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Article

Python programing Computational Analysis of Bulk-Layer Dynamic and Thermal Stability During Severe Dust Storms in Iraq

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Abstract: Dust storms are closely linked to atmospheric instability and its role in initiation, development and persistence of dust storms is especially significant in arid and semi-arid regions like Iraq. Although the dust storm has become more frequent and intense over the years, few quantitative measurements have been made of bulk-layer stability in the atmosphere over different climate regions of Iraq. In this study, a computational framework has been developed in Python, for the analysis of the severity, severity index, and severity analysis of the dust storm during severe, moderate, and light events, using ERA5 reanalysis data from the selected Iraqi meteorological stations, for atmospheric dynamic and thermal instability assessment.

The proposed framework combines cutting-edge atmospheric computation capabilities with automated data processing and visualization functionalities developed with Python scientific libraries, such as MetPy, NumPy, SciPy, Pandas, Matplotlib, and Xarray. Three physically meaningful stability indicators of the atmosphere were computed: Bulk Richardson Number (Ri), Wind Shear (WS) and Dry Air Index (DAI). They were studied at various pressure levels from 1000 to 200 hPa to provide the turbulence intensity, vertical wind interactions and dry air characteristics of dust storm evolution.

The results showed significant differences in the atmospheric stability between the studied stations in both spatial and temporal scales. The Bulk Richardson Number had a tendency to be lower for severe dust storms than for light and moderate dust storms, as did the wind shear, the DAI range and the instability score. The physical instability was highest in Ramadi, Hilla, Samawah, Baghdad and Al-Hayy, indicating the predominant role of dynamic turbulence and dry-air intrusions in the development of dust storms. The interpretation of Ri, WS and DAI has been combined and has successfully captured the atmospheric conditions suitable for dust lifting, transporting and persistence.

The study showed the advantages of using automatic computational meteorology for the diagnosis of the atmospheric instability and also presented a reproducible methodology for the dust storm monitoring, environmental assessment and environmental nanotechnology applications. The results have added to the knowledge of the dynamics of dust storms in Iraq, which can help developing advanced monitoring and early-warning systems for dust storms.

Keywords: python; programing; equation; dust storm; tephigram ; Richardson Number ; Dry Air Index ; Wind Shear.

1. Introduction

Dust storms are one of the most important hazards in the atmosphere in Arid and Semi Arid regions of the world. Geographically located in the Middle East, Iraq enjoys a large desert area, low vegetation cover and frequent occurrence of powerful synoptic scale weather systems, thereby making it a dust-prone country in the region. Over the last decade, the number of dust storms and their intensity has significantly increased, and their effects are becoming increasingly severe on transportation, public health, air quality, visibility, climate processes and socio-economic activities.[1]. Atmospheric stability conditions are very influential in the occurrence and development of dust storms. Dynamic and thermodynamic processes are necessary to generate turbulence, to mix dust particles upward and to accelerate the wind, in order to efficiently lift and transport dust particles. Therefore, knowledge of the vertical structure of the atmosphere and the stability parameters associated with it is a key to the initiation and development of dust storms [2].

In 2022, many dust storms have hit Iraq . One person died and 5,000 people were admitted to hospital. Flights from Baghdad and Najaf were grounded, Dust events occur frequently in arid and semi-arid areas, leading to a dramatic decline in visibility, severe air pollution and even adverse effects on human health. Because Iraq is geographically and climatically prone to dust storms, it is common to see intense urban dust storms occurring often during the spring and summer seasons [3]. Thermal stratification and mechanical forcing control atmospheric stability. The Bulk Richardson Number (Ri), Wind Shear (WS), and Dry Air Index (DAI) are examples of the most commonly used indicators to determine the evaluation of these processes. The Richardson Number represents the relative magnitude of buoyancy forces and dynamic turbulence, the Wind Shear represents the vertical wind shear and intensity of mechanical mixing, and the Dry Air Index gives information on the dryness of the atmosphere and the thermodynamic support for dust mobilization. These indicators are considered together to provide a full picture of the atmospheric conditions which are considered to be dust storm unstable. [4].

The application of computational meteorology has revolutionized atmospheric research by allowing the automatic processing of enormous meteorological data sets and the use of complex numerical calculations. Python has become one of the most widely used scientific computing packages because of the vast open-source library of tools to analyze the atmosphere, manage data, visualize data, and conduct numerical modeling. The combination of meteorological science and computational programming opens up new possibilities to enhance meteorological diagnosis and to minimize the uncertainties involved in hand calculations [5, 6]. Google Colab-based computerized calculation is implemented with the calculation of cloud for fast data handling and visualizing extraordinary measurements of atmosphere[7, 8]. This communitarian methodology exports numerical models and calculations to the figure of the Wind Shear, Richardson Number, and the Dry Air Index to determine insight into the condition of stability in the atmosphere at the various levels of pressing factor[9].

This examination centers around the 9 meteorology station in Iraq to cover the primary climatic and topographical changes[10]. The stations are Baghdad, Kirkuk, Ramadi, Al-Hayy, Al-Samawah, Nasiriyah, Najaf, and Hilla. This combines Urban, semiurban, and desert conditions, as well[11]. The information was taken from the ERA5 reanalysis dataset, which provides a high-resolution temporal and vertical portrayal of upper atmospheric conditions. The study requires three days of examinations per event from the very day before the day, the storm event, and the day following the storm day to compare the changes in stability[12].

Many studies have dealt with dust storm meteorology, air quality effects, and satellite observations in Iraq and the Middle East, yet most of them had been limited to the study of the synoptic meteorology, the satellite observations or the air quality effects. Less research has been conducted to perform multi-station, multi-level computational analysis of atmospheric stability using automated Python-based frameworks. Thus, the quantitative characterization of dynamic and thermal instability existing in different Iraqi climatic regions during dust storm is still a gap in research. This is addressed in this work through the creation of an integrated computational framework, based in Python, for the assessment of atmospheric stability from ERA5 reanalysis data. The framework includes automatic data processing, stability index calculations and graphical diagnostics for the study of atmospheric behavior of intense, moderate and light dust storms. The novelty of this work is that it is the first to integrate the three factors of Bulk Richardson Number, Wind Shear and Dry Air Index together in one computational environment to perform a comprehensive analysis of the dynamics of dust storms at various Iraqi stations and altitudes.

This study intends to accomplish is to evaluate the stability of the upper atmosphere during settling events using advanced computational instruments combined with meteorological datasets to give an exhaustive interpretation of significant atmospheric stability parameters[13]. It gives further insight into the dynamics of the atmosphere in Iraq and yields better future models of predictions for settling events and influences of stability parameters[14].

The Python-based study shows that automated data analysis and manipulation enhance meteorological data analysis by decreasing human errors [15].

2. Materials and methods

2.1 .Data Collection

The study investigated the changes in the stability of atmosphere at Bulk layer on dust storm days, for Iraq in 2022. Meteorological data collected at nine stations distributed across the country of Iraq, for 3 days running: dust day, before and after[16]. The data were obtained from the ERA5 reanalysis dataset and encompassed the subsequent variables:)Thermodynamic Temperature (Kelvin) ,Relative Humidity,Percentage ,Wind components (u and v), m/s ,Atmospheric Pressure(hectopascals) , the Applications and Instruments:

ERA5 data files have been uploaded to Google Colab. The data were filtered according to the geographical coordinates (latitude and longitude) of each station . The extracted data were organized by atmospheric pressure levels and hourly intervals.

2.1.1 Computation of Stability Metrics:

Simple parameters like the result of Wind Shear equation, Richardson Number, Dry Air Index and Hydrostatic Equation were used as the criteria of atmospheric stability[15] , To study the conditions of the atmosphere associated with dust storm events, an extensive computational system was developed by processing ERA5 reanalysis data and by using Python programming. The framework incorporates data extraction, pre-processing, vertical atmospheric analysis, computation of stability indicators, and dust properties analysis. The overall flow chart used in the present study is shown in figure (1), from data acquisition to the final evaluation of the atmospheric stability and its implications to the environment , shown in figure (1) The analysis started by downloading ERA5 reanalysis data and choosing 9 meteorological stations for Iraq. Vertical atmospheric analysis was performed at various pressure levels after extraction and pre-processing of such atmospheric variables as temperature (T), relative humidity (RH), and horizontal wind components (U and V). Then, the principal stability indicators – Potential Temperature (θ), Wind Shear (WS), Richardson Number (Ri) and Dry Air Index (DAI) – were computed to provide an indication of the atmospheric stability condition. These indicators were subsequently combined to assess atmospheric instability and create tephigram graphics to help interpret the vertical structure of the atmosphere during dust storms. Finally, the results obtained were assessed for dust storm dynamics and were also shown as their possible application in the field of environmental nanotechnology in monitoring air quality and assessing atmospheric particulate.

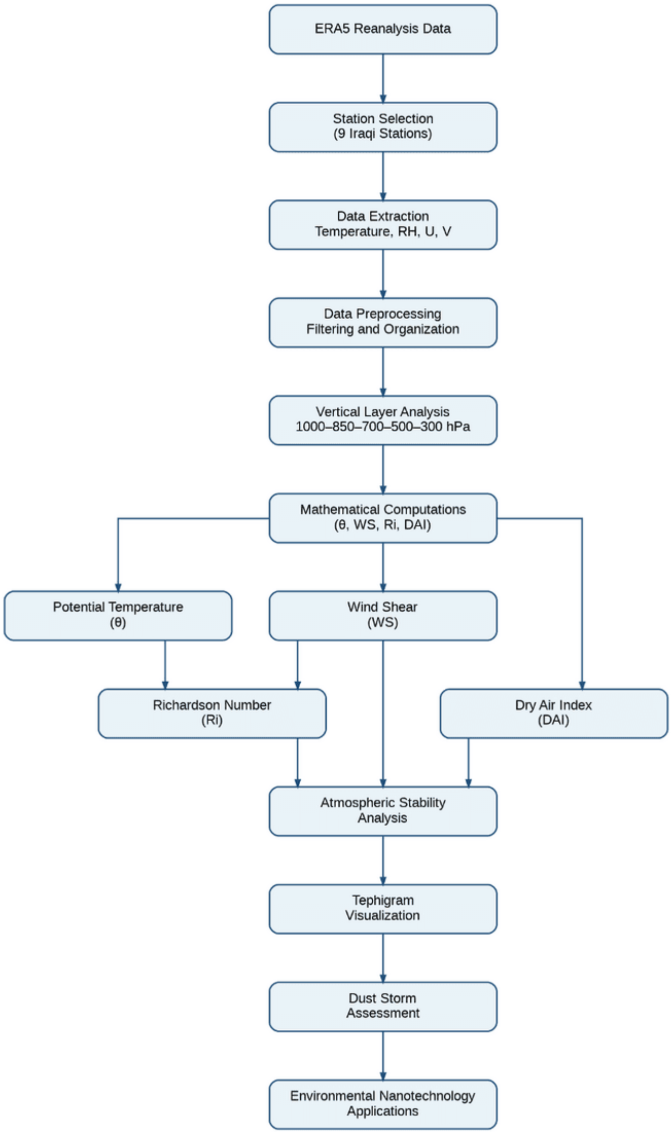

Figure 1 : Computational Framework of Atmospheric Stability Analysis

2.1.2 Data Programming

1. The Python language was used to run the data programming process on the Google Colab platform providing a cloud-based, collaborative coding environment. The study has been conducted through the Google Colab application using Python as the main programming language[17]. The measures of atmospheric stability and other related calculations were carried out in Python. The choice of Python was based on its flexibility and easy availability of powerful modules that simplified the data manipulation and analysis process [18] . The significant aspects of data programming as used in this study include

2. Preprocessing and Data Management:

- The **xarray** library was employed to effectively read, organize, and handle multi-dimensional ERA5 reanalysis data[19] , Data was organized and categorized according to atmospheric pressure levels and hourly intervals for analytical convenience , the following scientific computer libraries were used in the analysis (as Figure 2) , which was carried out in a Jupyter Notebook environment ,In this study, the software architecture used is shown in figure (2). The Python packages "Pandas" and "NumPy" were used for data management and numerical operations, and "SciPy" was used to access other scientific computation functions. MetPy was used for meteorological calculations, which included calculations of atmospheric stability indicators. The atmospheric profiles were produced and graphical visualizations were made with the help of the Xarray and Matplotlib packages for the ERA5 reanalysis datasets. The workflow and algorithm diagrams were also created with the help of Graphviz. These libraries were incorporated with the computation of Wind Shear (WS), Richardson Number (Ri), Dry Air Index (DAI) and Tephigram based analysis for dust storm evaluation.:

Matplotlib: to present the metrics of atmospheric stability[20].

NumPy: data processing and calculating numbers [21].

SciPy: used to handle computations in science, including the calculation of Wind Shear and Richardson Number[22].

MetPy : to handle and analyze meteorological data[5].

Pandas: manipulation and processing of structured data [23] :

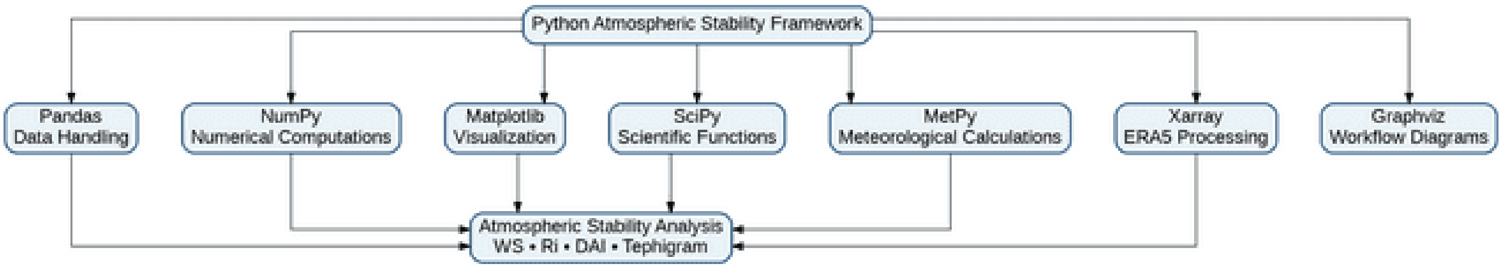

Fig. 2. computer python libraries .

3. Data Processing

Hourly atmospheric data were obtained for all upper-air pressure levels (200, 300, 400, 500, 600, 700, 850, and 1000 hPa)[24]. The following steps were implemented in each of the stations, the analysis of the atmosphere stability was carried out in Python, and the MetPy, SciPy, and Matplotlib modules were used. ,as an example the atmospheric stability analysis which uses the MetPy, SciPy and Matplotlib modules. The Richardson Number and Wind Shear were computed through the following method at different levels of pressure .

A data processing workflow was created using Python to process the data in a systematic and reproducible manner during a dust storm event. The workflow includes extraction and preprocessing of ERA5 reanalysis data, computing of atmospheric stability indicators and visualization procedures. The chain of computational steps used in the present study is shown in Figure (3), which presents the evolution of the raw meteorological data into scientifically meaningful outputs, which are useful for dust storm assessment.

The detailed algorithm used for processing atmospheric data from ERA5 is shown in figure (3). The steps start with loading and arranging meteorological variables, such as temperature (T), relative humidities (RH), and horizontal wind components (U and V) at various pressure levels. The vertical differences of the atmosphere are then computed and used in the determination of the principal characteristics of stability such as the Wind Shear (WS), the Richardson Number (Ri) and the Dry Air Index (DAI). The derived profiles and tephigrams are then analyzed and compared under various dust storm situations to assess the atmospheric instability, turbulence intensity and dryness characteristics during the development and evolution of dust storms.

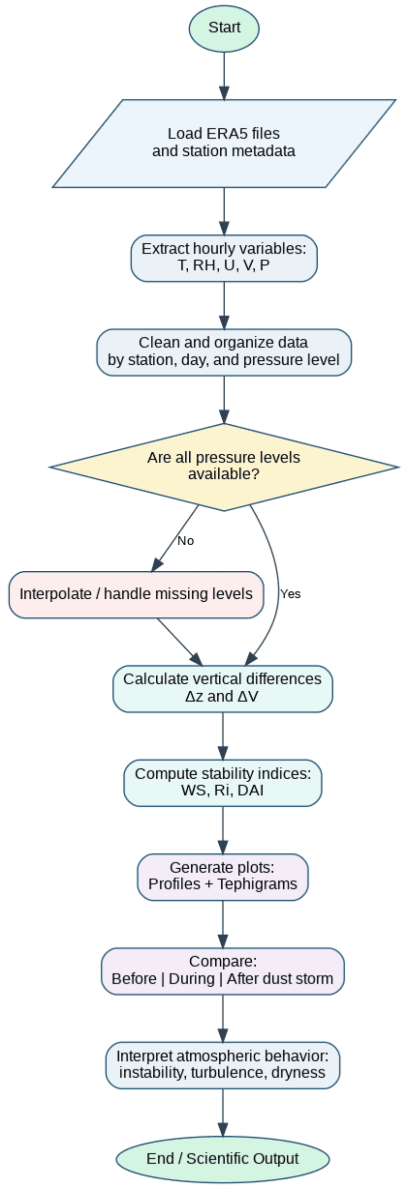

Figure (3) : Python-Based Data Processing Algorithm for Atmospheric Stability Analysis Using ERA5 Reanalysis Data.

4.Mathematical Computations:

Advanced numerical computations, encompassing the development of stability metrics (Wind Shear, Richardson Number, Dry Air Index), were executed directly in Python , Equations were solved automatically, ensuring consistency and minimizing manual errors by programing python [8].

The atmospheric stability indicators used in this study were calculated from a set of thermodynamic and dynamic atmospheric variables from the ERA5 reanalysis. The calculations were based on the interactions of temperature, humidity, wind components and pressure levels in order to define atmospheric stability conditions during dust storm events. Figure (4) displays the mathematical basis used to derive the main stability indices and the relationships between these and the dust storm dynamics, Figure (4) summarizes the mathematical relationships between the atmospheric variables and stability indicators presented in this study.

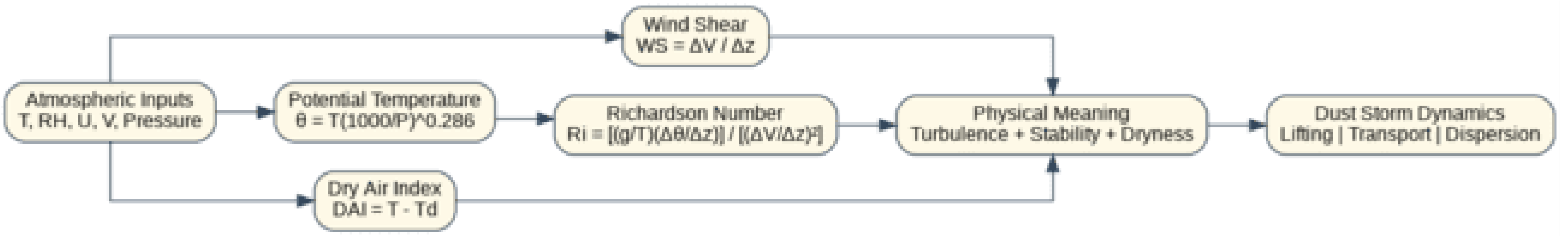

Figure (4) : Mathematical framework illustrating the derivation and interaction of Potential Temperature (θ), Wind Shear (WS), Richardson Number (Ri), and Dry Air Index (DAI)

A - Wind shear equation :

measures the change in wind speed with height. It is used to analyze turbulence and its role in dust storm dynamics eq (1) (Lima et al., 2020).

$$WS = \sqrt{((U_2 - U_1)^2 + (V_2 - V_1)^2)} \qquad (1)$$

ΔV: Change in wind speed (difference in velocity between two different levels).

Δz: Difference in altitude between the two levels.

significant wind shear is a sign of atmospheric turbulence, which can cause vortices and other disturbances that can cause instability in the atmosphere [25] .

B -Richardson Number equation (Ri) :

Ri evaluates atmospheric stability by comparing thermal and mechanical effects. Low values indicate turbulence, essential for assessing storm intensity eq (2).

$$Ri_B = \frac{g}{\theta m} \frac{\left(\frac{\Delta\theta}{\Delta z}\right)}{\left(\left(\frac{\Delta U}{\Delta z}\right)^2\right) + \left(\left(\frac{\Delta V}{\Delta z}\right)^2\right)} \qquad (2)$$

g: Earth's gravitational acceleration (9.81 m/s²).

T: Absolute temperature (in Kelvin).

Δθ: Difference in potential temperature between two different levels.

Δz: Difference in altitude between the two levels.

ΔV/Δz: Wind shear, as previously defined.

dimensionless metric used to measure atmospheric stability is the Richardson number (Ri). It explains how buoyant forces and shear effects are balanced. Increased turbulence and atmospheric instability are indicated by a lower Ri[26].

C- Dry Air Index equation:

This index is used to calculate the variation of temperature with altitude and is used to gain insight into thermal stratification and its effects on the development of dust storms eq (3).

$$DAI = (T - 273.15) * \left(1 - \frac{RH}{100}\right) \qquad (3)$$

T : Actual temperature.

Td: Dew point temperature.

The amount of moisture in the atmosphere is indicated by the Dry Air Index. While lower levels reflect more humid air, which increases the chance of precipitation and cloud formation, higher values indicate drier air[27].

D- Potential Temperature

The Potential temperature was calculated as:

$$\theta = T * \left(\frac{1000}{p}\right)^{0.286} \quad (4)$$

θ = Potential temperature (K)

T = Air temperature (K)

p = Atmospheric pressure (hPa)

5. Visualization: Tephigrams and Stability Measures

Both Matplotlib and MetPy tools were used to create graphs that accurately represented atmospheric variables [28].

The creation of lucid, publication-ready visuals was made easier by customizable options.

In order to help evaluate stability conditions, tephigrams were created to examine the thermal and kinetic structure of the atmosphere during dust storm episodes, Tephigrams were produced for all pressure levels to illustrate the atmospheric thermal and dynamic structure. Every graph contained:

Temperature (Celsius degrees)

Wind Velocity (m/s)

Relative Humidity Percentage

visualizations , created using the MetPy toolkit, help in the stability conditions analysis of atmosphere during the events of dust storm

Plotting the important stability measures of atmosphere against the pressure levels of upper air , such as Wind Shear, Richardson Number, and the index of Dry Air, was represented by the additional visualizations. These graphs give a more thorough understanding the dynamic features of the periods of storm by providing a thorough evaluation fluctuations of turbulence and stability[29].

5.Advantages of Python and Google Colab:

The utilization of Python facilitated the seamless integration of data pretreatment, analysis, and visualization under a singular framework [30] , Google Colab provided accessibility, facilitating real-time collaboration, code exchange, and the utilization of computational resources without necessitating local infrastructure[31] , Python is simple to use, but it is a real programming language, offering much more structure and support for large programs than the shell has , The methodology of programming not only speeded up the analytical process but also ensured repeatability, allowing other researchers to effortlessly replicate or expand the study[31].

A multi level assessment of the stability of atmosphere across several pressure layers was part of the analysis process, which made it possible to fully comprehend how stability measures changed over time. Using the method of comparison, the condition of stability conditions on the day of the dust storm were compared to the days before dust storm and after dust storm , emphasizing dynamic of the changes of atmosphere brought on by the dust storm . In order to evaluate regional differences in stability, a comparison at the station level was also carried out, combining data from every monitoring location. By highlighting the part dust storms play in changing upper-level dynamics, this method shed light on the vertical and temporal evolution of atmospheric stability

3. Results and discussion

3.1 Result of Bulk Boundary Layer stability assessment during dust storm

A. tephigram analysis across stations

This section delineates the findings of the Tephigram study performed at nine locations around Iraq over three pivotal intervals: the day preceding, the day of, and the day following dust storms. It focuses on examining the major atmospheric variables, namely temperature, speed of wind, and relative humidity, but at various pressure levels, with a visualization to each station. Such results explain the dynamic and thermal atmospheric conditions which favour the observed dust storms.

Structure of Analysis

Each of the stations is investigated on the following aspects:

1. Change of temperature between levels of pressure.

2. Dynamics and instability patterns in the wind speed.

3. Relative humidity data and signs of dryness as a cause of dust activity.

The Tephigram analysis of Baghdad in dust storm event implies(see Figure 5), A large decreasing trend of temperature with altitude, which implies that the high atmosphere is stable, but the upper atmosphere is less stable, Wind velocities that are approaching 50 m/s in the high atmosphere, which imply that the top atmosphere is stable, but the upper strata are unstable, Relative humidity is significantly decreasing in the top strata, which implies that the dry air is intruding during the dust storm incident.

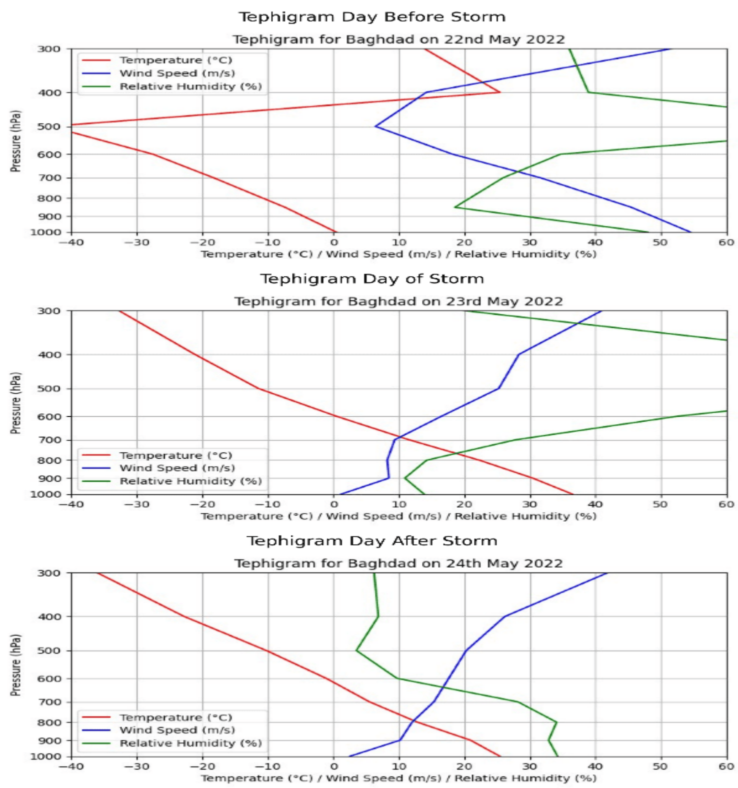

Fig. 5. Tephigram of Baghdad Station.

The Tephigram traces of Kirkuk show (see Figure 6) , gradual decrease in temperature at all altitudes, with great instability in the middle troposphere, Wind velocities above 30 m/s in high altitudes during dust storm, A relative humidity trend which shows gradual desiccation of the middle and upper strata, and suggests increased dust transport.

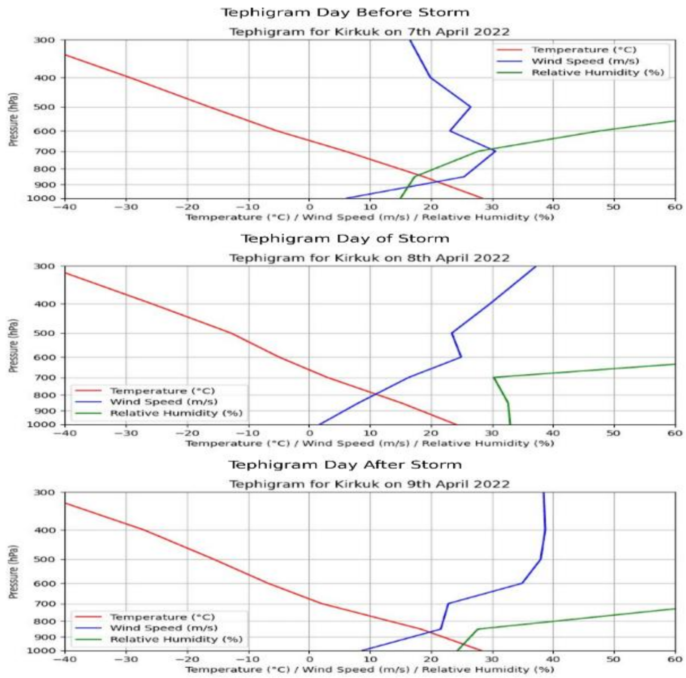

Fig 6 . Tephigram of Kirkuk Station .

The findings of Ramadi indicates (see Figure 7) A marked drop in temperature with height, this shows that there is a standard lapse rate, Wind speed has constant increases with height, reaching its peak of 40 m/s, Dry air infiltration is represented by the low relative humidity of the higher layers on the day of dust storm.

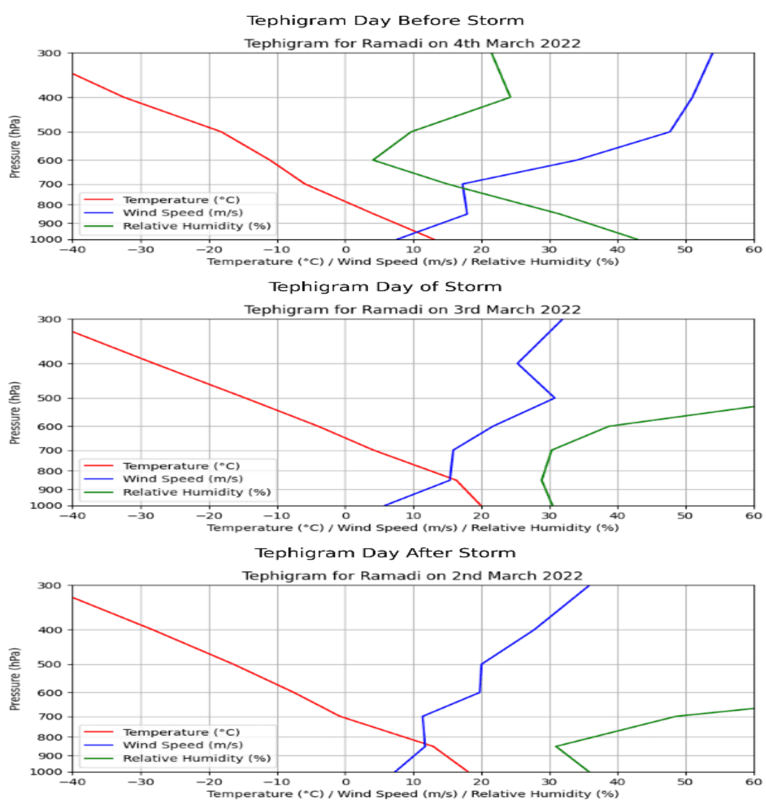

Fig.7. Tephigram of Ramadi Station.

According to Najaf, Tephigrams suggest (see Figure 8), A high lapse rate of temperature, with enhanced instability during the storm day, Wind speeds reaching 35 m/s, which enhanced the dust suspension and motion, A strong decrease of relative humidity across the air column, which increased the dust movement.

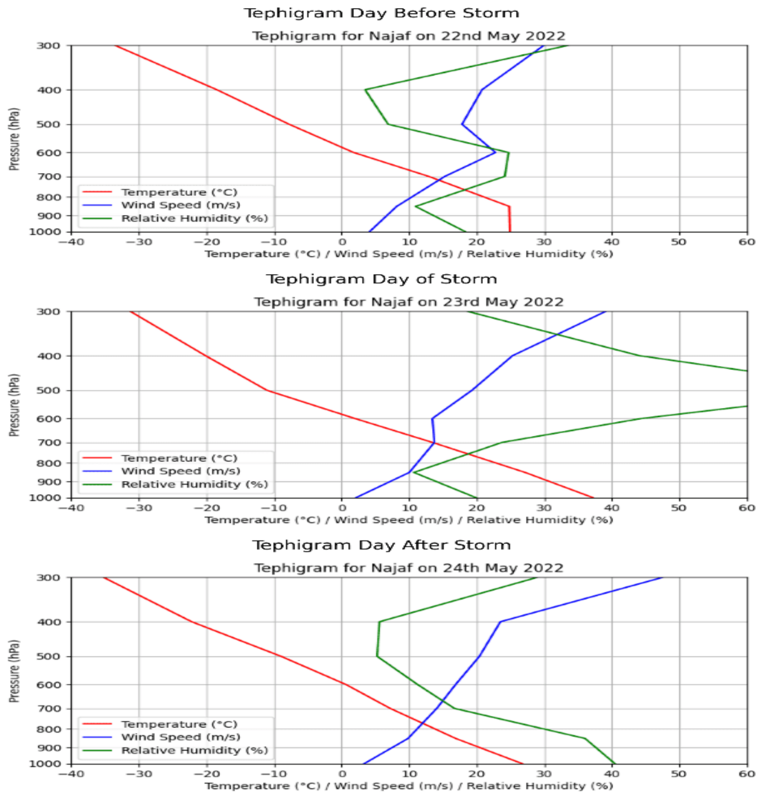

Fig.8.Tephigram of Najaf Station.

The Tephigram analysis of Al-Samawah shows (see Figure9) , Stable lower layers with cooling in high altitudes, which favors the occurrence of atmospheric instability, Moderate wind velocities of about 25 m/s, with maxima at higher altitudes mid-troposphere, and Dry air fingerprints through the constant low relative humidity is seen to facilitate the development of dust storms.

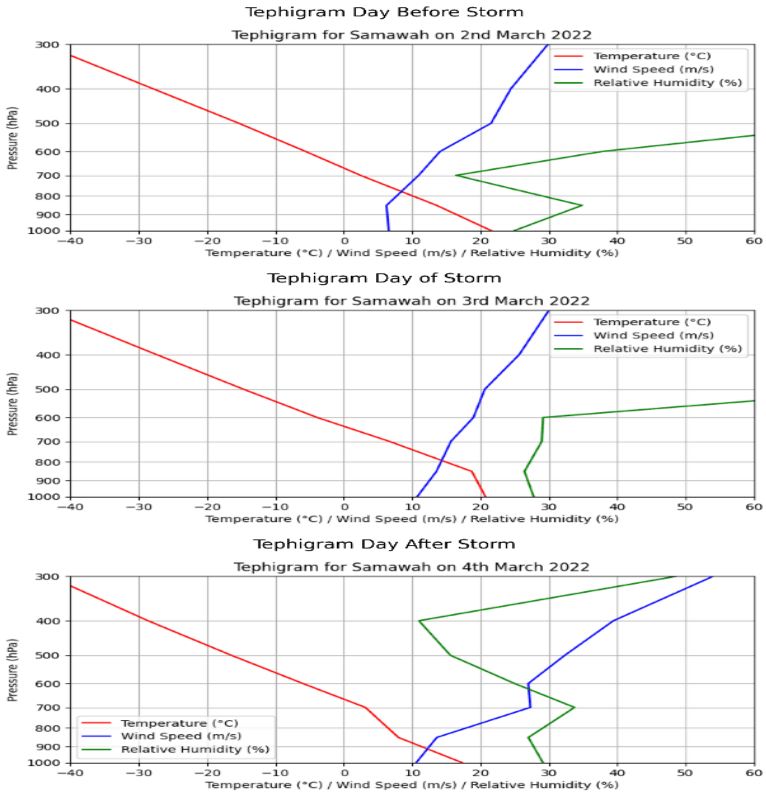

Fig.9. Tephigram of Al-Samawah station.

Nasiriyah shows (see Figure 10) , Significant cooling in the mid-to-upper atmosphere, accompanied with temperature inversions on specific days , Strong wind speeds beyond 30 m/s result in increased dust storm activity , Extremely low relative humidity values, signifying arid conditions.

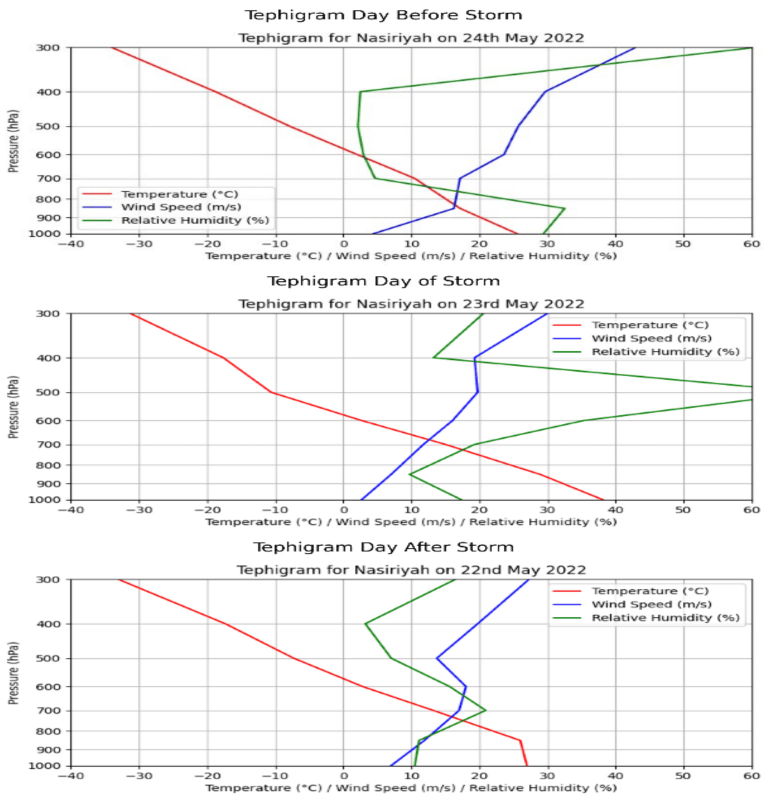

Fig. 10. Tephigram of Nassriyah Station .

Hilla's atmospheric structure indicates (see Figure 11) , A normal temperature lapse rate as altitude increases, In the middle layers, wind speeds can exceed 30 m/s, which helps move dust , Relative humidity levels showed signs of progressive drying.

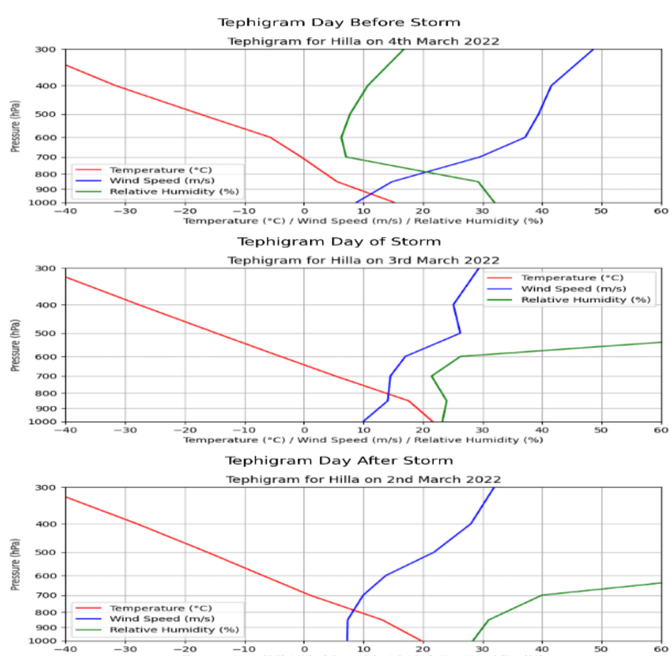

Fig.11. Tephigram of Hilla Station.

Al-Hayy's Tephigram analysis shows (see Figure 12) , There are no notable inversions, and the temperature drops sharply with height , High wind speeds, up to 30–40 m/s, especially at mid-levels , The dominance of dry air at all pressure levels increases the likelihood of dust storms.

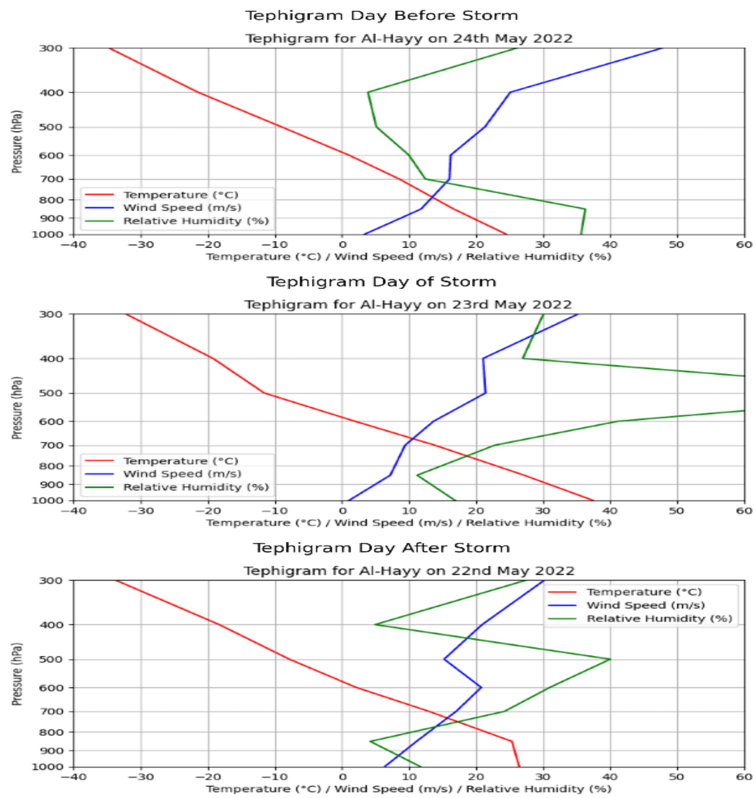

Fig.12. Tephigram of Al-Hayy Station.

B. Analysis of Meteorological Stations by equation

The computational analysis was done using Python programming language to analyze the Iraqi meteorological stations data and study the changes in the atmospheric stability indicators with time. ERA5 reanalysis data were used to perform the calculations, done through Python scripts to obtain Bulk Richardson Number (Ri), Wind Shear (WS), and Dry Air Index (DAI). Hourly plots for these indicators were done for each dust case, and severe, moderate, and light dust storm conditions were compared. The shaded portions of Figures (13-20) indicate the three types of dust, and the minimum Bulk Ri, maximum WS, DAI range, physics weight, instability score and physical interpretation for each station and dust case are summarized in Table (1).

Severe dust cases were generally reported with maximum instability scores at most stations as presented in Table (1). Ramadi exhibited physical instability with the highest score of 0.88, wind shear of 43.06 m/s and DAI range of 276.86 for severe case. Very high instability scores for Hilla (0.83) and Samawah (0.81) also were observed, with both areas having large differences in dryness and strong wind shear that contributed to intensity of the dust storms. The instability scores for Baghdad and Al-Hayy were also found to be 0.75 during severe cases, which is affirmation for the high value of the dynamic and thermal disturbance as seen in Figure (13) and (20).

As seen in Figure (13), there were clear differences in Bulk Ri, WS and DAI in severe, moderate and light cases at Baghdad. The high physical instability indicated in Table (1) corresponded to the severe case, which was characterized by strong wind shear and large DAI variation. The moderate case, however, had an overall lower instability score of 0.29, primarily because of the lower maximum wind shear and the limited DAI range. This means that the column in the atmosphere was less disturbed in the moderate case.

Figure (14) indicates that for Kirkuk severe and moderate cases were related to high wind shear values. This is consistent with the results in Table (1) which showed maximum WS in the severe case as 37.52 m/s while it was 38.14

m/s in the moderate case. The instability score for both the severe and moderate case was high, 0.70 and 0.64 respectively. This implies that mechanical turbulence, particularly the vertical shear, had a significant effect on Kirkuk.

Figure (15) shows that the station of Ramadi had the highest percentage of severe case instability among all the stations. From the computational results, presented in Table (1), one can see that the minimum Bulk Ri is very low being 1.52, while the maximum WS is 43.06 m/s and the large range of DAI is 276.86. These combined values are a sign of a very disturbed atmosphere of turbulence and variation of dryness. The curves generated by Python are clearly identifiable, as the severe case is more active than the light case.

Figure (16) shows that Najaf had a high physical instability during the severe case with an instability score of 0.72. The moderate and light cases however, had low instability scores of 0.25 and 0.31 respectively. The difference suggests that the strong event was primarily dominated by increased wind shear and increased DAI range, while the other two cases were dominated by weaker dynamic forcing.

During the severe case Samawah in Figure (17) had the highest instability score of 0.81. The maximum wind shear was 37.52 m/s, and the DAI range was 261.36, reflecting high variability of dryness with active turbulent mixing. The moderate and light cases had moderate instability, indicating that Samawah was still sensitive to wind shear and dryness fluctuations in the less severe dust cases.

One of the most pronounced responses to the instability was from Hilla as shown in Figure (18). Table (1) shows that among all stations the high value of DAI ranges from 288.29 at severe station, while maximum WS and instability score were 37.79 m/s and 0.83 at severe station respectively. This result indicates that the dust event was very well determined by both dynamic turbulence and thermal dryness, which is what was observed by Hilla. Interestingly, the light case also presented moderate instability, with an instability score of 0.64, which would mean that the disturbance of the atmosphere continued even under low dust conditions.

The figure (19) shows the Nasiriyah town which had high instability during the severe case, with an instability score of 0.69. But the moderate and light cases were only moderately unstable with a score of 0.29 and 0.12 respectively. This result clearly shows the distinction between severe and non-severe conditions of dust. A low instability score during the light case indicates lower wind shear as well as a more stable atmosphere.

Instability score of al-Hayy was high during the severe case (0.75), as shown in Figure (20). The maximum wind shear was 31.28 m/s and DAI reached, 254.42. The values correspond to dryness fluctuation and wind-driven turbulence, which both played a part in the development of dust storms. Moderate and light cases demonstrated moderate instability, which is a confirmation for continuous but varying disturbance in the atmosphere for all the categories of dust in Al-Hayy.

The overall results of the equation analysis with Python showed that the severe dust cases were mostly linked with the lower Bulk Ri value, higher wind shear, and larger DAI range. The hourly plots were correlated to the quantitative indicators in Table (1) to help give a better computational interpretation to the atmospheric instability. The results show that the intensity of dust storms over the Iraq is not influenced by a single factor but it is influenced by the combined effect of the dynamic turbulence, the vertical wind shear and the dryness of the atmosphere. This demonstrates the importance of using Python-based atmospheric computation to diagnose the behavior of dust storms and to aid future environmental monitoring and environmental nanotechnology applications.

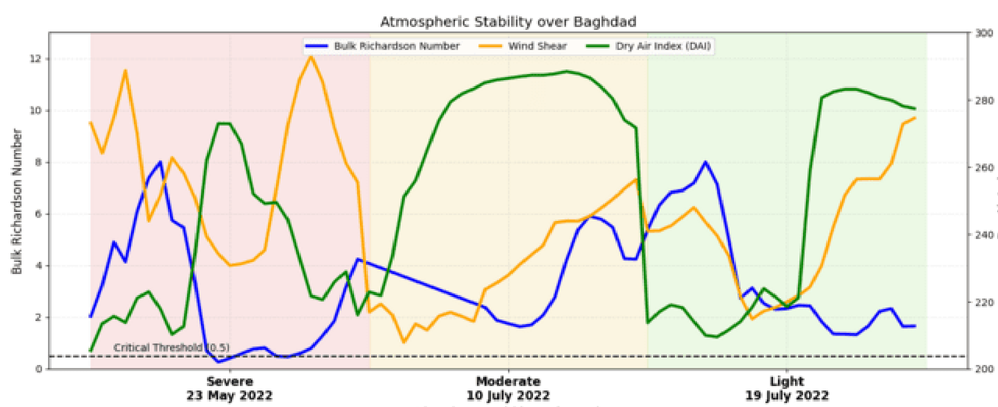

Fig. 11. Atmospheric Stability Profile for Baghdad.

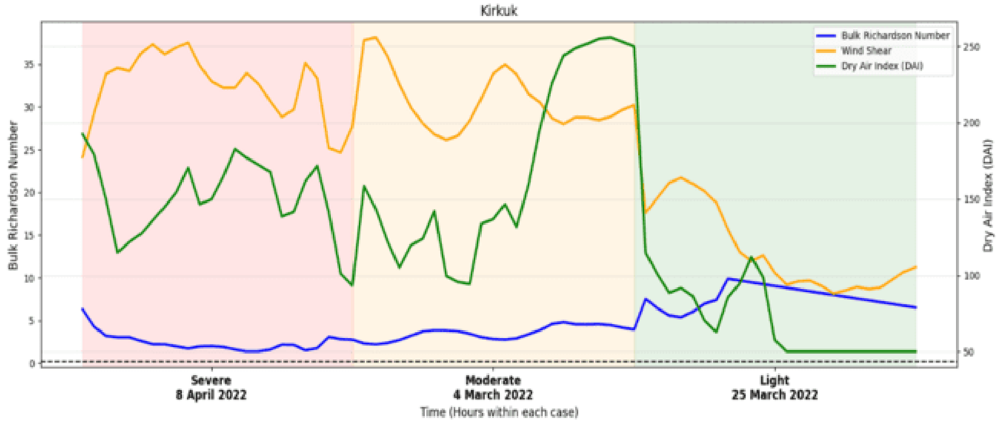

Fig.12. Atmospheric Stability Profile for Kirkuk

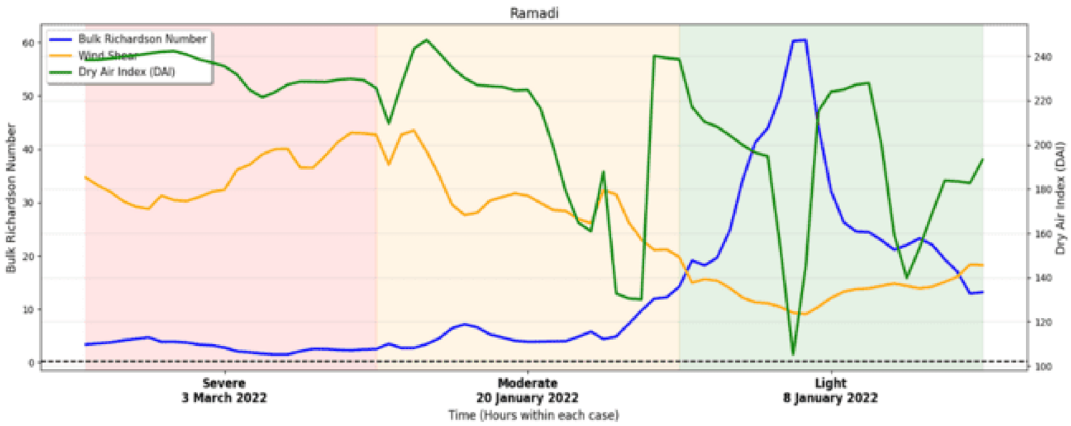

Fig.13. Atmospheric Stability Profile for Ramadi

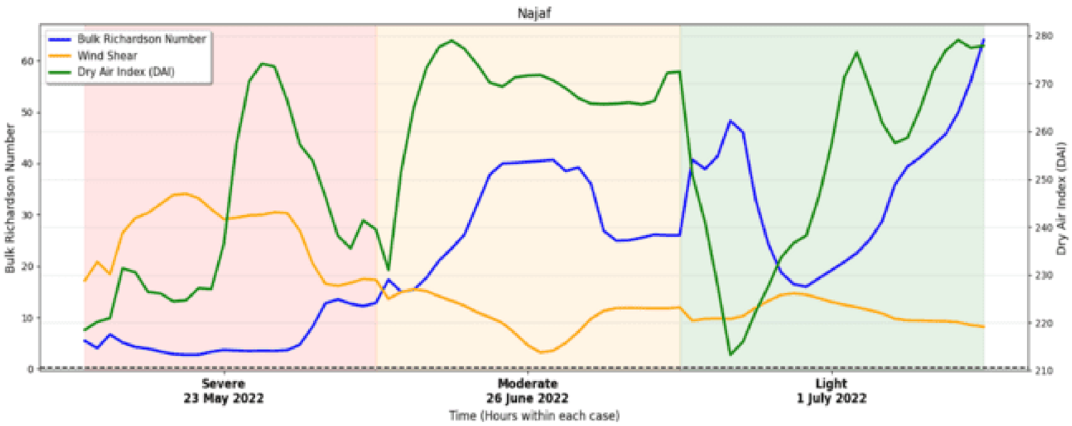

Fig.14. Atmospheric Stability Profile for Najaf.

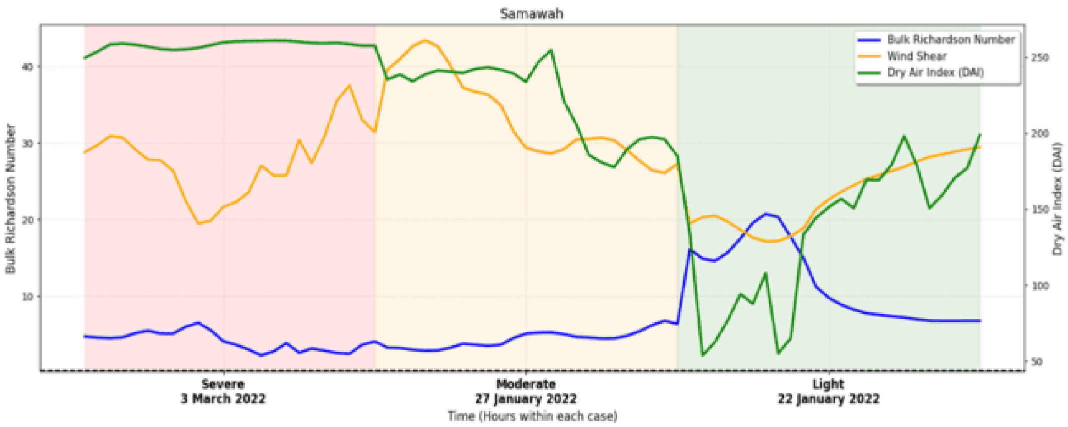

Fig.15. Atmospheric Stability Profile for Samawah.

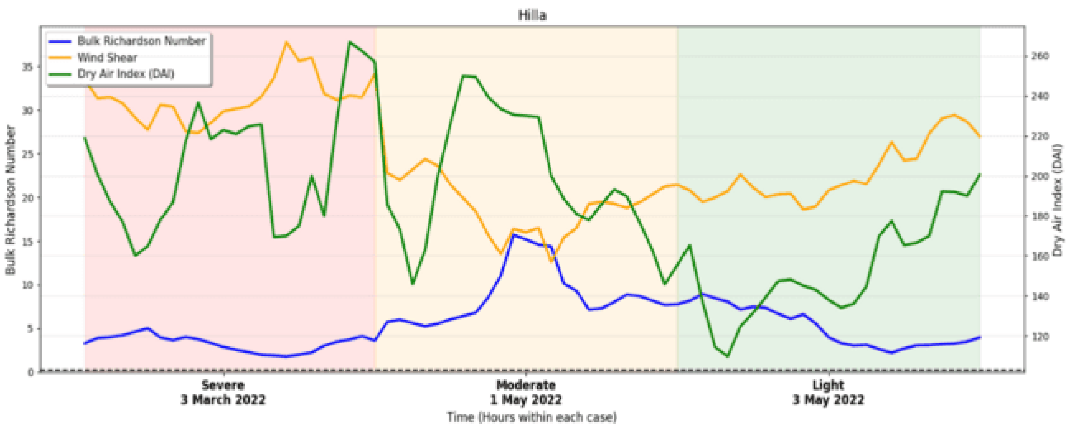

Fig.17. Atmospheric Stability Profile for Hilla.

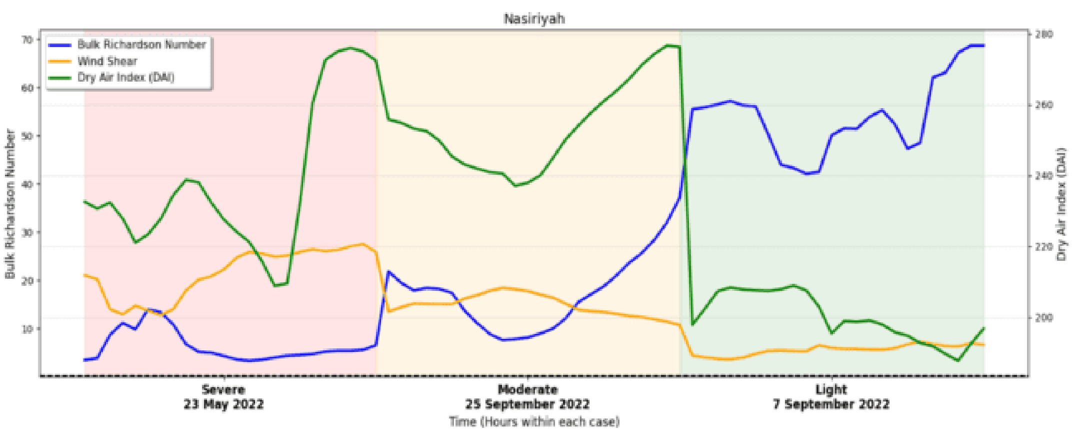

Fig.18. Atmospheric Stability Profile for Nasiriyah.

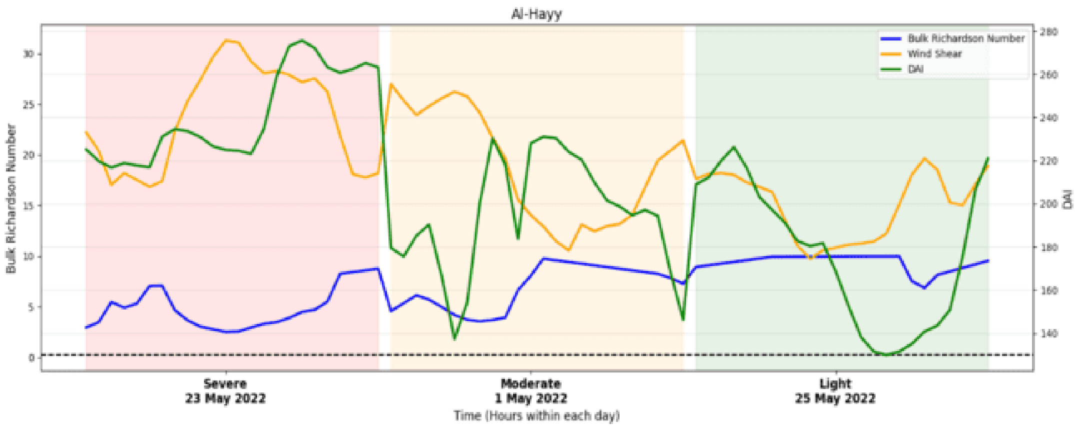

Fig.19. Atmospheric Stability Profile for Al-Hayy.

Station	Dust Case	Min Bulk Ri	Max WS (m/s)	DAI Range	Physics Weight	Instability Score	Physical Interpretation
Baghdad	Severe	2.71	32.92	254.27	4.01	0.75	High physical instability
Baghdad	Moderate	46.48	9.42	66.61	142.75	0.29	Low physical instability
Baghdad	Light	7.18	18.44	73.72	21.40	0.38	Moderate physical instability
Kirkuk	Severe	1.37	37.52	198.93	1.09	0.70	High physical instability
Kirkuk	Moderate	2.21	38.14	161.63	0.80	0.64	Moderate physical instability
Kirkuk	Light	5.38	21.72	204.33	9.21	0.60	Moderate physical instability
Nasiriyah	Severe	3.32	27.53	236.29	3.19	0.69	High physical instability
Nasiriyah	Moderate	7.61	18.46	39.62	7.88	0.29	Low physical instability
Nasiriyah	Light	42.10	7.27	104.65	7.79	0.12	Low physical instability
Al-Hayy	Severe	2.52	31.28	254.42	3.28	0.75	High physical instability
Al-Hayy	Moderate	3.57	26.98	185.01	4.14	0.59	Moderate physical instability
Al-Hayy	Light	6.86	19.64	132.59	4.50	0.45	Moderate physical instability
Hilla	Severe	1.79	37.79	288.29	0.92	0.83	High physical instability
Hilla	Moderate	5.25	24.38	161.10	3.21	0.50	Moderate physical instability
Hilla	Light	2.21	29.43	225.61	2.25	0.64	Moderate physical instability
Najaf	Severe	2.71	34.08	222.00	3.80	0.72	High physical instability
Najaf	Moderate	14.99	15.50	47.90	8.82	0.25	Low physical instability

Najaf	Light	16.00	14.71	81.08	13.63	0.31	Low physical instability
Ramadi	Severe	1.52	43.06	276.86	0.94	0.88	High physical instability
Ramadi	Moderate	2.73	43.50	133.76	3.12	0.63	Moderate physical instability
Ramadi	Light	12.93	18.35	142.67	13.83	0.42	Moderate physical instability
Samawah	Severe	2.24	37.52	261.36	1.22	0.81	High physical instability
Samawah	Moderate	2.86	43.39	88.85	1.13	0.56	Moderate physical instability
Samawah	Light	6.74	29.44	201.15	5.08	0.62	Moderate physical instability

3.2 DISSCUSSION

It is shown in the present study that the intensity of the dust storm over Iraq is not affected by any single parameter but a complex interaction between the dynamic turbulence, vertical wind structure and dryness of the atmosphere. These interactions have been captured through a combination of Bulk Richardson Number, Wind Shear and Dry Air Index in the computational framework developed in Python, and a quantitative (as well as visual) evidence of the atmospheric instability associated with development of dust storm has been obtained.

From the results given in Table (1), it is seen that a regular trend is followed at all the stations investigated. The minimum Bulk Richardson Numbers were significantly lower, the maximum Wind Shear values were significantly higher, the DAI were broader and the instability were significantly high for severe dust storm events as compared to moderate and light dust storm events. They show that mechanical turbulence and thermodynamic forcing are both required components for severe dust storms to develop, which brings the column to instability.

These results showed that in all stations, Ramadi had the highest value of instability (0.88) followed by Hilla (0.83) and Samawah (0.81). Additionally, some of the highest wind shear values and largest dryness indices were observed at these stations, indicating very favorable conditions for the lifting and transport of dust particles. The dominance of wind shear in these regions underscores the significance of dynamic forcing mechanisms in the development of atmospheric turbulence and increase of vertical momentum transfer.

The hourly computational profiles in Figures (13-20) offer additional information on the temporal characteristics of atmospheric instability. The atmospheric indicators rather than showing static behavior, varied greatly during the events studied. Such time variability is indicative of the dynamic interaction between thermal gradients, moisture distribution and wind-field dynamics with the development of dust storms. It is hard to detect such a behaviour by observation alone, and showcases the benefit of automated computational analysis.

The complementarity of the three stability indicators has been demonstrated to be an important result of the study. Bulk Richardson Number, in addition, gives information about the atmosphere stability thresholds, Wind Shear gives information about the mechanical turbulence generation, and Dry Air Index gives information about the thermodynamic support for dust mobilization. All of these factors must be taken into account at the same time to get a more realistic picture of dust storm motion than any one alone.

Computationally, the application of Python-based atmospheric analysis greatly enhanced reproducibility, automation, and efficiency in atmospheric analysis. The use of ERA5 reanalysis data together with scientific computing libraries allowed for processing large atmospheric datasets, spanning multiple levels, with less manual calculation errors. The following developed workflow can thus be used as a scalable basis on which to build future investigations and operational dust storm monitoring systems into atmospheric stability.

The results not only have implications for meteorology, but for environmental monitoring as a whole and environmental nanotechnology in particular. The transport and distribution of fine particulate matter (FPM) is directly influenced by the atmospheric instability, impacting the functionality of air quality monitoring networks, aerosol detection systems, and advanced nano-based environmental sensing technologies. Thus, knowledge of atmospheric stability aids not only in predicting the weather, but also in developing future plans for managing the environment and for assessing air quality. These findings are consistent with those of Abdullah et al. [1], who emphasized that wind shear is an important indicator for describing atmospheric dynamic behavior and stability conditions. Analysis of the dry air index also demonstrated the important role of atmospheric dryness during dust storms , High dry air index values indicate drier atmospheric conditions and reduced moisture availability, creating favorable conditions for dust activity and long-distance transport. Hassoun and Dabbagh [28] observed similar results, reporting that dry atmospheric conditions significantly influence atmospheric instability characteristics. Significant differences were observed between stations during the analysis. The Baghdad, Najaf, and Nasiriyah stations exhibited relatively stronger instability patterns compared to many other stations. These differences may be related to local geographical characteristics, land surface conditions, and regional atmospheric circulation patterns.

This study has additional implications for research in E-Nanotechnology. Concentrations of fine particles in the atmosphere are directly related to the distribution and the concentration of fine particles in the atmosphere, which is commonly monitored by means of nano-enabled sensing technologies, that are directly influenced by the atmospheric instability, turbulence and dust transport. The knowledge of the vertical structure of the atmosphere and the mechanisms of dust dispersion may help in designing future environmental monitoring systems, materials for air purification, and smart networks for detection of dust in the arid and semi-arid regions.

Overall, the results of this study are consistent with previous research regarding the impact of instability, wind disturbances, and atmospheric dryness on dust storm development. However, this study differs in its application of an automated computational approach using Python-based atmospheric calculations to investigate stability characteristics across multiple pressure levels throughout Iraq.

4. Conclusion

Through the developed computational framework, based on Python programming, the stability analysis of the atmosphere showed that the severe dust storms in Iraq are always accompanied by an increase in dynamic turbulence, increase in vertical wind interactions, and significant dryness in the atmosphere. The bulk Richardson number, wind shear and dry air index were well integrated to identify the physical mechanisms of dust storm formation and evolution in different climatic regions of Iraq.

These results indicated that, on the whole, high Richardson Numbers were associated with less severe dust events, high Wind Shear magnitudes with greater dust intensity, strong DAI with increased instability score, and greater instability score with higher dust intensity, thus substantiating the fact that both thermodynamic and dynamic forcing are important in the generation of dust storms. The strongest instability signatures were found at the investigated stations namely Ramadi, Hilla and Samawah which are high susceptible stations to dust storm activity.

One of the key advances of the present study is the creation of the full automatic computational methodology that integrates atmospheric physics, numerical analysis, and scientific visualization in a single environment based on a Python coding language. The framework allows handling of large ERA5 datasets in an efficient manner, while providing reproducible and physically interpretable stability diagnostics.

It draws attention to the fact that atmospheric instability needs to be considered a multidimensional phenomenon due to the effect of turbulence, vertical wind shear and dry-air intrusions. Therefore, it is necessary to use several dust storm stability indexes instead of a single atmospheric parameter to assess dust storms accurately.

This framework could be further expanded in the future by incorporating machine learning algorithms, satellite data and real-time forecasting systems, which would enhance the prediction of dust storms. The methodology presented is therefore a solid basis for future studies of atmospheric stability, environmental monitoring programs, early-warning systems and new applications of nanotechnology in the field of environment in the arid and semi-arid regions to mitigate the effects of dust storms.

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