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Investigation of wind effect at Samsun, Zonguldak, and Trabzon airports in Türkiye

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Abstract—Accurate management of weather conditions plays a critical role in ensuring safe and efficient flight operations in the aviation industry. In this context, the wind factor has a direct impact on aircraft performance and pilot decision-making mechanisms, especially during landing and takeoff processes. Within the scope of the study, 16 years of wind data recorded between 2008 and 2023 at Samsun Çarşamba, Zonguldak, and Trabzon airports located in the Black Sea Region are analyzed. Innovative Trend Analysis (ITA) and Innovative Polygon Trend Analysis (IPTA) methods are used to analyze the trends of wind direction, speed, and sudden changes. According to the results obtained, the dominant wind direction at Samsun Çarşamba and Zonguldak airports was determined as east (E), while a dominant wind effect was determined in the south-southwest (SSW) direction at Trabzon Airport. The study reveals the effects of wind factor on flight safety and operational efficiency and provides recommendations for the measures to be taken in the aviation sector and future practices.

Key-words: wind factor, flight safety, airport operations, crosswind and tailwind, trend analysis

1. Introduction

One of the key components of safe and efficient flight operations in the aviation industry is the correct management of weather conditions. In this context, the wind plays an important role in all phases of flight, but especially in the landing and takeoff processes. Based on the aviation accident database of the National Transportation Safety Board, *Fig. 1* shows the percentage of the different phases of flight in the total number of flight accidents (NTSB, 2019)

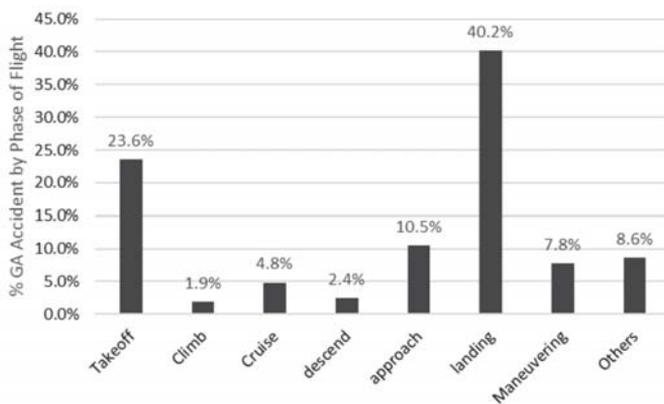


Fig. 1. Aircraft accidents by positions in 2019.

2022 data of the Flight Safety Foundation also provides up-to-date support for this information (*FSF, 2022; Fig. 2*).

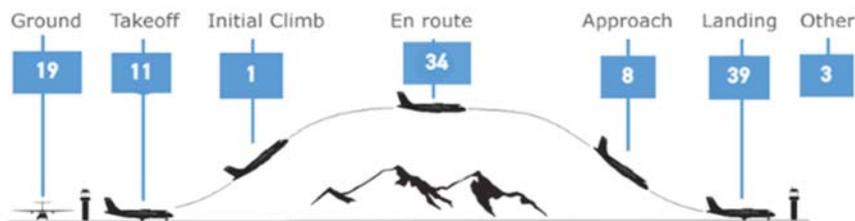


Fig. 2. Aircraft accidents according to positions in 2022.

Wind direction, speed, and sudden changes directly affect both aircraft performance and pilots decision-making processes. While headwind shortens the takeoff distance and enables the aircraft to take off quickly, tailwind lengthens

this distance and can make takeoff more complicated. Similarly, crosswind makes it difficult for the aircraft to move stably on the runway and increases the risk of deviation from the runway during landing (*Hahn, 1989; Robins and Delisi, 1993; Slihta et al., 2015; Stival et al., 2017; Castilho et al. 2018; Nechaj et al., 2019; Onwuadiochi et al., 2019; Maslovara and Mirković, 2021; Nae, 2021; Jiang et al., 2023; Ghozali et al., 2024; Khattak et al., 2024; Li et al., 2024; Lu, 2024; Scherllin-Pirscher et al., 2025; Yan and Song, 2024*).

Wind shear, which refers to sudden changes in wind direction and speed, is considered one of the most dangerous weather events in aviation. These events, especially during takeoff and landing, cause sudden speed and direction changes at low altitudes, making it difficult to control the aircraft. The FAA (Federal Aviation Administration) has been promoting advanced radar technologies and simulation systems to reduce the rate of wind shear-related accidents since the 1980s (*Kurdyukov et al., 2004; FAA, 2021; Zhang et al., 2019; Chen et al., 2025; Huang et al., 2024; Salahudden, 2024*). However, it has been proven by many studies that pilot training plays a key role in dealing with such situations (*Van Zante and Bond, 2003; Yang et al., 2021; Dolzhenko et al., 2024; Korecki et al., 2024*).

When evaluated from an aerodynamic perspective, the effect of wind on the aircraft is related to basic parameters such as lift, drag, and thrust. For example, a strong headwind reduces the aircraft's speed relative to the ground, significantly shortening the takeoff distance. In addition to reducing fuel consumption, this also increases operational efficiency (*FSF, 1999*). However, in the case of a tail wind, this advantage is lost and take-off distance increases significantly (*Aviation NZ, 2023; Liu et al., 2022*). Especially on short runways or high-density altitudes, tail wind can make the negative effects on aircraft performance more obvious (*Fahlgren, 2007*).

The effects of crosswind present a different aerodynamic challenge. Crosswind makes it difficult for the aircraft to remain in line with the runway during landing and is highly dependent on the pilot's control ability (*Ebbatson et al., 2007*). Aircraft manufacturers such as Airbus and Boeing have differentiated crosswind limits according to aircraft models, and these limits vary depending on the aircraft type and pilot experience (*Van Es et al., 2001; Airbus, 2020; Boeing, 2019; Wu and Liu, 2021*). Simulation-based studies have been conducted to better understand crosswind effects, and it has been emphasized that pilots' decision-making mechanisms in such conditions depend on the quality of training (*Castilho et al., 2018; Sumaja et al., 2019*).

The impact of wind on flight operations is not limited to the landing and takeoff phases. On long-haul flights, jet streams can significantly affect aircraft fuel consumption and flight times. Flight routes that are correctly aligned with jet streams provide great advantages both economically and environmentally.

The effect of wind on landing and takeoff is related not only to weather conditions, but also to the location of the airport and the runway arrangements.

Geographically, airports in areas subject to frequent wind shear present a higher risk during landing and takeoff. For example, the old Kai Tak Airport in Hong Kong witnessed great difficulties in landing aircraft due to frequent crosswind conditions, and this has inspired many analysis studies in aviation history (*Grace et al.*, 1957).

In addition, other factors such as atmospheric density, temperature, and humidity can increase the impact of wind. In hot and humid weather conditions, air density decreases, which negatively affects the ability of aircraft to generate lift. Especially at airports located at high altitudes, these effects become more pronounced. It is of great importance for pilots to correctly manage aircraft performance in such conditions (*Aviation NZ*, 2023).

Carefully monitoring the wind factor around airports is vital to ensure flight safety and operational efficiency. The use of weather radar systems and wind measuring devices enables accurate assessment of wind conditions. Predicting wind patterns by analyzing long-term weather conditions is also important for infrastructure planning of airports. In this context, international authorities recommend using at least 10 years of data in wind and wind trend studies. Both the NOAA Climate Prediction Center (*NOAA*, 2020) and the Federal Aviation Administration (*FAA*, 2020) support using 10 years or more of data in such operational and analysis studies. In this study, Samsun, Zonguldak, and Trabzon airports, which are three provinces from the Black Sea Region where wind has intense influence, were examined. 16 years of data between 2008 and 2023, which could provide maximum data for three cities, were used within the scope of the study.

Mismanagement of the wind factor can lead to adverse effects not only on aircraft performance but also on operational costs. Accurate analysis of atmospheric phenomena such as jet streams can reduce fuel consumption in long-haul flights and contribute to environmental sustainability. However, at airports in regions with frequent wind shear, the implementation of advanced simulation and training programs can strengthen safety by increasing pilots ability to cope with such situations.

As a result, constantly monitoring the wind factor around airports and taking appropriate measures not only increases flight safety, but also increases sectoral efficiency by shortening flight times and saving fuel. Maintaining such monitoring and management processes in an integrated manner will provide both technical and economic benefits in the aviation sector.

Also wind speed and direction play a critical role in airport design, because taking off and landing from the wind increases safety. Therefore, runways are positioned according to the long-term wind direction and speed in the region. Using wind rose analysis, prevailing wind directions are determined and the layout of the runways is planned accordingly. Since crosswinds can make flight operations difficult, this situation is also taken into account; if necessary, runways are designed in different directions. Since excessive wind speeds can increase the

risk of turbulence, this factor is evaluated during airport site selection. In addition, environmental factors and terrain structure can affect the behavior of the wind. All these analyses are necessary for airport operations to be safe and efficient.

The present study has been conducted for the purpose of investigating the temporal changes in wind speed values at Samsun, Trabzon, and Zonguldak airports in the Black Sea Region of Türkiye. To this end, monthly average wind speeds and directions from the Turkish State Meteorological Service for the period 2008–2023 were analyzed by Innovative Trend Analysis (ITA) and Innovative Polygon Trend Analysis (IPTA). The present paper is comprised of four chapters. Section 1 comprises a comprehensive literature review and the purpose of the paper. Section 2 delineates the study area and the methodologies that was employed. Section 3, the findings obtained as a result of the analyses are evaluated. Finally, Section 4 presents the conclusions of the study.

2. Materials and methods

2.1. Study area

The Black Sea Region is a region where the wind effect is felt intensely due to its environmental characteristics and geographical location. The region has the large water mass of the Black Sea in the north and the Eastern Black Sea Mountains in the south. This location causes the winds resulting from the pressure differences between the sea and the land to become stronger. Especially northerly winds blowing from the north and land winds from the northwest are dominant in the region. While the breeze blowing from the sea to the land provides coolness in the summer months, strong winds and storms are generally observed in the winter months. In addition, the fact that the Eastern Black Sea Mountains lie parallel to the coast creates an orographic effect on the speed and direction of the winds, which can lead to sudden wind changes and turbulence in the region. This is a decisive and critical factor for both local life and aviation operations.

Samsun-Çarşamba Airport is an airport located in the Black Sea Region and one of the important transportation points of the region. The airport, which was opened in 1998, serves domestic and international flights. The runway layout is designed parallel to the Black Sea and offers landing and takeoff opportunities for wide-body aircraft with its 3,000-meter-long runway. Since it is geographically close to the seashore, the effect of wind is carefully evaluated in operational activities. Especially northerly winds and northwesterly winds can be decisive on runway operations. In addition to commercial flights, the airport also serves training flights and cargo transportation (DHMI, 2023).

Zonguldak Airport is an airport located on the Black Sea coast and opened to civil aviation service in 2007. It is the only airport serving the Western Black Sea Region of Türkiye. The airport's runway is 1,881 meters long and is generally suitable for the landing and takeoff of small and medium-sized aircraft (DHMI,

2023). Due to its geographical location, intense winds and sudden changes coming from the Black Sea may occasionally put flight operations at risk. In addition to this information, the airport, located in the congested area between the sea and the mountains, can create difficult conditions during landing and takeoff.

Trabzon Airport is one of the busiest airports in the Eastern Black Sea Region and was put into service in 1957 (DHMI; 2023). The airport, which serves both domestic and international flights, is an important transportation gateway as it is the tourism and trade center of the region. The runway layout is designed parallel to the Black Sea and has a length of 2,640 meters. Due to its geographical location, the tight space between the sea and the mountains can cause wind turbulence. Crosswinds and sudden wind changes can pose difficulties for pilots, especially during landing (Scherllin-Pirscher *et al.*, 2025; Yan and Song, 2024). Trabzon Airport is the main entry point for many international flights to the Black Sea Region and plays a critical role in the economic development of the region. The location of these three airports can be seen in Fig. 3.



Fig.3. The location of airports.

2.2. Innovative Trend Analysis (ITA)

ITA was proposed by Şen (2012) with the objective of graphically examining the trends of hydrometeorological parameters. The method involves dividing the time series into two equal parts, sorting these parts from smallest to largest, and placing the first part on the horizontal axis and the second part on the vertical axis, with these parts positioned opposite each other in the distribution graph. The points situated in the upper part of the 1:1 (45°) line demonstrate an increasing trend, whilst the points positioned in the lower part exhibit a decreasing trend. ITA, as

developed by Şen (2012), was further refined by Şen (2017a, 2017b) through the incorporation of a statistical significance test (Eqs.(1–6)).

$$E(s) = \frac{2}{n} [E(\bar{y}_2) - E(\bar{y}_1)] \quad (1)$$

$$\sigma_s^2 = \frac{4}{n^2} [E(\bar{y}_2)^2 - 2E(\bar{y}_2\bar{y}_1) - E(\bar{y}_1)^2] \quad (2)$$

$$\rho_{\bar{y}_2\bar{y}_1} = \frac{E(\bar{y}_2\bar{y}_1) - E(\bar{y}_2)E(\bar{y}_1)}{\sigma_{\bar{y}_2}\sigma_{\bar{y}_1}} \quad (3)$$

$$\sigma_s^2 = \frac{8}{n^2} \frac{\sigma^2}{n} (1 - \rho_{\bar{y}_2\bar{y}_1}) \quad (4)$$

$$\sigma_s = \frac{2\sqrt{2}}{n\sqrt{n}} \sigma_s (1 - \rho_{\bar{y}_2\bar{y}_1}) \quad (5)$$

$$CL_{(1-\alpha)} = 0 \pm s_{critical} \sigma_s \quad (6)$$

In Eqs.(1–6), $E(s)$ represents the first-order moment of the slope, n represents the data length, ρ represents the cross-correlation coefficient between the two halves, σ represents the standard deviation of the entire data series, σ_s^2 represents the variance of the trend slope and σ_s represents the standard deviation of the slope. $s_{critical}$ represents the Z value obtained from the standard normal distribution at a certain confidence level. Should the gradient of the trend exceed the upper confidence limit, it is considered to be an increasing trend; conversely, if it exceeds the lower limit, it is considered to be a decreasing trend. If these conditions are not met, it is considered that there is no statistically significant trend at a certain confidence level. In this study, the ITA significance test was performed at a 95% confidence level (Şen, 2017a,2017b; Gümüş et al, 2021, 2022; Nacar et al., 2022).

2.3. Innovative Polygon Trend Analysis (IPTA)

In the IPTA method developed by Şen et al. (2019), which can be applied to different time scales, parameters such as the mean, minimum, maximum, standard deviation and skewness of time series of hydrometeorological climate parameters can also be used as input. Average values of parameters were used in this study. In this method, as in ITA, time series are divided into two halves for all segments. The mean of the two half-series for each segment is calculated and plotted in the Cartesian coordinate system to create a polygon. In the graphical evaluation, the process steps in ITA are followed (Şen et al., 2019; Çeribaşı et al., 2021; Gümüş et al., 2022; Hussain et al., 2023; Günes et al., 2024).

3. Results

Knowing the prevailing wind direction is of critical importance for airport designers, pilots and air traffic controllers to ensure the safety of flight operations. First of all, the prevailing wind direction is a fundamental factor in runway design and orientation. Runways are usually built against a headwind, because the headwind allows aircraft to move safely over shorter distances during takeoff and landing (ICAO, 2020). Knowing the prevailing wind direction also enables safer approach and landing plans. By minimizing side and cross wind effects, pilots can make a safer landing.

Moreover, information of prevailing wind direction provides effective guidance in creating emergency strategies. It supports pilots in making the right decisions by influencing the selection of alternative runways or airports in case of a potential emergency landing situation. In addition, wind direction should be taken into account when designing the land around the airport. As a result, it can be said, that accurate analysis of the prevailing wind direction not only increases flight safety, but also offers strategic advantages in terms of operational efficiency and environmental sustainability.

In this study, monthly prevailing wind directions for the 16 years between 2008 and 2023 were examined for Samsun, Zonguldak, and Trabzon airports. In this context, the prevailing wind directions are given in *Table 1*.

Table 1. Prevailing wind direction table

Airports	1	2	3	4	5	6	7	8	9	10	11	12	GENERAL
Samsun	S	E	E	E	E	NNW	NNW	NNW	SSE,E	SE,E	E	E	E
Trabzon	SSW	E	E	E	E	E	SSW	SSW	SSW	SSW	SSW	SSW	SSW
Zonguldak	S	E	E	N	N	N	NNW	NNW	E	E	E,S	E,S	E

In this context, according to the results obtained from the data, the prevailing wind direction for Samsun Çarşamba Airport was determined as east (E), for Trabzon Airport as south-southwest (SSW) and for Zonguldak Airport as east (E). Airports were selected as Zonguldak in the west of the Black Sea Region, Samsun in the middle, and Trabzon in the east in order to examine the behavior of the data more effectively.

The temporal changes of the monthly mean wind speed values of Samsun, Trabzon, and Zonguldak airports in the Black Sea region were investigated using ITA and IPTA. The ITA results of the airports are presented in *Table 2* and *Figs. 4, 5, and 6*, while the IPTA results are presented in *Table 2* and *Fig. 7*.

Table 2. ITA and IPTA results

	Samsun				Trabzon				Zonguldak			
	ITA		IPTA		ITA		IPTA		ITA		IPTA	
	CL _{0.95}	S	Trend	Trend	CL _{0.95}	S	Trend	Trend	CL _{0.95}	S	Trend	Trend
Jan.	0.16	0.02	↑	↑	0.28	0.11	↑	↑	0.14	0.03	↑	↑
Feb.	0.17	0.03	↑	↑	0.33	0.09	↑	↑	0.18	0.06	↑	↑
Mar.	0.18	-0.02	↓	↓	0.26	0.06	↑	↑	0.19	0.06	↑	↑
Apr.	0.15	0.00	↔	↔	0.39	0.14	↑	↑	0.18	0.05	↑	↑
May.	0.15	0.03	↑	↑	0.39	0.13	↑	↑	0.18	0.05	↑	↑
Jun.	0.16	-0.03	↓	↓	0.27	0.08	↑	↑	0.17	0.04	↑	↑
Jul.	0.16	0.01	↑	↑	0.31	0.10	↑	↑	0.18	0.04	↑	↑
Aug.	0.16	0.02	↑	↑	0.36	0.07	↑	↑	0.19	0.03	↑	↑
Sep.	0.14	0.01	↑	↑	0.30	0.11	↑	↑	0.16	0.03	↑	↑
Oct.	0.15	-0.02	↓	↓	0.29	0.12	↑	↑	0.15	0.03	↑	↑
Nov.	0.15	-0.02	↓	↓	0.32	0.14	↑	↑	0.17	0.06	↑	↑
Dec.	0.16	0.02	↑	↓	0.29	0.13	↑	↑	0.16	0.02	↑	↑

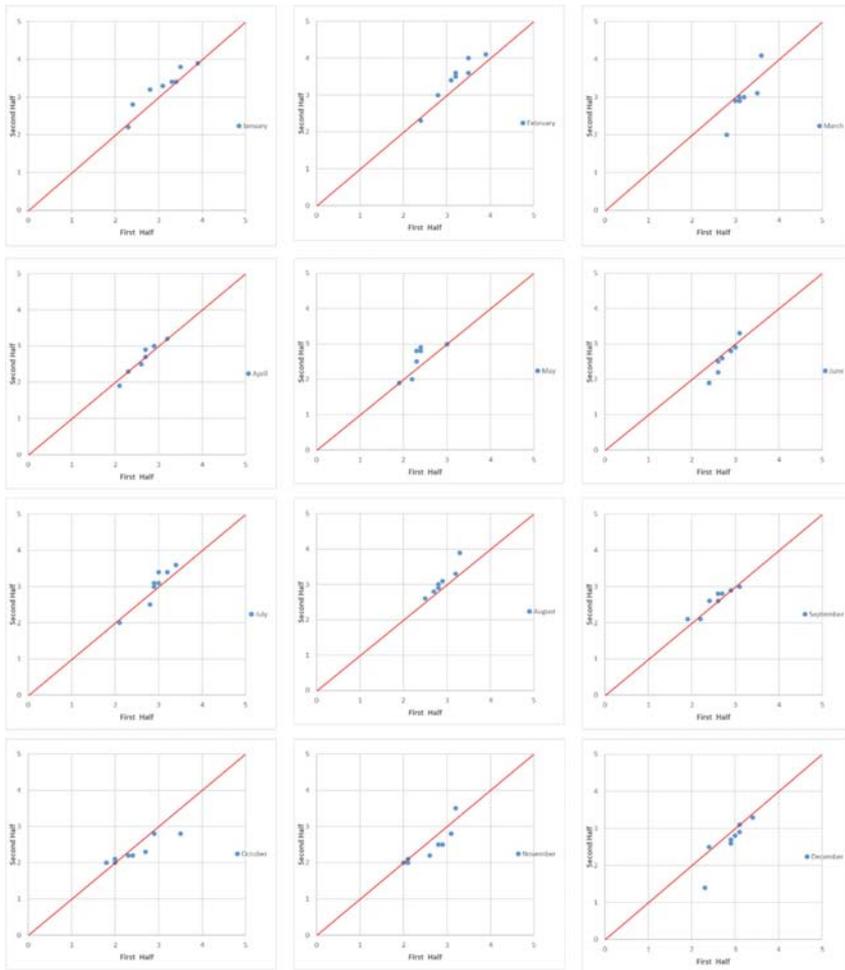


Fig. 4. ITA graphical results for Samsun.

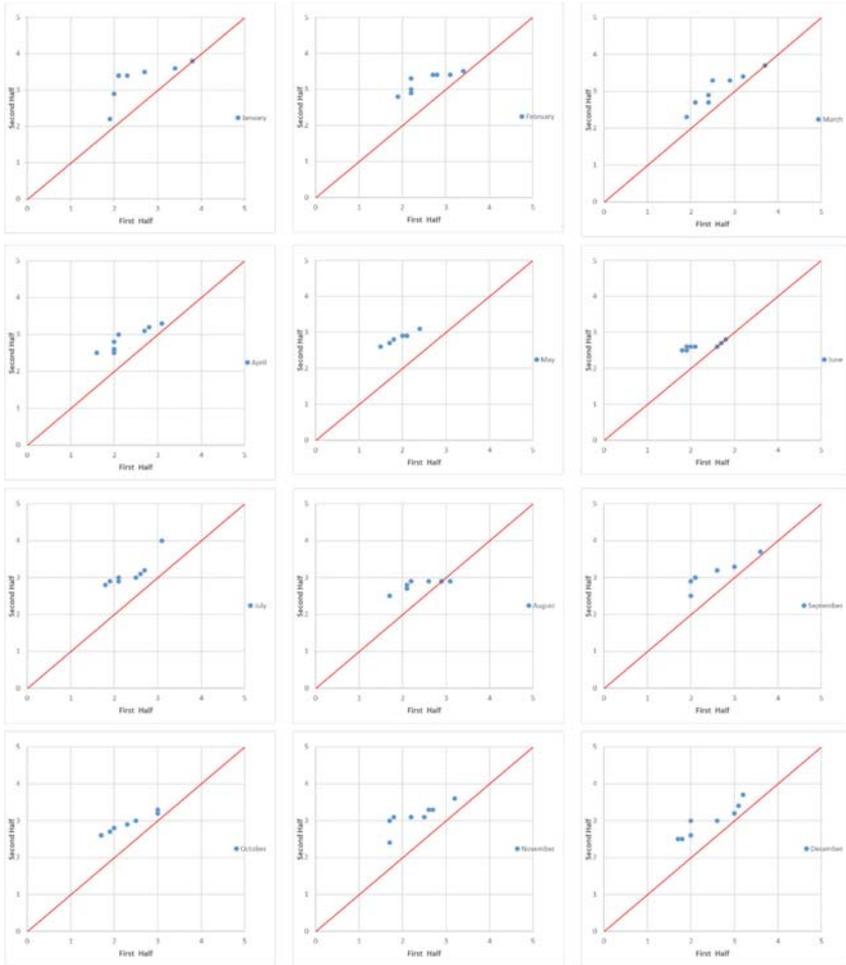


Fig. 5. ITA graphical results for Trabzon.

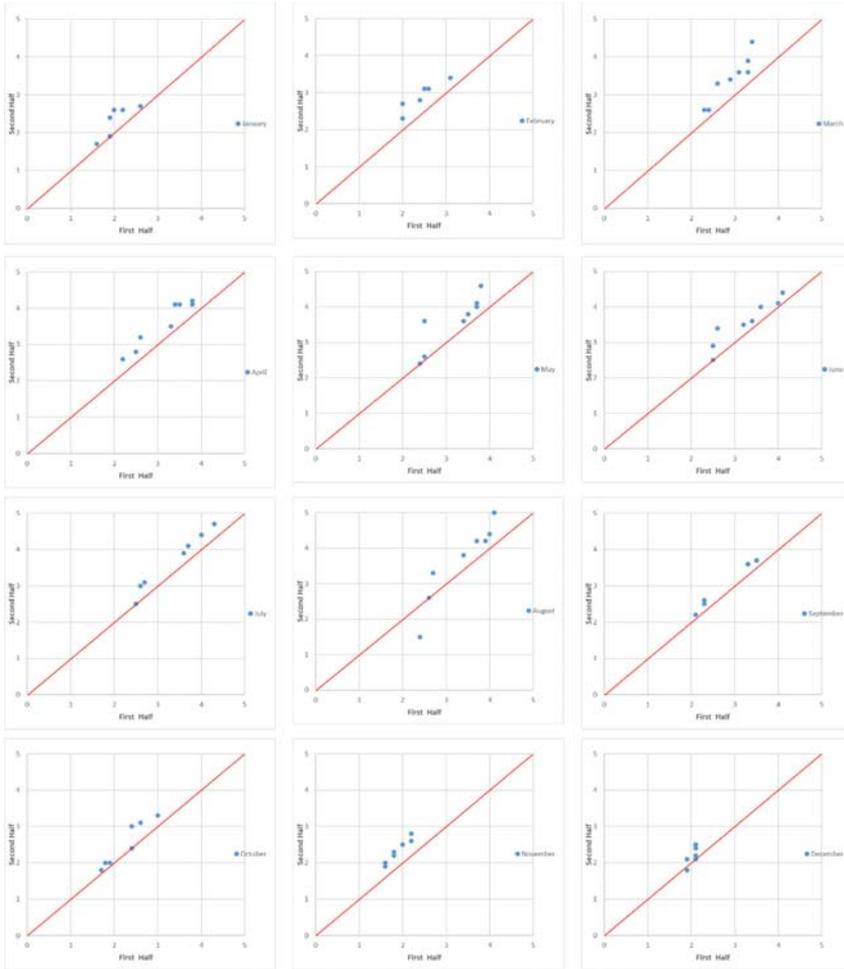


Fig. 6. ITA graphical results for Zonguldak.

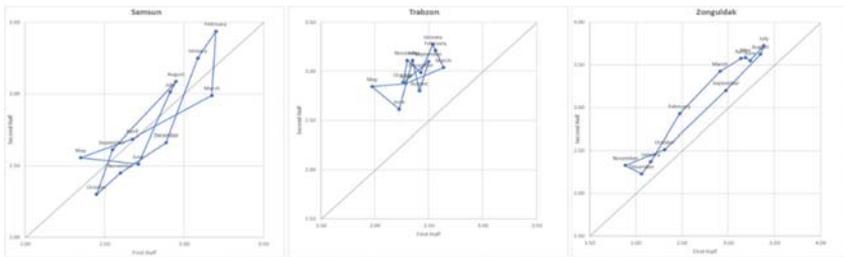


Fig. 7. IPTA graphical results for Samsun, Trabzon, and Zonguldak.

As demonstrated in *Table 2* and *Fig. 4*, which incorporate the ITA results for Samsun Airport situated within the Black Sea Region, it has been ascertained that wind speed trends exhibit variation by month. An increasing trend was identified in wind speed values in January, February, May, July, August, September, and December. Conversely, a decreasing trend was identified in March, June, October, and November. It is noteworthy that these increasing/decreasing trends are not statistically significant, as they are below the limit values at the 95% confidence level. In April, a value of “0” was calculated, indicating that wind speed did not exhibit a trend in that month. According to the IPTA results presented in *Table 2* and *Fig. 7*, they are parallel to ITA, with the exception of December. In December, IPTA determined a decreasing trend. As demonstrated in *Table 2*, *Figs. 5* and *6*, which incorporate the ITA and IPTA results of Trabzon airport in the east of the Black Sea Region and Zonguldak airport in the west, an increasing trend has been determined in all months at these two airports. These trends are not statistically significant when they remain below the limit values at the 95% confidence level.

The trend analysis of wind speed values at airports located in the center, western and eastern of the Black Sea Region has revealed an increasing trend in wind speeds in all months. According to the analysis results of Samsun, which is located in the center of the region, has shown variations in the determined trends according to the months of the year. The trend analysis results of the methods employed across the region indicate a generally supportive relationship between ITA and IPTA.

The influence of wind on air transportation holds significant importance in terms of operational efficiency and flight safety. Research and practical applications demonstrate that wind conditions play a pivotal role in shaping pilot decision-making processes and influencing the performance of aircraft, particularly during critical phases such as takeoff and landing. In this context, such studies are useful and important.

The study makes a unique and important contribution to the literature on reducing accident risks in airline transportation with the methods used and the analysis of meteorological factors. In particular, the effects of wind factor on flight safety are analyzed in detail and applicable recommendations are developed in many areas from runway arrangements to pilot training programs. The study provides a strategic basis for safer flight operations by determining the prevailing wind directions at Samsun, Zonguldak, and Trabzon airports. In addition, by predicting seasonal changes, the planability of flight operations is improved. The integration of simulation technologies to mitigate wind-related risks in pilots' decision-making processes has been proposed, and the sectoral benefits of these applications have been emphasized. The effects of wind factor on fuel consumption and flight times are also discussed in the context of environmental sustainability, and it is stated that these findings can shed light on sectoral innovations. In long-term planning, the potential impacts of climate change on

wind patterns should be considered. This study makes an important contribution to the future of the aviation industry, both theoretically and practically.

4. Conclusion

The effects of wind on air transport play a critical role in terms of operational efficiency and flight safety. In this study, 16 years of wind data for Samsun, Zonguldak, and Trabzon airports are analyzed, and the wind dynamics of the region are presented in detail. The findings of the study once again emphasized the importance of the wind factor not only in terms of flight safety but also in terms of airport infrastructure planning, development of pilot training programmes, and sectoral efficiency.

1. Regional wind characteristics and environmental factors

Geographical and climatic features in the Black Sea Region are the main factors determining the wind behavior in the region. Especially the locations of Samsun, Zonguldak, and Trabzon airports between the sea and the mountains cause difficulties such as orographic effects and sudden wind changes. In this study, it was determined that south-southwesterly winds prevail in Trabzon and easterly winds prevail in Samsun and Zonguldak. This information can be used to make flight operations in the region safer.

2. Contribution of methods: ITA and IPTA analyses

Innovative Trend Analysis (ITA) and Innovative Polygon Trend Analysis (IPTA) methods are the main analysis tools of this study. Thanks to these methods, changes in wind speeds and directions were analyzed in detail. Especially understanding the seasonal changes will increase the predictability in flight operations. The usability of these methods in airport design, risk management, and long-term planning provides a significant advantage.

3. Airport design and safety improvements

Wind factor plays a critical role in runway routing and airport layout. The findings of the study show that runway arrangements considering the prevailing wind directions will increase takeoff and landing safety. It can be emphasized that alternative runway designs should be evaluated, especially in areas where the side wind effect is intense.

4. Updating pilot training programmes

The effects of wind on flight are of great importance in the decision-making processes of pilots. In this context, the development and integration of simulation technologies into pilot training programmes will play a key role in the management of wind-related risks. Pilots who experience especially hazardous weather conditions in simulation environment will be more prepared for real operations.

5. Operational efficiency and environmental sustainability

The impact of the wind factor on fuel consumption and flight times is also important in terms of environmental sustainability. More effective utilization of natural advantages such as jet streams can reduce environmental impacts by saving fuel. The study reveals the potential for such impacts to improve operational efficiency.

6. Climate change and future strategies

Climate change may lead to changes in wind patterns, posing new operational challenges. Therefore, the effects of climate change need to be taken into account in long-term planning. The ITA and IPTA methods used in this study provide a suitable basis for long-term monitoring of such changes.

7. Importance of local microclimatic analyses

Microclimatic analyses specific to each airport will provide a better understanding of wind factors. Especially at airports with different geographical characteristics such as Trabzon, Zonguldak, and Samsun, local analyses can provide critical data to improve flight safety.

8. Land use and landscaping

Planning the land arrangements around the airports by considering the wind directions will be effective in reducing operational risks. The prevailing wind directions determined in the study can provide guidance for environmental regulations and construction around the airport.

9. Standardisation of data use and technology integration

Standardization of long-term wind data and integration with new technologies can increase operational efficiency. In particular, the integration of artificial intelligence-supported decision support systems will enable real-time analysis of wind data, offering both security and economic advantages.

10. Multidisciplinary cooperation and future investments

Effective management of the wind factor requires the cooperation of different disciplines such as meteorology, engineering, air traffic control, and pilotage. Strengthening this co-operation will contribute to the sector both technically and economically. Furthermore, increasing investments in technological developments should be a strategic priority for the future of the aviation sector.

As a result, wind factor management is of great importance not only for flight safety but also for operational efficiency, environmental sustainability, and infrastructure planning. This study has made significant contributions to the understanding and management of wind effects and has shed light on future studies. With long-term strategic plans, technological innovations, and

interdisciplinary cooperation, the aviation industry can achieve a safer, more efficient, and sustainable structure.

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References

- Airbus. 2020: Aircraft performance in tailwind conditions. Retrieved from <https://www.airbus.com>
- Aviation NZ. 2023: Take-off and landing performance. Retrieved from <https://www.aviation.govt.nz>
- Boeing. 2019: Operational challenges of crosswind landings. Retrieved from <https://www.boeing.com>
- Castilho, D. S., et al. 2018: "STPA for continuous controls: A flight testing study of aircraft crosswind takeoffs." *Safety Science*, 108, 129–139. <https://doi.org/10.1016/j.ssci.2018.04.012>
- Ceribasi, G., Ceyhunlu, A.I. and Ahmed, N. 2021: Analysis of temperature data by using innovative polygon trend analysis and trend polygon star concept methods: a case study for Susurluk Basin, Turkey. *Acta Geophys.* 69, 1949–1961. <https://doi.org/10.1007/s11600-021-00632-3>
- Chen, F., Li, C., Peng, H., Chan, P. W., and Chen, J., 2025: Low-level Wind Shear Induced by Airport Buildings: A Numerical Simulation Study. *KSCE J. Civil Engin.* 29(6), 100103. <https://doi.org/10.1016/j.ksej.2024.100103>
- DHMI . 2023: Türkiye'deki havalimanları. Retrieved from <https://www.dhmi.gov.tr>
- Dolzhenko, N., Assilbekova, I., Abzhapbarova, A., Mussayeva, G., and Sarzhanov, T., 2024: Unification of Training Programs for Aviation Professionals as a Flight Safety Criterion. *J. Aerospace Technol. Manage.* 16(2), <https://doi.org/10.1590/jatm.v16.1320>
- Ebbatson, M., Harris, D., and Jarvis, S., 2007: Crosswind landings in general aviation: a modified method of reporting wing information to the pilot. *Int. J. Aviation Psychol* 17(4), 353–370.
- FAA., 2020: Airport Design Advisory Circular 150/5300-13B: Airport Design. Retrieved from <https://www.faa.gov/airports/engineering/design>
- FAA., 2021: Wind shear and turbulence: Mitigation strategies in aviation. Washington, DC: FAA Technical Center.
- Fahlgren, G. 2007: Tail Wind Traps. *AeroSafety world*, 2(3), 46–47.
- FSF., 1999: Killer in aviation: FSF task force presents facts about approach and landing and controlled flight into terrain accidents (II ed.). Alexandria, USA: Flight Safety Foundation.
- FSF., 2022: Airline accidents 2022. Retrieved from <https://aviation-safety.net/database/2022-analysis> (Access date: 23.09.2024)
- Ghozali, A. L., Kuresih, K., Cahyanto, K. A., Iryanto, I., and Gernowo, R., 2024: Web Based Dashboard of Airplane Turbulence Mitigation. *Jurnal Ekonomi Teknologi dan Bisnis (JETBIS)*, 3(11), 1821–1826. <https://doi.org/10.57185/jetbis.v3i11.158>
- Gümiş, V., Dinsever, L. D., Şimşek, O., 2021: Trend Analysis of Historical Drought During 1929-2016 in Diyarbakır Station with Innovative Şen Method. *J. Nat. Haz. Environ.* 7(2), 362–373. <https://doi.org/10.21324/dacd.884682>
- Gümiş, V., Şimşek, O., Açar, M. K. 2022: Assessing the Monthly Total Rainfall Trends at Artvin and Rize Stations using Different Methods. *Harran University Journal of Engineering* 7(3), 204–216. <https://doi.org/10.46578/humder.1207593>

- Güneş, B., Demirtaş, B., Tuncer, G., Sönmez, O. 2024: Analysis of Temperature and Precipitation Data Using Innovative Trend Analysis Methods: Kucuk Menderes Basin, Türkiye. *Uludağ University Journal of The Faculty of Engineering*, 29(2), 443–462. <https://doi.org/10.17482/uumfd.1473532>
- Grace, H., Henry, J.K.M., Skempton, A.W., Lloyd Jones, R.F., Jones, R.F.L., Golder, H. Q., ... and Alston, J., 1957: Discussion On Airport Paper No. 35: The Planning And Design Of The New Hong Kong Airport. *Proceedings of the Institution of Civil Engineers*, 7(2), 305–325.
- Hahn, K. U. 1989: Effect of wind shear on flight safety. *Progress in Aerospace Sciences*, 26(3), 225–259. [https://doi.org/10.1016/0376-0421\(89\)90004-3](https://doi.org/10.1016/0376-0421(89)90004-3)
- Huang, X., Zheng, J., Shao, A., Xu, D., Tian, W., and Li, J. 2024: Study of low-level wind shear at a Qinghai-Tibetan Plateau airport. *Atmos. Res.* 311, 107680 <https://doi.org/10.1016/j.atmosres.2024.107680>
- Hussain, F., Wu, R.S., Nabi, G. et al., 2023: Analysis of Temperature Data Using the Innovative Trend Pivot Analysis Method and Trend Polygon Star Concept: A Case Study of Soan River Basin, Potohar, Pakistan. *Pure Appl. Geophys.* 180, 475–507. <https://doi.org/10.1007/s00024-022-03203-9>
- ICAO. 2020: Aerodrome design manual: Part 1 – Runways (4th ed.). ICAO. Retrieved from <https://www.icao.int>
- Jiang, W., Chang, R. C., Yang, N., and Xu, Y. 2023: Severity assessment of sudden plunging motion for jet transport aircraft in response to severe atmospheric turbulence. *Aircraft engineer. aerospace technol* 95(10), 1633–1641.
- Khattak, A., Zhang, J., Chan, P. -w., Chen, F., and H. Almaliki, A. 2024: A New Frontier in Wind Shear Intensity Forecasting: Stacked Temporal Convolutional Networks and Tree-Based Models Framework. *Atmosphere* 15(11), 1369. <https://doi.org/10.3390/atmos15111369>
- Korecki, Z., Hoika, T., Bauer, M., and Smrž, V. 2024: New approach to military pilot education and training in the new security environment. *Transport Problems* 19, 137–150. <https://doi.org/10.20858/tp.2023.19.2.11>
- Kurdyukov, A. P., Pavlov, B. V., Timin, V. N., and Vladimirov, I. G. 2004: Longitudinal anisotropy-based flight control in a wind shear. *IFAC Proceedings Volumes*, 37(6), 423–426. [https://doi.org/10.1016/S1474-6670\(17\)32211-5](https://doi.org/10.1016/S1474-6670(17)32211-5)
- Li, F., Xu, X., Li, J., Hu, H., Zhao, M., and Sun, H. 2024: Wind Shear Operation-Based Competency Assessment Model for Civil Aviation Pilots. *Aerospace* 11(5), 363. <https://doi.org/10.3390/aerospace11050363>
- Liu, J., Qian, W., Bai, Y., and Xu, X. 2022: Numerical and Experimental Research on Flight Control of a V-Tail Configuration for the Wind Tunnel Model of Aircraft. *Aerospace*, 9(12), 792. <https://doi.org/10.3390/aerospace9120792>
- Lu, C., Le, N., Ding, Z. 2024: Flight Safety Assessment Method of Civil Aircraft During Approach Based on Cluster Analysis. In: Proceedings of the 6th China Aeronautical Science and Technology Conference. *CASTC 2023. Lecture Notes in Mechanical Engineering*. Springer, Singapore. https://doi.org/10.1007/978-981-99-8864-8_39
- Maslovara, A., and Mirković, B. 2021: Impact of Tailwind on Airport Capacity and Delay at Zurich Airport. *Transportation Research Procedia* 59, 117–126. <https://doi.org/10.1016/j.trpro.2021.11.103>
- Nacar, S., Şan, M., Kankal, M., Okkan, U. 2022: Trend Analysis of Meteorological Droughts for Different Climate Change Scenarios in Eastern Black Sea Region. *J. Inst. Sci. Technol.* 12(2), 843–856. <https://doi.org/10.21597/jist.998196>
- Nae, G. 2021: Wind shear associated with mediterranean cyclones activity and the impact on flight safety during winter operations at henri coanda otopeni and aurel vlaicu baneasa airports. *Review of the Air Force Academy* 43(1), 5–16. <https://doi.org/10.19062/1842-9238.2021.19.1.1>
- NOAA. 2020: Climate Prediction Center: Understanding ENSO. Retrieved from <https://www.cpc.ncep.noaa.gov/>
- Nechaj, P., Gaál, L., Bartok, J., Vorobyeva, O., Gera, M., Kelemen, M., and Polishchuk, V. 2019: Monitoring of Low-Level Wind Shear by Ground-based 3D Lidar for Increased Flight Safety, Protection of Human Lives and Health. *Int. J. Environ. Res. Public Health*, 16(22), 4584. <https://doi.org/10.3390/ijerph16224584>

- NTSB. 2019: Aviation accident database and synopses. Retrieved from https://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx (Access date: 20.09.2024).
- Onwuadiochi, I. C., Ijioma, M. A., Ezenwaji, E. E., and Obikwelu, M. C. 2019: Effects of wind shear on flight operations in Sam Mbakwe Airport, Imo State, Nigeria. *Tropical Built Environ. Journal*, 7(1), 39–49.
- Robins, R.E. and Delisi, D.P. 1993: Potential hazard of aircraft wake vortices in ground effect with crosswind. *Journal of Aircraft*, 30(2), 201–206. <https://doi.org/10.2514/3.48266>
- Salahudden, S. 2024: Impact of Wind and Wind Shear on Sliding Mode Controller Assisted Aircraft Spin Recovery. *Control Engin. Practice*, 145,105872. <https://doi.org/10.1016/j.conengprac.2024.105872>
- Scherllin-Pirscher, B., Nickovic, S., Votsis, A., Cvetkovic, B., Amiridis, V., Bolic, T., Brenot, H., Brock, G., Clarkson, R. J., Durant, A., Hirtl, M., Lekas, T. I., Mona, L., Nasser, H., Ryder, C. L., Ryuzaki, J., Suárez-Molina, D., Vimic, A. V., and Basart, S. 2025: Airborne soil-derived dust hazards in aviation. *Bull. Amer. Meteorol. Soc.* 106(1) E125–E145. <https://doi.org/10.1175/BAMS-D-23-0311.1>
- Slihta, M., Lazareva, I., and Šestakovs, V. 2015: Evaluation of the dynamic characteristics of aircraft during landing in crosswinds. *Transport Aerospace Engin.* 2, 27–35. <https://doi.org/10.1515/tae-2015-0004>
- Stival, L.J.L., Guetter, A.K., and de Andrade, F.O. 2017: The impact of wind shear and turbulence intensity on wind turbine power performance. *Espaço Energia*, 27, 11–20.
- Sumaja, K., Syahdian, A. S., and Satriyabawa, I. K. M. 2019: Analysing Crosswind, Headwind, And Tailwind At I Gusti Ngurah Rai Airport For Aircraft Risks Assessment During Take-Off And Landing Process.
- Şen Z, 2012: Innovative Trend Analysis Methodology. *J. Hydrol Engin* 17, 1042–1046.
- Şen Z, 2017a: Innovative trend significance test and applications. *Theor. Appl. Climatol.* 127, 939–947. <https://doi.org/10.1007/s00704-015-1681-x>
- Şen, Z., 2017b: Innovative Trend Methodologies in Science and Engineering. Springer.
- Şen, Z., Şişman, E., and Dabanli, I. 2019: Innovative polygon trend analysis (IPTA) and applications. *J. Hydrol.* 575, 202–210. <https://doi.org/10.1016/j.jhydrol.2019.05.028>
- Van Es, G. W., van der Geest, P. J., and Nieuwpoort, A. M. H. 2001: Safety aspects of aircraft operations in crosswind, NLR-TP-2001-217.
- Van Zante, J., and Bond, T. 2003: Overview of NASA's In-Flight Icing Education and Training for Pilots. In 41st Aerospace Sciences Meeting and Exhibit (p. 18) <https://doi.org/10.2514/6.2003-18>
- Yan, Y., and Song, L. 2024: Wind Shear Response of Aircraft with C* and C*U Controller during Approach. *Aerospace*, 11(6), 476. <https://doi.org/10.3390/aerospace11060476>
- Yang, S., Yu, K., Lammers, T., and Chen, F. 2021: Artificial intelligence in pilot training and education—towards a machine learning aided instructor assistant for flight simulators. In *International Conference on Human-Computer Interaction*, 581–587. Cham: Springer International Publishing https://doi.org/10.1007/978-3-030-78642-7_78
- Zhang, H., Wu, S., Wang, Q., Liu, B., Yin, B., and Zhai, X. 2019: Airport low-level wind shear lidar observation at Beijing Capital International Airport. *Infrared Phys. Technol.* 96, 113–122. <https://doi.org/10.1016/j.infrared.2018.07.033>
- Wu, Y., and Liu, Y. 2021: Research on Flight Technique and Hazard Control for Civil Airplane Crosswind Flight Test. In 2021 International Symposium on Electrical, Electronics and Information Engineering, 19–22. <https://doi.org/10.1145/3459104.3459109>