocity as:

$$T_L = \int_0^\infty R_L(t')\,dt' \tag{5}$$

Where $R_L(t')$ is the Lagrangian velocity autocorrelation function, describing how the velocity at a given time is related to its velocity at a later time, which can be written as:

$$R_L(t') = \int_0^\infty R_L(t')\,dt' \tag{6}$$

w_L the wind speed is related to the longitudinal direction of the particles, and because the path is turbulent, the particle velocity is variable. Although we cannot accurately determine the path of an individual particle, we can use statistical methods to study the overall behaviour of the column.

$$\overline{w_L^2} = \sigma_w^2 \tag{7}$$

where σ_w (= $\sqrt{\overline{w'^2}}$) is the standard deviation of vertical velocity fluctuations, and represents a measure of turbulence intensity. R_L has unity for 0 and zero for (t). The function adopted here, that satisfies these requirements, is:

$$R_L(t') = \exp\left(-\frac{t}{T_L}\right) \tag{8}$$

It is the time rate of an air sample displaced from one place to another and is used in the derivation of dispersion coefficients for pollutants (Blackadar, 2012).

$$\sigma_z(t) = \sigma_w(2 * T_L * t)^{1/2} \text{ for large } t \quad (9)$$

where σ_Z is the dispersion coefficient in the z-dimension, which represents the standard deviation in the vertical wind dispersion of the concentration distribution and depends on the topography of the region of interest, atmospheric stability, distance (x), and travel time ($t = x/U$) was substituted in Eq. (9),

$$\sigma_z(X) = \sigma_w * \left(2 * T\_L * \frac{X}{U}\right)^{1/2} \quad (10)$$

where U is the mean wind speed calculated by the formula given by (Mazumder et al. (2019).

$$U = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2} \quad (11)$$

To execute the objectives of this work, we suggested several horizontal distances in meters for application (Eq. 9), such as 100, 300, 500, 700, 1000, 2000, 3000, 4000, and 5000. Finally, the statistical parameter, or R^2, is a measure of how well a model fits. It is close to 1, indicating that the regression predictions fit the data perfectly. In the context of regression, it is a statistical measure of how well the regression line approximates the actual data (Al-Jiboori et al., 2020).

Result and Discussion

Stability Behaviour in the Atmosphere of Baghdad

Turbulence data in urban areas is important for wind engineering and dispersion modelling applications. This was implemented by applying some criteria, such as the observation level at 19 meters and the observation times being during sunrise, day, sunset, and night. This choice was made to obtain many runs within the boundary layer, especially for the neutral and near-neutral data, which are in the range (±0.1), as well as to understand the structure of the turbulence. After processing the raw data, the three-component velocity (u', $'$, w') and temperature (T') fluctuations were obtained from Eq. (1), by subtracting their means from the actual instantaneous values. The calculated results, which were only affected by the fluctuations and did not show any significant changes during the period (15 minutes), constitute a set of master data. This was done after examining the data and eliminating unreliable measurements. Stability has been determined based on the M-O length dimensionless stability using equations (2 and 3). In this paper, using 70 runs, the results of nondimensional stability, *Z/L*, were found to be in the three stabilities; stable, neutral, and unstable conditions. To determine the intensity of air stability, the *Z/L* values were divided into several ranges. These ranges with their numbers and relative frequencies are presented in Figure 3.

In the convective conditions(or very unstable when *Z/L*<-5), the percentage of relative frequency was 11%, which occurred during the day. In the moderate and slightly unstable regimes, the relative frequencies have the larger percentage reaching 16% and 51%, respectively. The neutral (*Z/L* between ±0.1) and moderate ranges have a small number of runs with a ratio of 4%.Lastly, very stable with a ratio of 6% mostly occurred during the dawn night. The rarity of neutral cases in the atmospheric surface layer was expected because of the constant influence of surface heating or cooling, which drives either stable or unstable conditions most of the time.

The single most important factor in determining the shape of the column extending in the direction of the wind from a continuous point source is the standard deviation of vertical velocity fluctuations, $\overline{w^2}$ which was calculated from the root mean square of .Also, the Lagrangian time scale was computed using Eqs. (6 and 8) for each run. The mean values for Z/L, σw, T_L, and U with their standard deviation (SD) were calculated for each stability range. Table 2 displays the results of these parameters. It is an interesting result in this table that in neutral conditions, the ratio σ_w/U was 0.22 approaching the typical value (around **0.2)** (Al-Jiboori et al., 2001), reflecting turbulence generated by mechanical shear rather than buoyancy-driven processes**,** which dominate in unstable conditions.

The large SD was clear in *Z/L* values under very stable classification with values of 63.6 m/s. This

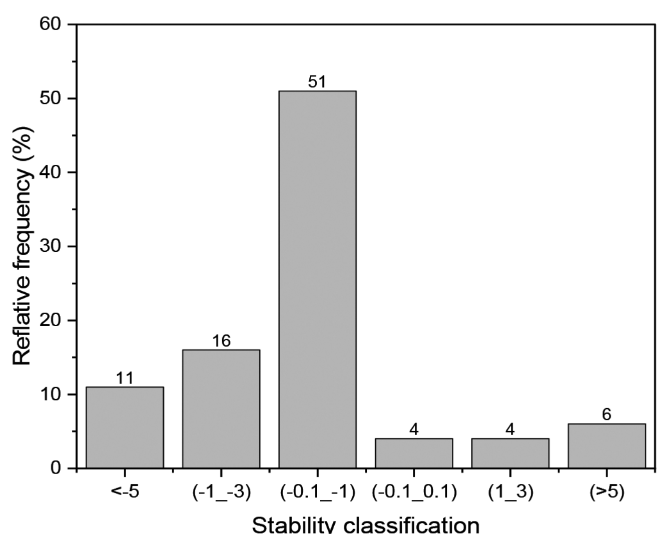

Figure 3: Histogram for Z/L results and their relative frequencies.

deviation became small in neutral and unstable air. In stable air, the σ_w values are smaller than those in neutral and unstable air. While mean T_L has large values in stable conditions and small values in neutral and unstable conditions. Lastly, mean wind speed was found to be low under stable conditions and becomes large in neutral and unstable segments, as shown in Table 2.

Vertical Wind Standard Deviation

This statistic is usually well expressed by the ratio (σ_w/U), which is a sensitive function of atmospheric stability and is independent of height, as shown in Figure 4. The non-linear relationship between the dimensionless quantities σ_w/U and Z/L was evident under unstable and stable conditions. There is a clear reduction in high instability that occurs in the daytime (Figure 4a). We notice an increase in the (σ_w/U) values at slightly stable conditions (Figure 4b) that usually occurs at night and then a decrease in Z/L. Several non-linear functions were tried to pass the best line through the data points, but the following expressions were the best to carry out this task.

$$\sigma_w/U = 0.15 - 0.01*(Z/L) + 0.001*(Z/L)^2 - 2.57*10^{-5}*(Z/L)^3 + 1.84*10^{-7}*(Z/L)^4 \ (Z/L<0) \quad (12)$$

$$\sigma_w/U = 0.12 + 0.002*(Z/L) + 1.86*10^{-4}*(Z/L)^2 (Z/L>0) \quad (13)$$

The results show that there is an inverse relationship between Z/L and σ_w/U. The quadratic correlation coefficient (R^2) indicated that the high value (~0.17) was in an unstable atmosphere compared to that in stable conditions to reach 0.13.

The Stability Parameter with Lagrangian Time Scale

Although we cannot accurately determine the particle trajectory, we can use statistical means to study the behaviour of pollutants at a very large distance from the source with atmospheric stability. This is done through an integrated Lagrangian time scale because atmospheric stability is a function of pollutant travel time, and therefore atmospheric stability has a major role in the mixing and dispersion of pollutants. In unstable conditions, the atmospheric mixing of pollutants is high, so the concentration of ground-level pollutants is low, and in stable atmospheric conditions, the atmospheric mixing of pollutants is low, so the concentration of ground-level pollutants is high. This can be explained by Figure 5, where Figure 5a shows the non-linear behaviour of T_L in unstable air, whereas in stable air this behaviour became linear as shown in Figure 5b. However, the best lines passed through the data points for both conditions. Eq. (14) below could obey the non-linear variation with $R^2 = -0.2$, while the linear equation (15) effectively fits the data for both Z/L and T_L, indicating the strong correction of pollutant diffusion over a large distance from the source with time scale.

$$T_L = (0.88 - 0.07*(Z/L)^{(0.53)})^{-1} \ (Z/L<0) \quad (14)$$

$$T_L = 1.39 + 0.52*(Z/L) \ (Z/L>0) \quad (15)$$

Since the vertical distance dispersion coefficient represents the standard deviation (σ_z) of the vertical wind distribution of the pollutant concentration, we discuss turbulent dispersion in the z-direction here

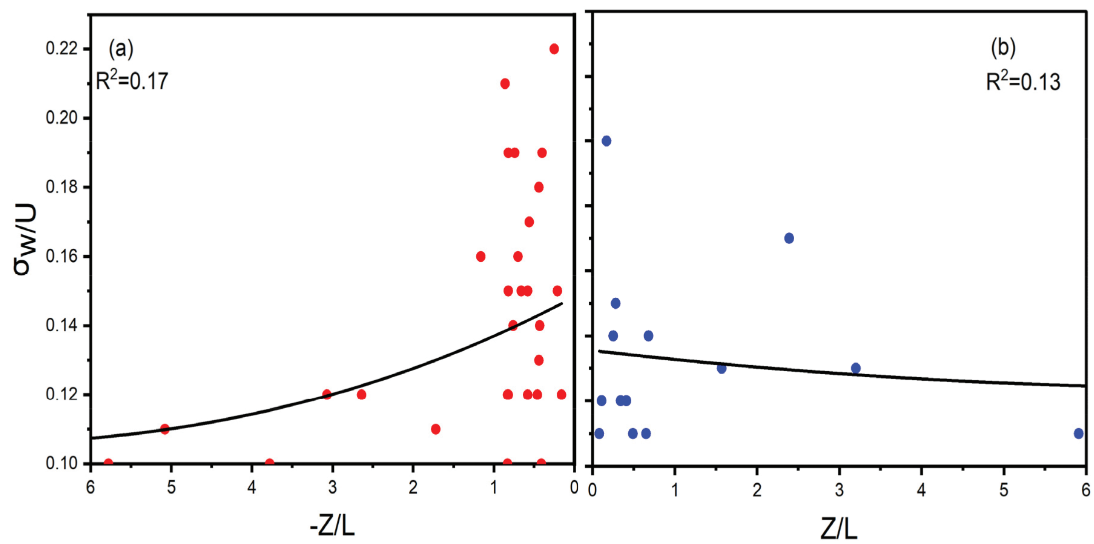

Figure 4: Variations of nondimensional quantity σ_w/U under (a) unstable and (b)stable conditions.

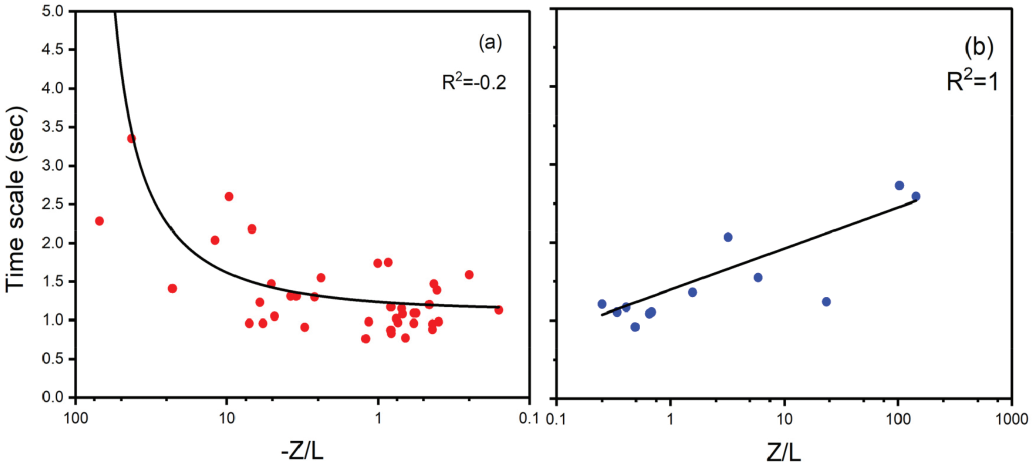

Figure 5: Pollutant dispersion behaviour during time scale with atmospheric stability.

because of its important role in measuring the dispersion of pollutants in the z-direction. Based on the results for σ_w and T_L at each classification of mean stability reported in Table 2, σ_z values were calculated using Eq. (9) for horizontal distances: 100, 300, 500, 700, 1000, 2000, 3000, 4000, and 5000 m, for the city of Baghdad to ensure the difference in the generation of atmospheric turbulence.

Figure 6 shows the variation of the standard deviation in the direction of z with distance for the types of stability. It has been shown that there is a non-linear variation in the values of (σ_z) for all particles above a certain distance and stability. It is also noted that (σ_z) is a function of the distance of the downdraft and the atmospheric stability so that the concentration of pollutants is greatest at the beginning and decreases with distance. In the convective boundary layer (Z/L>-5), the vertical dispersion in the urban atmosphere of Baghdad has large variation values with increasing horizontal distance, followed by moderate instability, while slightly unstable, neutral, and stable conditions have almost similar variations, as shown by their adjacent curves in Figure 6. This result is not surprising as the urban atmosphere of Baghdad is characterized by large amounts of solar radiation combined with mostly low wind speed.

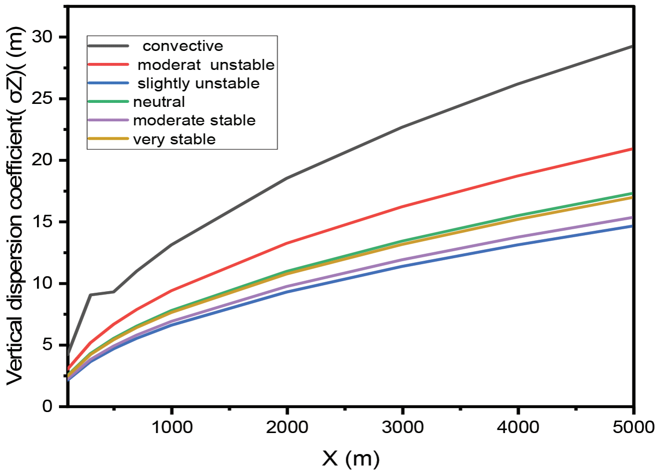

Figure 6: The variation of σ_z with horizontal distance for different stability intervals.

Conclusions

Turbulence observations obtained from a fast-responding 3D ultrasonic anemometer located 19 m above the roof of the Department of Atmospheric Sciences in Baghdad, during 10 selected days in the first six months of the year (2016), were used to demonstrate the importance of the vertical scattering coefficient in measuring the dispersion of pollutants under different atmospheric

Table 2: Mean values for Z/L, σ_W, T_L, and U with their SD

Z/L ranges	*Stability type*	*Z/L±SD*	*σ_w±SD(m/s)*	*T_L±SD(s)*	*U(m/s)*
<-5	Very unstable	-4.34±1.1	0.22+0.03	1.17+0.23	2.71
-1_-3	Moderate unstable	-2.27±1.1	0.28+0.04	1.42+0.65	2.63
-0.1_-1	Slightly unstable	-0.71±0.3	0.39+0.04	1.44+1.36	2.58
-0.1_0.1	Neutral	0.01±0.2	0.22+0.03	1.33+0.37	2.18
1_3	Moderate stable	2.39±0.8	0.12+0.02	2.07+0.71	1.19
>5	Very stable	55.76±63.6	0.14+0.05	2.03+0.74	1.35

conditions. An inverse relationship was found between σ_w/U and atmospheric stability. When *Z/L* was very unstable and moderately unstable, σ_w/U increased. In stable air, σw/U slowly decreases. Also, for stable conditions, a positive relationship was found between *Z/L* and the time interval for the dispersion of the pollutants T_L; as the T_L increases, the pollutants disperse vertically away from the source. The conclusion is significant; the vertical dispersion coefficient was significant with large values at increasing horizontal distances, especially in very unstable and moderately unstable conditions. Other remaining stability classifications show almost similar behaviour. To calculate the autocorrelation of the vertical wind speed with lag = 1, the lag time scale has large values of 2 s in moderately unstable air and smaller values of 1.2 s in very unstable air. The findings of this study can help in developing strategies for urban planning and environmental management such as providing insights into how pollutants move, mix, and dilute over time. Its use in urban planning allows for better decision-making regarding air quality control, pollution mitigation, and public health protection, ultimately leading to more sustainable cities.

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References

Al-Samarrai, H.M. and M.H. Al-Jiboori (2022). Estimation of the daily maximum air temperature for Baghdad city using multiple linear regression. *Al-Mustansiriyah J. of Science*, **33(4):** 9-14.

Al-Jiboori, M.H., Xu, Y. and Y. Qian (2001). Effects of different terrain on velocity standard deviations. *Atmospheric Science Letters*, **2(1-4):** 25-31.

Al-Jiboori, M.H., Al-Shaeer, M.A. and A.S. Hassan (2020). Statistical forecast of daily maximum air temperature in arid areas in the summertime. *J. Math. Fundam. Sci.*, **52(3):** 353.

Anfossi, D., Rizza, U., Mangia, C., Degrazia, G. and E.P. Marques Filho (2006). Estimation of the ratio between the Lagrangian and Eulerian time scales in an atmospheric boundary layer generated by large eddy simulation. *Atmospheric Environment*, **40(2):** 326-337.

Blackadar, A.K. (2012). *Turbulence and Diffusion in the Atmosphere: Lectures in Environmental Sciences*. Springer.

Carvalho, J.C., Vilhena, M., Degrazia, G.A. and M. Sallet (2013). A general Lagrangian approach to simulate pollutant dispersion in atmosphere for low-wind condition. *American Journal of Environmental Engineering*, **3(1):** 8-12.

Garratt, J.R. (1994). The atmospheric boundary layer. *Earth-Science Reviews*, **37(1-2):** 89-134.

Gyun, J., Kim, Y.G., Lee, S.J., Kwon, Y.S. and C.H. Cho (1986). Evaluation of the horizontal and vertical dispersion coefficients for the urban area. *J. Korean Soc. Atmos. Environ.*, **2(1):** 23-31.

Haraj, S.A. and M.H. Al-Jiboori (2019). Study of aerodynamic surface roughness for Baghdad city using signal-level measurements. *Baghdad Science J.*, **16(1):** 215-220.

Mazumder, G.C., Ibrahim, A.S.M., Shams, S.N. and S. Huque (2019). Assessment of wind power potential at the Chittagong Coastline in Bangladesh. *Dhaka University J of Science*, **67(1):** 27-32.

Maldaner, S., et al. (2014). Derivation of the turbulent time scales and velocity variances from LES spectral data: Application in a Lagrangian stochastic dispersion model. *The Open Atmospheric Science J*, **8(1):** 16-21.

McAlpine, J.D. (2009). *Lagrangian Stochastic Dispersion Modeling in the Atmospheric Surface Layer with an Embedded Strong Flow Perturbation*. University of Nevada, Reno.

Perrino, C., Pietrangelo, A. and A. Febo (2001). An atmospheric stability index based on radon progeny measurements for the evaluation of primary urban pollution. *Atmospheric Environment*, **35(31):** 5235-5244.

Peirce, J.J., Vesilind, P.A. and R. Weiner (1998). *Environmental Pollution and Control*. Butterworth-Heinemann.

Redah, G.A., Al-Jiboori, M.H. and O.T. Al-Taai (2023). Turbulent diffusion effect on $PM_{2.5}$ concentration above an urban canopy. *IOP Conference Series: Earth and Environmental Science*, **1223(1):** 012005.

Roth, M. and T. Oke (1993). Turbulent transfer relationships over an urban surface. I. Spectral characteristics. *Quarterly J of the Royal Meteorological Society*, **119(513):** 1071-1104.

Shen, Z., Cui, G. and Z. Zhang (2017). Turbulent dispersion of pollutants in urban-type canopies under stable stratification conditions. *Atmospheric Environment*, **156:** 1-14.

Stull, R.B. (2012). *An Introduction to Boundary Layer Meteorology*. Springer Science & Business Media.

Su, Y. and L. Sun (2021). Direct Numerical Simulations of Three-Dimensional Secondary Streaming of Oscillating Flows Through a Cylindrical Pellet, *In: ASTFE Digital Library*, Begel House Inc.

Wyngaard, J.C. (2010). *Turbulence in the Atmosphere*. Cambridge University Press.

Xia, H., Francois, N., Punzmann, H. and M. Shats (2013). Lagrangian scale of particle dispersion in turbulence. *Nature Communications*, **4(1):** 2013.

Xin, L., Fei, H., Yifen, P., Al-Jiboori, M., Zhaoxia, H. and H. Zhongxiang (2002). Identification of coherent structures of turbulence at the atmospheric surface layer. *Advances in Atmospheric Sciences*, **19:** 687-698.