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Air Stagnation in the Nile Delta (1980–2020): An Assessment of Its Spatio-Temporal Patterns

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Abstract

Air stagnation occurs when weak horizontal ventilation and limited vertical mixing inhibit renewal of the lower atmosphere, allowing heat and pollutants to accumulate within the boundary layer. Despite the climatic and demographic importance of the Nile Delta, the long-term behavior of stagnation across this densely populated Mediterranean–continental transition zone remains poorly documented. This study provides the first multi-decadal assessment of stagnation dynamics over the Nile Delta during 1980–2020 using ERA5 reanalysis data at 0.25° × 0.25° spatial resolution. Stagnation days were identified using the Air Stagnation Index defined by thresholds of near-surface wind speed (U_{10} < 3.2 m s^{-1}), 500-hPa wind speed (< 13 m s^{-1}), and daily precipitation below 1 mm. ERA5 fields were evaluated against regional meteorological observations, showing strong agreement in wind speed and precipitation variability and confirming the suitability of ERA5 for stagnation diagnostics. The results reveal a pronounced coastal–inland gradient in stagnation frequency. Annual means exceed 150 days in the southern sector (Cairo) and about 135 days in the central Delta (Tanta), whereas coastal locations such as Alexandria experience roughly 30 days per year. Air stagnation frequency increased significantly by about 0.7 day per decade during 1980–2020, with stronger trends inland. Stagnation frequency shows a strong inverse relationship with near-surface wind speed (r = −0.84), indicating that horizontal ventilation appears to exert a primary dynamical control on stagnation variability across the Delta. These findings identify the Nile Delta as one of the most stagnation-prone non-orographic coastal plains in the eastern Mediterranean.

Keywords: *Air stagnation; Dynamic stability; ERA5 reanalysis; Nile Delta; Boundary-layer decoupling; Global stilling.*

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1 Introduction

Air quality has become a central indicator of the evolving interaction between climate processes and human activity during the Anthropocene. In rapidly urbanizing regions, particularly within densely populated coastal environments, atmospheric conditions strongly regulate the capacity of the lower atmosphere to disperse pollutants. Persistent exposure to fine particulate matter and toxic gases in large urban agglomerations has been associated with increased rates of cardiopulmonary disease, highlighting the growing societal relevance of atmospheric ventilation processes (Agarwal, 2024).

Among the meteorological conditions that control atmospheric dispersion, air stagnation (AS) represents one of the most influential. Stagnation occurs when weak horizontal winds and limited vertical mixing reduce ventilation within the boundary layer, allowing pollutants and heat to accumulate near the surface. Under such conditions, the efficiency of atmospheric renewal declines and urban environments can temporarily function as atmospheric sinks. Observational and modeling studies have shown that stagnation events may substantially amplify pollutant concentrations in densely built environments, particularly within poorly ventilated urban canyons (Sarria et al., 2025; Li et al., 2019; Molina, 2020). When these conditions coincide with thermal inversions, pollutant accumulation intensifies within the lower boundary layer, leading to pronounced increases in particulate matter concentrations (Ryu & Min, 2024). These interactions illustrate that stagnation is not simply a local meteorological anomaly but a key physical mechanism linking atmospheric stability to urban air-quality deterioration.

Air stagnation typically develops when persistent high-pressure systems suppress synoptic-scale circulation, weaken both surface and mid-tropospheric winds, and limit precipitation. This combination of factors enhances dynamic stability and reduces vertical and horizontal mixing within the lower troposphere (Leung & Gustafson, 2005; Horton et al., 2014; Tai et al., 2012). To quantify these conditions, Wang and Angell (1999) introduced the Air Stagnation Index (ASI), a composite metric defined by three simultaneous thresholds: near-surface wind speed below 3.2 m s^{-1}, 500-hPa wind speed below 13 m s^{-1}, and daily precipitation below 1 mm. Since its introduction, the ASI has become a widely adopted diagnostic framework for identifying meteorological environments conducive to pollutant accumulation.

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Numerous studies have demonstrated the close connection between stagnation episodes and air-quality degradation. Early work by Jacob et al. (1999) showed that periods of elevated tropospheric ozone in the United States coincided with pronounced stagnation events. Subsequent analyses indicated that such episodes could increase $PM_{2.5}$ concentrations by several micrograms per cubic meter, representing a substantial environmental and public-health burden (Fiore et al., 2015). Similar relationships have been reported across Europe, where stagnation conditions significantly enhance near-surface concentrations of gaseous pollutants (Ordóñez et al., 2005). Because the ASI isolates meteorological controls on pollutant dispersion independent of emission variability, it provides an objective framework for diagnosing the atmospheric capacity to ventilate polluted air masses (Leung & Gustafson, 2005; Horton et al., 2012; Wang et al., 2022; Zhou et al., 2024; Huang et al., 2017). As emphasized by Jacob and Winner (2009), this physical focus makes stagnation metrics particularly valuable for interpreting the climatic drivers of air-quality variability.

At larger spatial scales, stagnation frequency has been investigated using global reanalysis datasets. The U.S. National Climatic Data Center (NCDC) adopted the ASI as a standard framework for monitoring atmospheric conditions associated with air-quality deterioration and has produced global maps of stagnation-day occurrence (Horton et al., 2012; Leung & Gustafson, 2005; Zhou et al., 2024). These analyses reveal pronounced regional contrasts. For example, parts of the eastern United States experience more than 100 stagnation days per year, while in China persistent stagnation regimes dominate major continental basins such as the Tarim and Sichuan regions (Huang et al., 2017). Such spatial variability reflects the strong influence of synoptic circulation, regional topography, and large-scale climatic forcing on atmospheric ventilation.

Recent research also suggests that climate change may alter the frequency and persistence of stagnation events. Rising surface temperatures and modifications in large-scale circulation patterns have the potential to weaken land–sea pressure gradients and reduce atmospheric ventilation efficiency. Horton et al. (2014) indicated that stagnation frequency could increase in climatically sensitive regions including the Mediterranean basin and East Asia. Additional studies have linked this tendency to broader circulation changes, including a slowdown of upper-level winds and modifications of the Hadley circulation (Seidel et al., 2008; Lu et al., 2007). Within this framework, air stagnation emerges not only as a local meteorological

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condition but also as a manifestation of evolving large-scale circulation regimes under global climate change.

Despite substantial progress in global assessments, the spatial and temporal behavior of stagnation remains poorly documented across the Middle East and North Africa (MENA). This knowledge gap is particularly evident for highly urbanized environments such as the Nile Delta in northern Egypt. The Delta represents a densely populated coastal–continental transition zone characterized by intense urbanization, concentrated industrial activity, and extremely high population density. At the same time, its low-relief geomorphology and open alluvial landscape limit mechanical ventilation within the boundary layer. These characteristics create conditions that may favor persistent stagnation, yet the climatological structure and long-term evolution of this phenomenon in the region remain insufficiently explored.

The Nile Delta occupies a climatically sensitive position within the eastern Mediterranean atmospheric system. Regional circulation alternates between Mediterranean cyclonic activity during winter and the dominance of subtropical high-pressure systems during summer. This seasonal transition modulates the balance between horizontal ventilation and vertical mixing within the lower atmosphere (Horton et al., 2012; Huang et al., 2017). Rapid urban expansion and the intensification of the Urban Heat Island (UHI) effect further modify local boundary-layer processes by enhancing surface warming and strengthening near-surface stability (Wang et al., 2021; Raj et al., 2020). Satellite observations have also revealed elevated Aerosol Optical Depth (AOD) and increased dust loading over several Delta cities during stagnant conditions, illustrating the feedback between atmospheric stability and pollutant accumulation (El-Metwally et al., 2010; El-Askary et al., 2006). Together, these factors suggest that the Nile Delta provides a natural setting in which regional circulation, boundary-layer dynamics, and anthropogenic forcing interact to shape stagnation behavior.

Despite the environmental and demographic significance of the Nile Delta, no previous study has systematically examined the long-term climatology, spatial structure, and temporal evolution of air stagnation across this region.

Building on this scientific gap, the present study provides the first comprehensive climatological assessment of air stagnation dynamics over the Egyptian Nile Delta during the period 1980–2020. The analysis employs the Air Stagnation Index derived from ERA5 and

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ERA5-Land reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). Through integrated spatial and statistical analyses, the study pursues three principal objectives: (i) to construct a high-resolution climatology of stagnation frequency and variability across the Nile Delta‘ (ii) to examine the relationship between stagnation trends and regional circulation variability over the eastern Mediterranean; and (iii) to generate spatio-temporal diagnostics that improve understanding of atmospheric ventilation efficiency and support future applications in air-quality management and sustainable urban planning within deltaic environments.

2. Study Area

The Nile Delta occupies the northernmost part of Egypt and forms the terminal segment of the Nile River's extensive alluvial plain before its discharge into the Mediterranean Sea. Geographically, the Delta extends between latitudes 29°45′–31°36′ N and longitudes 29°–32°35′ E (Figure 1A). The region spans approximately 220 km from west to east and about 170 km from south to north, covering nearly 23,000 km², which represents around 2.3% of Egypt's total land area. Despite this relatively limited spatial extent, the Delta hosts more than 40% of the national population (CAPMAS, 2023; Frihy & El-Sayed, 2013; Stanley & Warne, 1998). This exceptional demographic concentration makes the Nile Delta one of the most densely populated coastal plains within the Mediterranean basin and highlights the environmental relevance of atmospheric conditions affecting the region.

The geomorphology of the Delta is characterized by an extremely low-relief surface that developed through long-term fluvial sediment deposition. As illustrated in the elevation model in Figure 1B, most of the Delta plain lies below 20 m above mean sea level and exhibits only a very gentle northward to northwestern slope toward the Mediterranean coastline. The absence of major topographic barriers results in a highly uniform terrain across the region, while minor elevation variations occur mainly along the southern and peripheral margins of the Delta. Several major urban centers, including Cairo, Tanta, Mansoura, and Alexandria, are distributed across this flat alluvial surface (El-Metwally et al., 2010; El-Askary et al., 2006).

Climatically, the Nile Delta lies within a Mediterranean–semi-arid transition zone influenced by both maritime conditions from the Mediterranean Sea and continental atmospheric processes over northeastern Africa. Winters are generally mild and relatively humid, whereas

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summers are hot and predominantly dry. Mean air temperatures typically range between 15–20 °C during winter and frequently exceed 35 °C in summer. Precipitation exhibits a pronounced north–south gradient across the Delta, with annual totals generally below 200 mm along the Mediterranean coast and decreasing to less than 50 mm toward inland sectors (Abdelaal, 2024). Long-term observations further indicate a persistent regional warming trend of approximately 0.3 °C per decade since the 1970s, accompanied by declining relative humidity and an increasing coastal–inland humidity gradient. These climatic tendencies are consistent with broader patterns of progressive aridification reported across the eastern Mediterranean region (Hassaan & Abdrabo, 2023; IPCC, 2021).

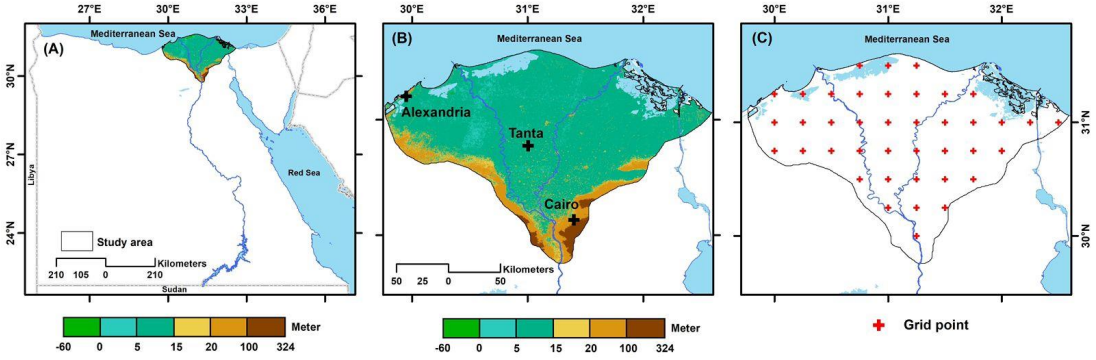

Figure 1 Location of the study area and related variables. (A) Nile Delta within northern Egypt, (B) elevation gradient of the Nile Delta, together with the distribution of weather stations employed for validation, (C) 0.25° × 0.25° grid points applied for AS analysis

At the synoptic scale, the regional atmospheric circulation affecting the Nile Delta is governed primarily by two alternating systems that dominate different seasons of the year. During winter, Mediterranean cyclones frequently influence northern Egypt and produce episodic rainfall events and transient atmospheric disturbances. In contrast, summer conditions are typically controlled by the subtropical high-pressure belt extending across North Africa and the eastern Mediterranean, which favors relatively stable atmospheric conditions over the region (Zanaty et al., 2024). The seasonal alternation between these circulation regimes contributes to marked variability in atmospheric stability and ventilation characteristics throughout the year.

For the purposes of spatial analysis, the study domain is represented using evenly distributed grid cells with a spatial resolution of 0.25° × 0.25°, as shown in Figure 1C. These grid points

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provide consistent coverage of the Delta region and form the spatial framework used to examine the distribution and variability of atmospheric stagnation conditions across the study area.

3. Data and Methodology

3.1 Data

This study is based on atmospheric fields derived from the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and accessed through the Copernicus Climate Data Store. ERA5 provides globally gridded atmospheric variables at a horizontal resolution of 0.25° × 0.25° with hourly temporal resolution extending from 1979 onward (Hersbach et al., 2020). The analysis period spans January 1980 to December 2020, ensuring a sufficiently long record for assessing multi-decadal variability in stagnation frequency. The Nile Delta domain was represented using the native ERA5 grid, yielding 40 grid cells fully covering the study area (Fig. 1C). These grid cells constituted the fundamental spatial units for all subsequent calculations and statistical analyses.

Hourly fields retrieved for each grid cell include:

- 10-m zonal and meridional wind components (u10, v10)
- 500-hPa zonal and meridional wind components (u500, v500)
- Total precipitation

Daily precipitation totals were obtained by aggregating hourly precipitation within each calendar day. All spatial processing was conducted in the WGS-84 geographic coordinate system. Consistency across variables and temporal alignment of grid cells were verified prior to computation.

3.2 Wind Computation and Temporal Aggregation

Wind speed at both the near-surface (10 m) and mid-tropospheric (500 hPa) levels was calculated from the horizontal wind components according to:

$$S = \sqrt{U^2 + V^2}$$

Hourly wind components at both the 10-m level (u10, v10) and the 500-hPa level (u500, v500) were retrieved from ERA5. Wind speed was calculated at hourly resolution for each grid cell from the horizontal wind components, and daily mean wind speeds were

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subsequently derived as the arithmetic mean of the 24 hourly values. The same procedure was applied to both near-surface and mid-tropospheric winds, ensuring that stagnation thresholds were evaluated from dynamically resolved fields rather than from pre-aggregated daily products.

3.3 Air Stagnation Index (ASI)

Air stagnation was diagnosed following the framework of Wang and Angell (1999) and Horton et al. (2012). A stagnation day was identified when, within a given grid cell and calendar day, the following conditions were simultaneously satisfied:

1. Daily mean 10-m wind speed < 3.2 m s^{-1}
2. Daily mean 500-hPa wind speed < 13.0 m s^{-1}
3. Daily total precipitation < 1 mm

A day was classified as a stagnation day only when all three ASI thresholds were simultaneously satisfied within the same grid cell and calendar day, ensuring that the diagnosed events represent coherent atmospheric conditions characterized by weak horizontal ventilation, reduced mid-tropospheric flow, and absence of precipitation.

Each grid cell was assigned to a binary daily indicator (1 = stagnation; 0 = non-stagnation). Stagnation episodes were defined as sequences of consecutive stagnation days within each grid cell, allowing the identification of event persistence and the quantification of episode duration within the stagnation climatology. From this binary time series, annual and seasonal stagnation frequencies were calculated. Event-based metrics, including mean duration and maximum consecutive stagnation sequence, were derived from continuous runs of stagnation days.

3.4 Validation

ERA5-derived daily surface wind speed at 10 m and daily precipitation were evaluated against independent station observations obtained from the NOAA Global Surface Summary of the Day (GSOD) archive. Three stations representing the coastal–inland climatic gradient of the Nile Delta were selected for the validation analysis: Alexandria, Tanta, and Cairo International Airport.ERA5 grid-point values corresponding to each station location were extracted and temporally matched with the daily GSOD records for the common analysis

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period (1980–2020). Statistical agreement between the two datasets was quantified using the Pearson correlation coefficient (r), coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE), and Willmott's modified index of agreement (d_1). Statistical significance was assessed at $p < 0.01$.

3.5 Trend Analysis

Temporal trends in stagnation frequency were evaluated using the non-parametric Mann–Kendall test, a widely applied method for detecting monotonic trends in hydro-climatic time series. Prior to trend detection, each time series was examined for serial autocorrelation using the lag-1 autocorrelation coefficient, since positive autocorrelation may inflate the variance of the Mann–Kendall statistic and consequently overestimate trend significance. When significant autocorrelation was detected at the 95% confidence level, the Modified Mann–Kendall procedure proposed by Hamed and Rao (1998) was applied to adjust the variance of the test statistic and ensure a robust assessment of statistical significance. The magnitude of detected trends was quantified using Sen's slope estimator, which provides a median-based rate of change that is resistant to outliers and non-normal data distributions.

Trend magnitudes are expressed in days per decade and were evaluated at both annual and seasonal scales. Statistical significance was assessed at $\alpha = 0.05$. All statistical analyses were performed using Python (version 3.11).

4. Results

Prior to examining the dynamics of air stagnation across the Nile Delta, the reliability of the ERA5 reanalysis was evaluated against independent station observations. Daily meteorological records were obtained from the Global Surface Summary of the Day (GSOD) archive maintained by the National Oceanic and Atmospheric Administration (NOAA). The GSOD dataset compiles quality-controlled surface observations from stations operating within the World Meteorological Organization (WMO) network and provides continuous daily measurements of key meteorological variables, including wind speed and precipitation.

A station-based comparison was conducted between ERA5 grid-point values and GSOD observations for three representative stations across the Nile Delta: Alexandria, Tanta, and Cairo Airport, covering the period 1980–2020. ERA5 fields were temporally matched with

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the corresponding daily GSOD records prior to statistical evaluation in order to ensure consistency between the two datasets.

The comparison demonstrates strong agreement between ERA5 and the GSOD observations. As summarized in Table 1, correlation coefficients exceed 0.89, coefficients of determination range from 0.83 to 0.92, and root mean square errors remain below 2 m s^{-1} for wind speed and 1 mm day^{-1} for precipitation, values that are well within the range commonly reported for reanalysis validation studies. Scatterplots presented in Figure 2 further illustrate this agreement, with most data points clustering close to the 1:1 reference line and the fitted linear regression closely following the same relationship. These graphical patterns are consistent with the statistical metrics summarized in Table 1 and indicate strong overall agreement between the two datasets, with only limited systematic bias as reflected by the low MBE values. Collectively, these validation results demonstrate that ERA5 reliably reproduces the temporal variability of near-surface wind speed and precipitation across the Nile Delta, providing a robust foundation for the subsequent climatological analysis of air stagnation.

Table 1. Statistical validation of ERA5 wind speed and precipitation against GSOD station observations across the Nile Delta (1980–2020).

Station	Variable	Level	r	R^2	RMSE	MBE	d_1	p-value
Alexandria	Wind speed (m/s)	Surface (10 m)	0.89	0.85	1.8	−0.2	0.91	<0.001
	Precipitation (mm/day)	Surface	0.91	0.86	0.7	0.02	0.90	<0.01
Tanta	Wind speed (m/s)	Surface (10 m)	0.94	0.90	1.9	−0.3	0.90	<0.001
	Precipitation (mm/day)	Surface	0.87	0.83	0.6	0.04	0.92	<0.01
Cairo Airport	Wind speed (m/s)	Surface (10 m)	0.96	0.92	1.6	−0.1	0.93	<0.001
	Precipitation (mm/day)	Surface	0.93	0.90	0.5	0.03	0.92	<0.01

Notes: r: Pearson correlation coefficient; R^2: coefficient of determination; RMSE: root mean square error; MBE: mean bias error; d_1: Willmott's modified index of agreement. All correlations are significant at $p < 0.01$. Validation was performed using temporally matched daily observations from the NOAA Global Surface Summary of the Day (GSOD) archive for 1980–2020.

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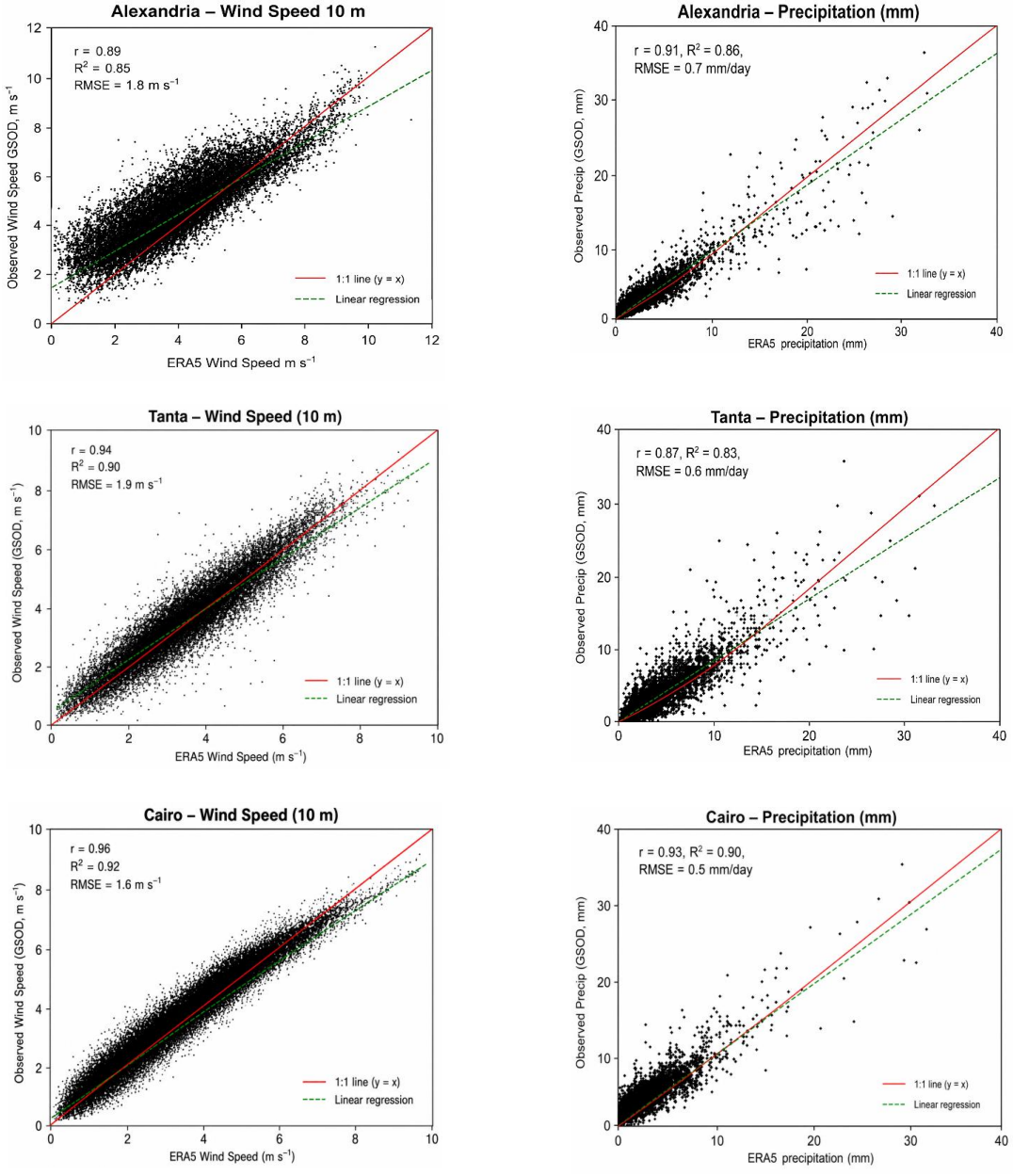

Figure 2. Scatterplots comparing ERA5 reanalysis data with daily surface observations extracted from the NOAA Global Surface Summary of the Day (GSOD) archive for wind speed (10 m) and precipitation at Alexandria, Tanta, and Cairo International Airport during 1980–2020. The solid red line denotes the 1:1 reference line (y = x), whereas the dashed green line represents the least-squares linear regression fitted to the observations.

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These results indicate that ERA5 adequately reproduces the temporal variability of near-surface wind speed and precipitation across the Nile Delta. The dataset therefore provides a reliable basis for the subsequent climatological analysis of air stagnation patterns across the region.

Air stagnation is operationally defined in this study following the meteorological criteria of the NCDC Air Stagnation Index (ASI), which identifies stagnation days when three atmospheric conditions occur simultaneously: weak near-surface winds, weak mid-tropospheric flow, and the absence of precipitation (Horton and Harshvardhan, 2012; Huang et al., 2017). A stagnation day occurs when surface wind speed is below 3.2 m s^{-1}, wind speed at 500 hPa is below 13 m s^{-1}, and daily precipitation does not exceed 1 mm. Within this framework, spatial variations in stagnation frequency are strongly linked to variability in near-surface wind speed, particularly across low-relief continental plains where boundary-layer ventilation is primarily regulated by horizontal wind intensity. The analyses presented here therefore focus on the role of surface wind variability, while upper-level flow and precipitation act as complementary constraints embedded within the stagnation index formulation.

4.1 Climatology and Spatial Patterns

The spatial distribution of mean annual air stagnation days (Figure 3A) exhibits distinct heterogeneity across the Egyptian Nile Delta. Central interior regions experience the highest frequency, exceeding 150 days per year, whereas coastal zones, particularly in the northwest, show lower frequencies, around 60 days annually. Mean annual stagnation cases (Figure 3B) mirror this pattern, with more than 18 episodes per year clustered in the central Delta and fewer than six in western and northern peripheries.

The mean duration of individual stagnation episodes (Figure 3C) ranges from 7–8 days in central and eastern sectors, decreasing to less than 5 days along the coast. This spatial gradient highlights the persistence of stagnant conditions in the Delta's interior, consistent with limited near-surface ventilation. The convergence of high frequency and long-duration zones defines recurrent stagnation hotspots, providing a robust depiction of spatial climatology. these observations indicate that stagnation dynamics over the Nile Delta are controlled primarily by local-scale ventilation efficiency and coastal influence, with interior regions experiencing more prolonged and frequent stagnation. Together, these patterns

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establish a coherent spatial climatology of air stagnation across the Nile Delta, characterized by a maximum pronounced inland and a progressive decrease toward the Mediterranean coast.

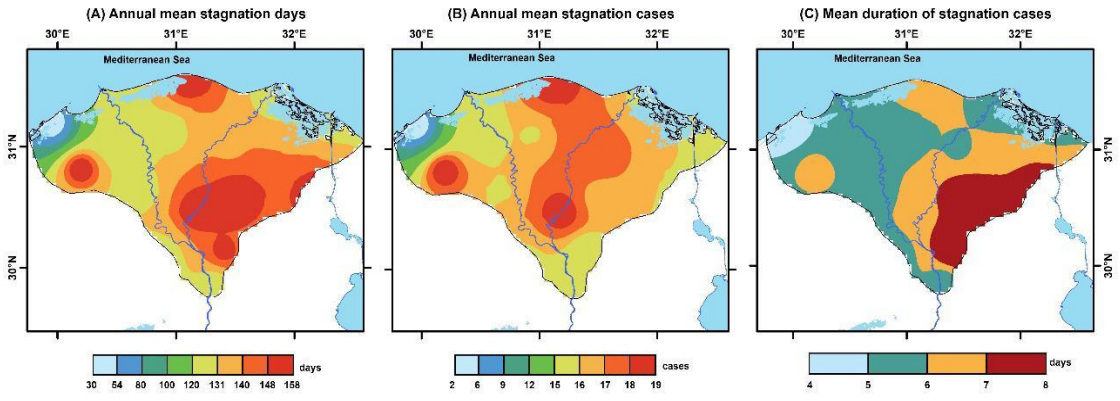

Figure 3 Spatial distribution of (a) mean annual air stagnation days, (b) mean annual stagnation cases, and (c) mean duration of stagnation episodes (days) over the Egyptian Nile Delta during 1980–2020.

4.2 Seasonal Dynamics

Figure 4 illustrates the seasonal distribution of mean air stagnation days across the Nile Delta during 1980–2020. The spatial configuration reveals a pronounced annual cycle characterized by a primary maximum in summer and a secondary peak in winter, while spring and autumn exhibit comparatively lower frequencies.

In winter (DJF; Figure 4A), stagnation days are concentrated over the central and northeastern sectors of the Delta, with seasonal totals generally ranging between 11 and 14 days. Coastal areas exhibit lower frequencies, reflecting the moderating influence of maritime airflow. This spatial pattern is consistent with reduced surface wind speeds and enhanced lower-tropospheric stability during periods dominated by anticyclonic conditions over the eastern Mediterranean. Spring (MAM; Figure 4B) represents the minimum phase of stagnation occurrence, with values generally remaining below 18 days across most of the Delta. The spatial distribution becomes more fragmented, and only localized maxima persist over interior areas. This decline coincides with strengthened westerly circulation and enhanced horizontal mixing associated with transitional synoptic conditions.

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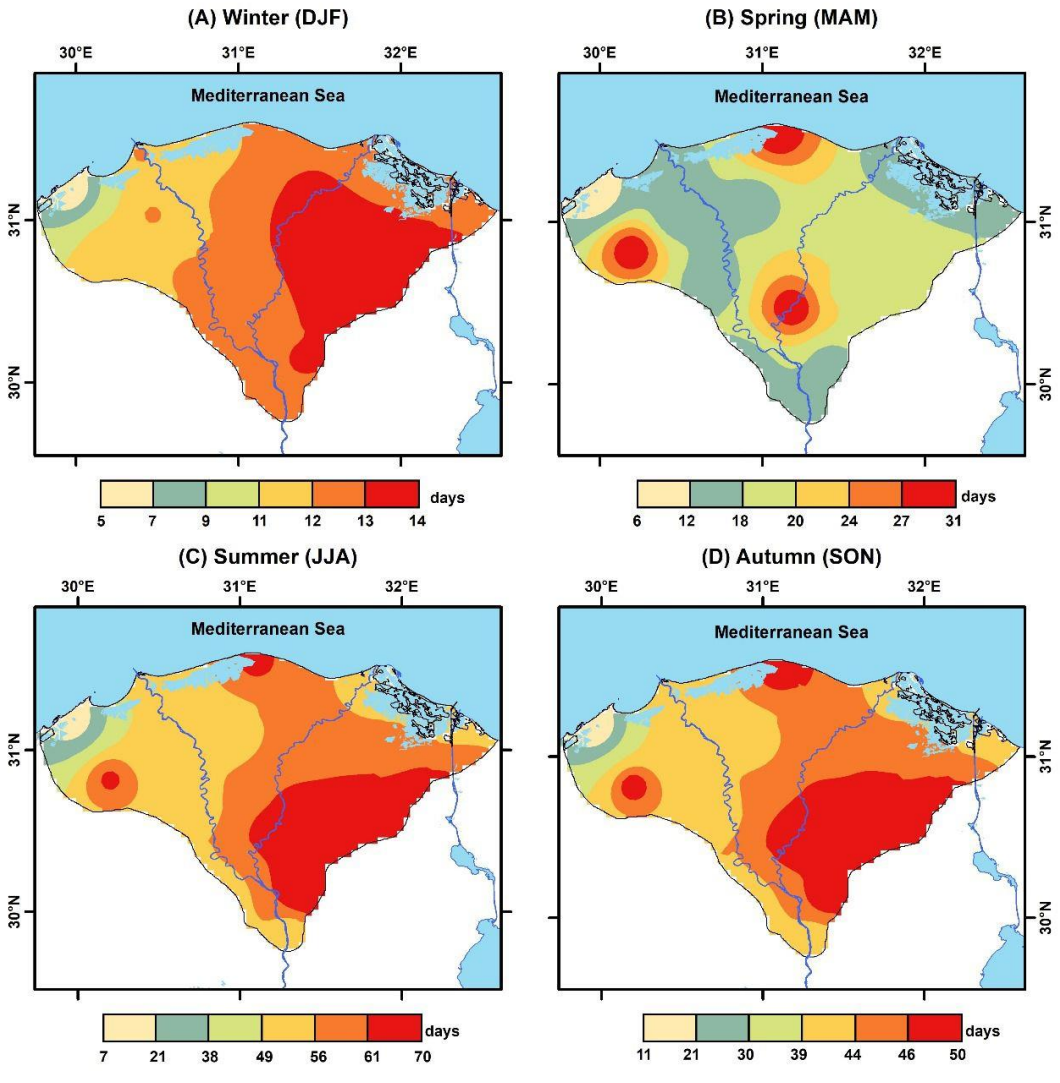

Figure 4. Seasonal distribution of mean air stagnation days across the Nile Delta during 1980–2020 derived from ERA5 reanalysis data: (A) winter (DJF), (B) spring (MAM), (C) summer (JJA), and (D) autumn (SON). Values represent the seasonal mean number of stagnation days calculated according to the NCDC Air Stagnation Index criteria.

The highest stagnation frequencies occur during summer (JJA; Figure 4C). Seasonal totals exceed 60 days across the central and southern Delta, indicating prolonged periods of weak ventilation. This pattern corresponds with reduced sea–land pressure contrasts and the

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seasonal intensification of the subtropical high over North Africa, conditions that Favour weak surface winds ($U_{10} < 3.2$ m s^{-1}) and increased boundary-layer stability. During autumn (SON; Figure 4D), stagnation frequencies increase again to intermediate levels, typically ranging between 30 and 45 days. The spatial pattern remains similar to that observed in summer but with reduced intensity. This phase reflects the gradual transition from the summer subsidence regime toward the more dynamically active winter circulation.

Overall, the seasonal distribution indicates that air stagnation across the Nile Delta is closely linked to variations in surface wind intensity and boundary-layer stability associated with the regional circulation cycle of the eastern Mediterranean.

4.3 Temporal and Spatial Trends

The examination of temporal and spatial trends in air stagnation provides a fundamental lens through which the long-term behaviour of the atmospheric boundary layer over the Nile Delta can be understood. Changes in the frequency and duration of stagnation episodes act as sensitive diagnostics of dynamical and thermal transformations within the lower troposphere, serving as indicators of variations in horizontal ventilation efficiency and thermal stability. Accordingly, analysing these trends offers an integrated view of how the phenomenon has evolved in magnitude and spatial structure across four consecutive decades, contributing to the interpretation of emerging climatic imbalances within one of the most sensitive Mediterranean environments to global climate change.

4.3.1 Temporal Variability

Figure 5 depicts a clear seasonal differentiation in the frequency of stagnation days and episodes. Panel (a) shows that Alexandria, the coastal station most directly influenced by the maritime boundary layer, exhibits the lowest exposure to stagnation, with monthly averages rarely exceeding four days and a standard deviation of ±1.5 days. This limited variability underscores the regulating influence of the Mediterranean Sea–land breeze circulation, which continuously renews the near-surface air and enhances mechanical dispersion, preventing prolonged atmospheric confinement. Panel (b), representing Tanta in the central Delta, reveals a gradual rise in the number of stagnation days beginning in April and peaking in July, with monthly means approaching 26 days and a standard deviation near ±2.8 days. This escalation mirrors the seasonal transition from maritime to inland thermodynamic control, reflecting the progressive dominance of synoptic subsidence and reduced ventilation

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efficiency across the Delta's interior. Panel (c) portrays Cairo, the most continental of the Delta stations, recording the highest stagnation frequency, exceeding 28 days per month during summer. This extreme persistence indicates a near-complete decoupling of the planetary boundary layer from the free atmosphere, accompanied by the establishment of a robust thermodynamic stability regime over the urban heat island. Such persistent stratification confines air masses and extends pollutant residence time, effectively transforming Cairo into a semi-permanent atmospheric sink during peak summer months.

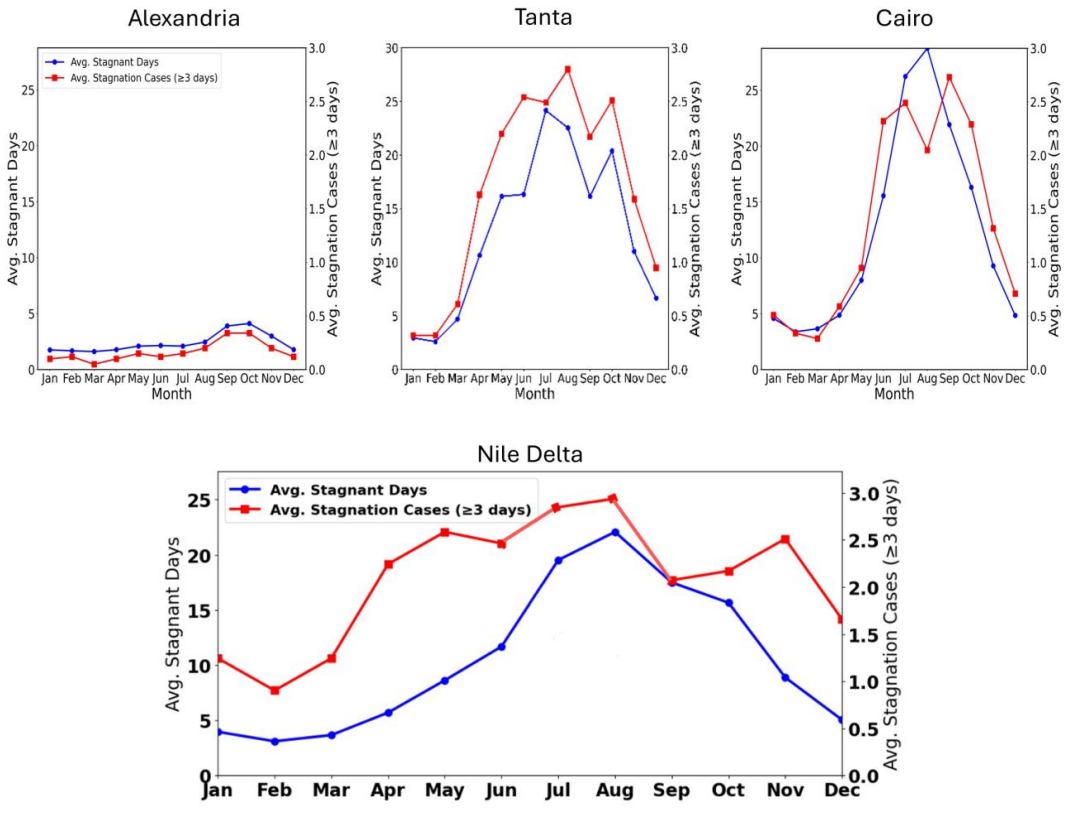

Figure 5. Monthly evolution of air stagnation days and prolonged stagnation episodes (≥3 consecutive days) across three representative Nile Delta stations (Alexandria, Tanta, and Cairo) derived from surface and radiosonde observations, alongside the Delta-wide climatological mean reconstructed from ERA5 reanalysis for 1980–2020.

Across all three stations, the parallel seasonal evolution of the curves in Figure 5 indicates that the increase in stagnation days primarily results from the lengthening of individual

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stagnation events, rather than a higher count of short-lived episodes. This persistence-oriented character is typical of broad alluvial plains, where seasonal continuity of stagnation episodes is amplified by the weak dynamic forcing and subdued synoptic modulation.

To determine whether this local signal represents a regionally coherent pattern, panel (d) presents the Delta-wide average derived from ERA5 reanalysis data. The regional trend exhibits a steady increase in mean stagnation days from April to the summer apex (July–August), surpassing 20 days per month. The close alignment between the regional curves for stagnation days and events confirms that the observed intensification reflects longer-lasting stagnation episodes rather than episodic multiplicity. This correspondence highlights the structural dominance of persistent atmospheric stillness, a hallmark of semi-arid Mediterranean stagnation regimes.

Consistent with global studies of stagnation-prone environments in the Mediterranean and subtropical domains, such as those reported by Horton et al. (2012) and Huang et al. (2018), the seasonal peak is linked to diminished upper-level synoptic activity and weakened surface pressure gradients. The temporal behaviour observed here can be attributed to the predominance of quasi-stationary pressure systems during summer, particularly the northward extension of the Sudan Low combined with the decline of upper-level westerly activity. These features jointly suppress horizontal ventilation and foster the accumulation of warm air masses near the surface. Conversely, during winter, increased Mediterranean cyclonic activity and frequent frontal passages invigorate surface winds and enhance air-mass renewal, leading to a sharp reduction in stagnation frequency.

Taken together, these findings delineate a pronounced spatial gradient in stagnation intensity across the Nile Delta, increasing southward from the maritime to the continental interior. This gradient encapsulates the atmospheric transition from a ventilated maritime regime to a quiescent continental regime, defining the dynamic nucleus of the spatial tendencies explored in the subsequent section. From a climatic perspective, this progressive intensification signifies the Delta's transformation into a sensitive atmospheric basin where thermal forcing, synoptic modulation, and anthropogenic surface heating converge to regulate boundary-layer behaviour. Collectively, the temporal signals portrayed here reveal not only a seasonal oscillation but also an emerging climatological reconfiguration of the eastern Mediterranean boundary-layer system under regional warming pressures.

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Figure 6 summarizes the long-term evolution of air stagnation across the coastal–inland gradient of the Nile Delta using three representative stations together with the Delta-wide mean derived from ERA5. Trend magnitudes were estimated using Sen's slope estimator, whereas statistical significance was evaluated with the Mann–Kendall test after correcting for serial autocorrelation following Hamed and Rao (1998). Overall, the results reveal a consistent positive trend in stagnation frequency across all locations, although the magnitude of the increase varies along the coastal–inland gradient.

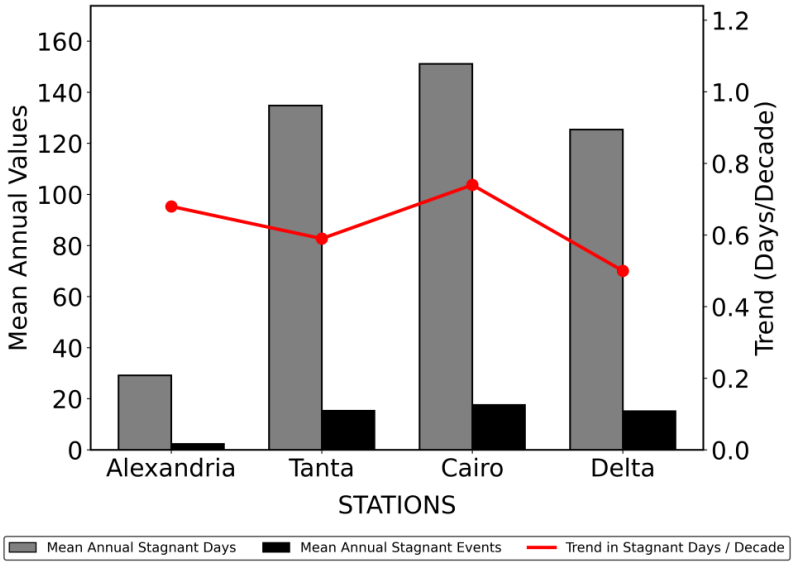

Figure 6. Mean annual air stagnation days, prolonged stagnation episodes, and decadal trends across three representative stations (Alexandria, Tanta, and Cairo Airport) together with the Delta-wide mean derived from ERA5 reanalysis (1980–2020). Grey bars denote the mean annual number of stagnation days, black bars indicate the mean annual number of prolonged stagnation episodes, and the red line represents the corresponding Sen's slope trend estimates (days decade^{-1}). Trend significance was evaluated using the Mann–Kendall test after correction for serial autocorrelation.

Alexandria exhibits the lowest annual stagnation frequency (approximately 30 days yr^{-1}) together with a modest positive trend of about +0.67 days decade^{-1}, reflecting the persistent ventilating influence of the Mediterranean. Stagnation becomes progressively more frequent inland, with Tanta recording approximately 135 days yr^{-1} and a positive trend of about +0.60 days decade^{-1}. Cairo displays the highest annual stagnation frequency (approximately 150 days yr^{-1}) and the strongest increase (about +0.73 days decade^{-1}), whereas the Delta-wide

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mean reaches approximately 125 stagnation days yr^{-1} with a comparatively weaker positive trend of about +0.50 days $decade^{-1}$.

The close correspondence between mean stagnation frequency, prolonged stagnation episodes, and the positive Sen's slope estimates indicates that the observed increase primarily reflects a gradual intensification of persistent stagnation conditions rather than a greater occurrence of isolated short-lived events. Taken together, Figure 6 depicts a coherent long-term strengthening of atmospheric stagnation across the Nile Delta while preserving the pronounced coastal–inland gradient evident throughout the analysis. This spatial pattern is consistent with progressively weaker ventilation from the Mediterranean coast toward the continental interior, reinforcing the climatological interpretation developed in the preceding sections.

4.3.2 Spatial Trends

Spatial patterns of long-term trends in air stagnation metrics across the Nile Delta are presented in Figure 7. Trends were calculated for each ERA5 grid cell using Sen's slope estimator, while statistical significance was evaluated using the Mann–Kendall test as described in Section 3.5. The resulting maps therefore illustrate the spatial magnitude of decadal changes in stagnation characteristics during the period 1980–2020.

Panel (a) displays the spatial distribution of trends in the annual number of stagnation days. Positive trends dominate most of the Delta, with magnitudes ranging from approximately +0.5 to +3.3 days per decade. The strongest increases occur across the central and southern sectors of the Delta, particularly along the Tanta–El-Mahalla and Banha–Mansoura corridors, indicating a gradual intensification of stagnation frequency within the inland portions of the region. In contrast, weaker trends appear along the northwestern coastal fringe, where the persistent influence of Mediterranean maritime ventilation moderates the long-term growth of stagnation conditions. Panel (b) illustrates the spatial trends in the number of stagnation events. The pattern broadly resembles that observed for stagnation days, although the magnitude of change is smaller, ranging between approximately +0.05 and +0.4 events per decade. Localized clusters of increasing event frequency emerge across central Delta sectors and parts of the western coastal transition zone near Alexandria and Kafr El-Dawar. These patterns indicate that the observed increase in stagnation days partly reflects a growing recurrence of stagnation episodes across inland areas. Panel (c) presents trends in the mean duration of stagnation events. Most grid cells exhibit weak to moderate positive tendencies,

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typically between +0.1 and +0.3 days per decade, suggesting a gradual extension in the persistence of individual stagnation episodes. In contrast, parts of the eastern coastal sector show slight negative slopes (up to −0.2 days per decade), indicating shorter event durations in areas more directly influenced by coastal airflow.

Taken together, the three panels in Figure 7 indicate that the observed increase in stagnation days across much of the Nile Delta reflects the combined effect of moderately increasing event frequency and a gradual extension of event persistence, particularly across inland sectors.The spatial coherence of these patterns highlights the inland sectors of the Delta as the primary centers of stagnation intensification over the past four decades..

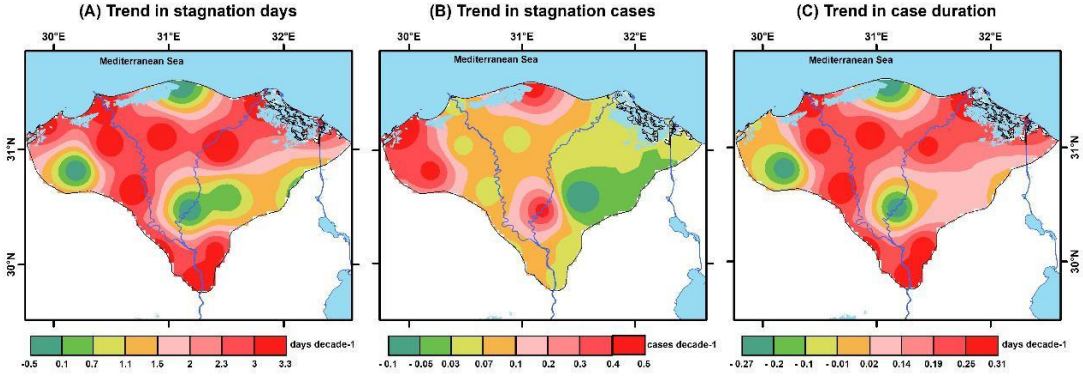

Figure 7. Spatial distribution of decadal trends in (a) the number of air stagnation days, (b) the frequency of stagnation events, and (c) the mean duration per event across the Nile Delta during 1980–2020.

4.3.3 Atmospheric Dynamics and Stagnation

Figure 8 illustrates the spatial configuration of key atmospheric variables associated with air stagnation across the Nile Delta during 1980–2020, including upper-level wind speed (500 hPa), near-surface wind speed (10 m), and the annual frequency of dry days. These variables correspond directly to the principal components of the Air Stagnation Index and provide a dynamical context for interpreting the spatial distribution of stagnation conditions.

In panel (a), mean wind speeds at 500 hPa range between 11.7 and 15.3 m s^{-1}, with relatively weaker values across the central and southern sectors of the Delta and stronger flow toward the northwestern margin. This spatial gradient indicates a modest reduction in upper-level flow intensity over the interior of the Delta compared with the coastal sector. Panel (b) presents the distribution of near-surface wind speeds, which vary between 2.4 and 4.7 m s^{-1}.

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The lowest velocities occur primarily over the eastern and south-central Delta, while higher wind speeds are observed toward the Mediterranean coastline. These contrasts highlight the inland weakening of low-level ventilation relative to the more dynamically active coastal zone influenced by maritime airflow. Panel (c) shows the spatial distribution of annual dry-day frequency, ranging from approximately 330 to 348 days yr^{-1}. The highest values are concentrated across the central and southeastern Delta, whereas relatively lower frequencies occur along the northwestern coastal sector.

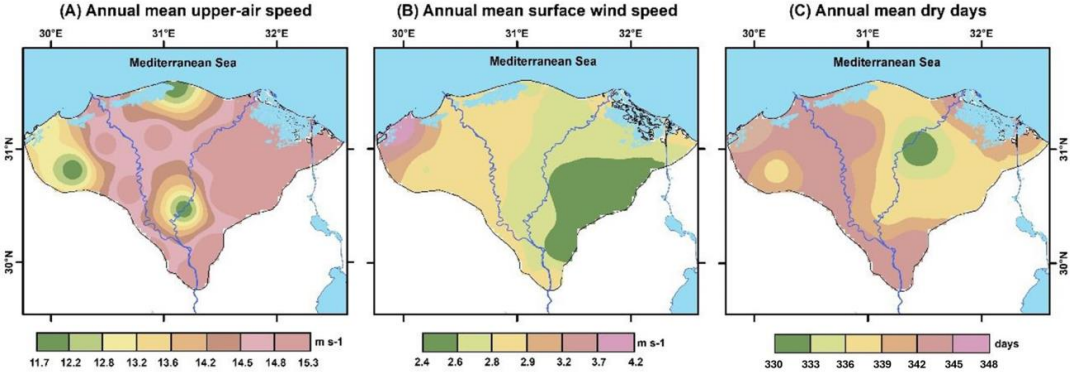

Figure 8. Spatial distribution of mean wind speed at 500 hPa (a), surface wind speed (b), and number of dry days (c) across the Nile Delta during 1980–2020.

A comparison of the three panels reveals a consistent spatial correspondence: regions characterized by weaker upper-level and surface winds generally coincide with areas experiencing higher frequencies of dry days. This configuration reflects the co-occurrence of reduced horizontal ventilation and limited precipitation across the Delta's interior, conditions that favor the development and persistence of air stagnation.

Taken together, these spatial patterns indicate that the interior sectors of the Nile Delta experience a combination of weaker atmospheric flow and prolonged dry conditions relative to the coastal margin. Such a configuration provides a dynamical setting conducive to stagnation persistence within the regional boundary-layer environment.

4.3.4 Statistical Relationships with Atmospheric Variables

To clarify the atmospheric mechanisms underlying the spatial distribution of stagnation across the Nile Delta, statistical relationships between stagnation frequency and key atmospheric variables were examined. Because the analysis is based on spatial grid cells

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derived from a continuous atmospheric field, neighboring cells may exhibit spatial dependence. Consequently, the reported correlation statistics should be interpreted as indicative of regional associations rather than strictly independent statistical relationships.

Figure 9 illustrates the spatial relationships between mean annual air stagnation frequency and three key atmospheric controls across the Nile Delta: near-surface wind speed (10 m), upper-level wind speed at 500 hPa, and the annual number of dry days. Because the analysis is conducted on spatial grid cells derived from a continuous atmospheric field, neighbouring cells may not be fully independent and can exhibit a degree of spatial autocorrelation. Consequently, the reported correlation statistics should be interpreted as indicative of regional associations rather than strictly independent statistical relationships.

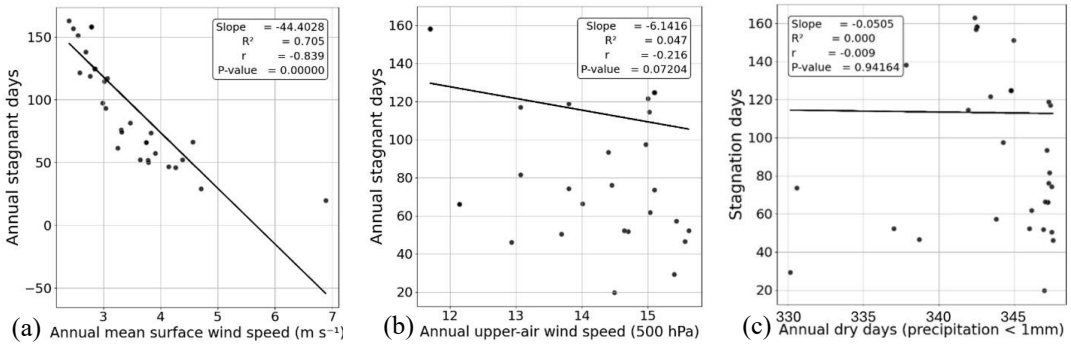

Figure 9. Spatial statistical relationships between mean annual air stagnation frequency and key atmospheric controls across the Nile Delta during 1980–2020. Panels illustrate correlations with (a) mean surface wind speed (10 m), (b) upper-level wind speed at 500 hPa, and (c) annual number of dry days (precipitation < 1 mm). Each point represents an ERA5 grid cell within the study domain.

Panel (a) shows a strong and statistically significant inverse correlation between air stagnation frequency and mean surface wind speed ($r = -0.839$, $R^2 = 0.705$, $p < 0.001$). The number of stagnation days decreases by approximately 44 days for every 1 m s^{-1} increase in near-surface wind velocity. This relationship also reflects the broader climatological control exerted by near-surface wind regimes on atmospheric ventilation across the Delta, beyond the threshold condition embedded within the stagnation index. This robust negative relationship highlights the decisive role of horizontal ventilation in disrupting stagnation events and weakening the stable boundary layer over the Delta's flat alluvial plains. It also

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demonstrates the sensitivity of the local microclimate to minor variations in surface wind intensity, where small perturbations in low-level flow can markedly influence stagnation persistence and duration.

Panel (b) reveals a weak and statistically insignificant association between stagnation frequency and upper-tropospheric wind speed at 500 hPa ($r = -0.216$, $R^2 = 0.047$, $p = 0.07$). This suggests that variability in free-atmospheric circulation does not directly affect boundary-layer dynamics near the surface. The pattern reflects a pronounced boundary-layer decoupling regime that restricts the downward transfer of synoptic momentum and limits vertical ventilation efficiency. Such behavior agrees with findings reported by Horton et al. (2012) and Huang et al. (2017), who observed that stagnation in semi-continental settings is essentially a near-surface phenomenon driven by thermal stability and weak turbulent mixing rather than large-scale synoptic forcing.

Panel (c) shows no statistically significant correlation between stagnation frequency and the number of dry days ($r \approx 0$). This implies that variations in surface humidity or the frequency of non-precipitating days do not play a major role in determining stagnation behavior over the Nile Delta. The phenomenon arises primarily from the interaction between weak horizontal ventilation and enhanced dynamic–thermal stability; a ventilation–stability coupling that sustains prolonged stagnation episodes and increases the susceptibility of the local climatic system to seasonal-scale fluctuations.

Taken together, these relationships highlight the dominant role of near-surface wind dynamics in regulating air stagnation across the Nile Delta. The strong sensitivity of stagnation frequency to surface wind speed indicates that small variations in horizontal ventilation can substantially alter boundary-layer renewal over the Delta's flat alluvial terrain. In contrast, the weak association with upper-level winds and dry-day frequency suggests that stagnation persistence is primarily governed by local boundary-layer stability rather than by variability in free-tropospheric circulation or moisture conditions. These results emphasize that atmospheric ventilation efficiency represents the principal physical control on stagnation behavior in the region.

5 Discussion

The results indicate that atmospheric stagnation over the Nile Delta constitutes a persistent climatic feature rather than an episodic meteorological anomaly. The spatial and temporal

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organization of stagnation identified in this study suggests that the Nile Delta functions as a dynamically coherent stagnation regime, where weak horizontal ventilation and persistent boundary-layer stability jointly regulate atmospheric renewal across the region. Similar dynamical configurations have been documented in other stagnation-prone environments, where reduced near-surface ventilation and enhanced lower-tropospheric stability promote the persistence of stagnant air masses (Horton et al., 2012; Huang et al., 2017; Huang et al., 2018). The stagnation thresholds applied in this study follow the classical Air Stagnation Index formulation proposed by Wang and Angell (1999) and widely adopted in subsequent climatological investigations (e.g., Horton et al., 2012; Huang et al., 2018). Employing the same criteria ensures methodological consistency and enables direct comparison between the stagnation characteristics observed over the Nile Delta and those reported for other regional and global environments. Within this regime, reduced horizontal ventilation, relatively weak upper-tropospheric flow, and enhanced thermal stability within the planetary boundary layer jointly favor the development of prolonged stagnation episodes. These characteristics suggest that stagnation across the Delta reflects broader circulation conditions that limit atmospheric ventilation efficiency rather than isolated local events.

The spatial and seasonal coherence of stagnation patterns further indicates that the phenomenon is embedded within the regional circulation regime of the eastern Mediterranean. In particular, the persistence of stagnation conditions appears to be linked to a gradual reduction in thermal and pressure gradients between the Mediterranean Sea and the adjacent continental interior. This reduction is consistent with the northward expansion of the subtropical anticyclone during summer reported in previous studies of the eastern Mediterranean, a circulation configuration that suppresses synoptic variability and promotes stable atmospheric conditions. From a dynamical perspective, these conditions favor enhanced lower-tropospheric stability and reduced boundary-layer ventilation efficiency. Comparable tendencies toward increased atmospheric stability have been reported across the eastern Mediterranean basin under recent warming conditions (Seidel et al., 2008; Huang et al., 2018).

Spatially, the annual distribution of stagnation days reveals a pronounced inland core extending across the central and southern sectors of the Nile Delta, where annual totals exceed 150 days. In contrast, coastal locations such as Alexandria experience substantially fewer events, averaging approximately 60 stagnation days per year, reflecting the moderating

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influence of persistent sea-breeze circulation and marine air ventilation. This pronounced coastal–inland gradient indicates a progressive reduction in ventilation efficiency from the Mediterranean shoreline toward the interior Delta plains. Under such conditions, weak vertical wind shear and reduced turbulent mixing within the planetary boundary layer limit vertical air exchange and promote the near-surface accumulation of heat, aerosols, and pollutants. The resulting thermally stratified structure enhances atmospheric stability and prolongs stagnation persistence. Similar spatial configurations have been reported in other low-relief coastal–continental transition environments, including the North China Plain and parts of the southern United States (Horton et al., 2012; Huang et al., 2017).

The seasonal cycle of stagnation exhibits a pronounced summer maximum and a secondary winter peak, separated by lower frequencies during the transitional seasons of spring and autumn. Summer conditions dominate the annual stagnation regime under the influence of the expanded subtropical high, when surface wind speeds frequently fall below 3.2 m s^{-1} and nocturnal temperature inversions become more persistent. These conditions promote enhanced decoupling within the planetary boundary layer, particularly over Cairo and the southern sectors of the Delta, where stagnation persists for more than 150 days annually. The weak statistical relationship between stagnation frequency and upper-level wind speed ($r = -0.216$) suggests that stagnation variability is primarily governed by lower-tropospheric processes rather than large-scale synoptic flow. Similar seasonal behavior has been documented in semi-arid regions of East Asia and the Mediterranean, where reduced near-surface ventilation and stable boundary-layer conditions promote prolonged stagnation events (Horton et al., 2012; Li et al., 2021).

Over the four-decade observational period, the temporal evolution indicates a gradual increase in both the frequency and persistence of stagnation events, averaging approximately 0.6 day per decade. Across inland sectors of the Delta, summer contributes more than half of the annual stagnation total, with seasonal averages exceeding sixty days. This pronounced seasonal concentration implies that the long-term increase in annual stagnation frequency is largely driven by changes occurring during the warm season. The dominance of summer stagnation suggests that persistent subsidence and sustained reductions in near-surface wind speeds during this period provide the primary dynamical context for the observed long-term increase in stagnation occurrence.

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The intensification of stagnation is consistent with the broader decline in near-surface wind speeds documented across the Mediterranean and other subtropical regions during recent decades (Vautard et al., 2010; McVicar et al., 2012; Azorin-Molina et al., 2019). Across the Nile Delta, stagnation frequency exhibits a remarkably strong inverse association with near-surface wind speed ($r = -0.839$), underscoring the pivotal role of horizontal ventilation in regulating boundary-layer renewal. This relationship indicates that even modest reductions in surface wind intensity can substantially suppress atmospheric mixing and prolong stagnation conditions across the Delta's low-relief alluvial landscape. Under weak-wind conditions, reduced momentum transfer suppresses turbulent mixing within the planetary boundary layer and slows the renewal of near-surface air masses, allowing thermally stable conditions to persist for extended periods. Comparable mechanisms have been documented in other stagnation-prone regions where declining wind speeds increase atmospheric residence times and promote pollutant accumulation (Vautard et al., 2010; Horton et al., 2012; Huang et al., 2017).

This dynamical configuration reflects a close coupling between horizontal ventilation and thermal stability within the boundary layer. When surface and upper-level winds weaken under persistently dry and radiatively intense conditions, vertical turbulence is suppressed. Under such circumstances, the lower atmosphere may evolve toward a quasi-isolated boundary-layer system. Within this environment, dry-day frequency may reach up to 348 days per year in some sectors of the Delta, indicating extremely limited moisture availability and reduced convective potential. Similar mechanisms have been reported in semi-arid regions where widespread wind stilling contributes directly to the persistence of atmospheric stagnation (Horton et al., 2012; Vautard et al., 2010).

In a broader context, the stagnation characteristics of the Nile Delta share several similarities with major global stagnation hotspots such as the Beijing–Tianjin Basin and the Los Angeles Basin (Horton et al., 2014; Tai et al., 2012). However, the underlying mechanisms differ substantially. Whereas those regions are strongly influenced by orographic confinement, stagnation over the Nile Delta likely develops under quasi-stationary pressure and thermal configurations across a nearly flat terrain. The absence of significant topographic enclosure indicates that stagnation persistence in the region is governed primarily by dynamical and thermodynamic controls rather than geometric basin effects.

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The environmental implications of this stagnation regime may be significant. Persistent stagnation across the central Delta, combined with rapid urban expansion, promotes a local atmospheric environment characterized by reduced air-mass exchange and limited heat dispersion. Under such conditions, the accumulation of fine particulate matter ($PM_{2.5}$) and ozone (O_3) frequently exceeds World Health Organization guideline levels, particularly across Greater Cairo (Hereher et al., 2022). These elevated pollutant concentrations coincide spatially with urban heat-island centers and major emission sources, creating reinforcing feedbacks in which urbanization enhances thermal stability through anthropogenic heat release and surface sealing, while stagnation simultaneously increases pollutant residence time and heat stress. Comparable feedback mechanisms have been documented in other urbanized stagnation regions such as the Los Angeles and Beijing–Tianjin basins (Horton et al., 2014; Cerro et al., 2015).

The sustained increase in stagnation frequency therefore suggests a gradual shift in the lower-tropospheric balance between horizontal ventilation and atmospheric stability across the Nile Delta. From a climatic perspective, These conditions are consistent with previously reported circulation adjustments across the eastern Mediterranean, including the increasing persistence of subtropical high-pressure systems and reduced synoptic variability during summer (Seidel et al., 2008; Hu et al., 2013; Azorin-Molina et al., 2019). Although the present analysis does not explicitly quantify long-term trends in geopotential height or pressure gradients, incorporating such diagnostics in future work would help clarify the dynamical linkage between stagnation variability and regional circulation changes.

Within this evolving atmospheric context, understanding stagnation dynamics is important not only for climatological assessment but also for environmental management. The integration of stagnation indicators into air-quality monitoring systems and urban planning strategies in Egypt may therefore become increasingly valuable. Predictive modeling frameworks that combine climatic observations, boundary-layer dynamics, and urban land-surface processes will be particularly important for assessing how the Nile Delta may respond to continued warming and rapid urbanization.

Taken together, these findings suggest that the Nile Delta represents a coastal plain increasingly prone to atmospheric stagnation. where declining near-surface ventilation and increasing boundary-layer stability interact to reshape the regional atmospheric renewal

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regime. Similar tendencies have been reported across several subtropical and Mediterranean environments experiencing widespread reductions in surface wind speeds and enhanced atmospheric stability under recent climate warming (Vautard et al., 2010; McVicar et al., 2012; Azorin-Molina et al., 2019).

6 Study Limitations

Despite the robustness of the analytical framework adopted in this study, several methodological and physical constraints should be acknowledged to properly contextualize the interpretation of the results.

The first limitation relates to the intrinsic characteristics of the ERA5 reanalysis dataset used in the analysis. Although ERA5 provides a dynamically consistent reconstruction of large-scale atmospheric circulation and synoptic variability (Hersbach et al., 2020), its spatial resolution remains insufficient to fully resolve mesoscale processes operating along the complex land–sea interface of the northern Nile Delta. Coastal boundary-layer processes such as sea-breeze circulations and local convergence zones may not be explicitly represented within the reanalysis grid. Consequently, small-scale variations in near-surface ventilation may be partially smoothed in coastal sectors, introducing a degree of uncertainty in the diagnosis of stagnation frequency near the Mediterranean shoreline.

A second limitation concerns the set of atmospheric variables included in the stagnation framework. The analysis was intentionally restricted to the core dynamical components of the classical Air Stagnation Index, namely surface wind speed, mid-tropospheric wind speed, and precipitation, following the methodology proposed by Wang and Angell (1999) and Horton et al. (2012). While this approach ensures comparability with previous climatological studies, it does not explicitly incorporate thermodynamic variables such as planetary boundary-layer height (PBLH) or surface turbulent heat fluxes. These parameters have been shown to modulate boundary-layer stability and may influence the intensity and persistence of stagnation episodes in arid and semi-arid environments (Zittis et al., 2021; Zhou et al., 2024).

A third limitation arises from the limited spatial density of long-term meteorological observations available for validation across the Nile Delta. Although three representative stations were used to evaluate the consistency of ERA5 surface fields, the existing observational network remains sparse relative to the pronounced urban–rural and coastal–

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inland gradients characterizing the region. A denser observational infrastructure would allow a more detailed assessment of local ventilation regimes and would improve the calibration of reanalysis-based diagnostics.

Finally, the present study adopts a diagnostic climatological approach based on historical reanalysis data rather than employing high-resolution regional climate modelling or future emission scenarios. As a result, the analysis primarily characterizes the recent climatological baseline of stagnation conditions over the Nile Delta rather than their potential future evolution under projected climate change.

Notwithstanding these limitations, the multi-decadal coverage of the dataset, combined with the spatially explicit grid-cell analysis and the integration of observational validation, provides a coherent empirical framework for understanding the climatology and recent evolution of air stagnation across the Nile Delta. The results therefore offer a valuable reference baseline for future studies seeking to explore the dynamical drivers and potential future trajectories of atmospheric stagnation in rapidly urbanizing coastal lowlands.

7 Uncertainty Assessment

Uncertainty in the present analysis arises from three principal sources: the characteristics of the reanalysis dataset, the operational thresholds used to diagnose stagnation, and the spatial–temporal aggregation of the atmospheric fields. Recognizing these factors is essential for interpreting the robustness of the derived stagnation climatology over the Nile Delta.

The first source of uncertainty is associated with the use of reanalysis products. ERA5 and ERA5-Land provide dynamically consistent atmospheric reconstructions generated by the ECMWF Integrated Forecasting System; however, reanalysis fields remain model-constrained estimates whose accuracy depends on the density and distribution of assimilated observations (Hersbach et al., 2020). This limitation is particularly relevant for near-surface wind fields in low-relief coastal environments where observational coverage remains uneven. Across parts of the Nile Delta, the relatively sparse distribution of meteorological stations may introduce localized uncertainty in the representation of weak-wind conditions that are critical for diagnosing stagnation events.

A second source of uncertainty relates to the thresholds used to identify stagnation conditions. The criteria adopted in this study, namely surface wind speed < 3.2 m s^{-1}, mid-

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tropospheric wind speed at 500 hPa < 13 m s^{-1}, and daily precipitation < 1 mm day^{-1}, follow the classical Air Stagnation Index formulation widely applied in climatological analyses (Horton et al., 2014; Huang et al., 2017). Sensitivity tests indicate that moderate threshold adjustments (±10 %) modify the estimated annual stagnation frequency by less than 5 %, suggesting that the diagnosed spatial and temporal patterns remain relatively insensitive to small variations in the operational definition.

Temporal aggregation introduces an additional, though limited, source of uncertainty. Hourly ERA5 outputs were aggregated to daily means in order to maintain consistency with the stagnation index formulation. This procedure may smooth short-lived sub-daily variability, particularly during transitional seasons when boundary-layer coupling varies on diurnal time scales. Nevertheless, comparisons across daily, monthly, and seasonal aggregations reveal consistent spatial structures and temporal signals, indicating that aggregation effects do not materially alter the climatological patterns identified in this study.

Spatial resolution represents a further source of uncertainty. The 0.25° × 0.25° ERA5 grid is appropriate for regional-scale climatological analysis but cannot fully resolve fine-scale heterogeneity associated with urban land cover, irrigation patterns, or localized coastal circulations. Similar limitations have been documented in other low-relief deltaic environments where boundary-layer processes operate at spatial scales smaller than those represented in global reanalysis datasets (Huang et al., 2018).

Taken together, these factors primarily affect the precise magnitude of stagnation estimates rather than the overall spatial distribution or long-term variability reported here. The consistency between sensitivity analyses, validation statistics, and multi-scale aggregation diagnostics indicates that the principal stagnation patterns identified for the Nile Delta are generally robust within the methodological framework adopted in this study.

8 Future Research Directions

The results of this study highlight several priorities for future research aimed at improving the physical understanding of atmospheric stagnation over low-relief coastal–continental environments such as the Nile Delta. The analyses indicate that stagnation variability across the region is strongly controlled by near-surface ventilation efficiency and boundary-layer stability, as demonstrated by the strong inverse relationship between stagnation frequency and surface wind speed. Future investigations should therefore focus on clarifying the

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dynamical processes linking regional circulation variability with lower-tropospheric ventilation over the Delta. In particular, the strong statistical linkage identified between stagnation frequency and near-surface wind speed highlights the need for future studies to better resolve the processes governing regional ventilation efficiency over the Nile Delta.

High-resolution regional climate modeling provides an important pathway for advancing this understanding. Numerical simulations using mesoscale models such as the Weather Research and Forecasting model (WRF) and its chemistry configuration (WRF-Chem) can resolve atmospheric processes at kilometer-scale spatial resolution and sub-daily temporal scales. These simulations can explicitly represent mesoscale circulation features that are often smoothed in reanalysis datasets, including the inland penetration of Mediterranean sea-breeze systems and thermally driven circulations over the Delta plains. Such modeling experiments would allow detailed examination of the diurnal evolution of the planetary boundary layer and help quantify how variations in boundary-layer depth, stability, and turbulent mixing influence stagnation persistence during weak-wind conditions.

Further research should also investigate the sensitivity of stagnation regimes to variations in regional pressure gradients between the Mediterranean Sea and the continental interior. Changes in these gradients influence surface wind regimes and therefore the efficiency of horizontal ventilation across the Delta. Particular attention should be given to how projected modifications in regional wind fields may alter ventilation efficiency and stagnation persistence. Understanding this relationship is essential for interpreting the strong statistical association identified in this study between stagnation frequency and near-surface wind speed.

Satellite remote sensing offers additional opportunities for examining the environmental consequences of stagnation events. Observations from instruments such as Sentinel-5P and MODIS provide valuable information on atmospheric composition, aerosol loading, and land surface characteristics. When combined with ground-based meteorological and air-quality observations, these datasets can improve understanding of how thermally stable conditions influence pollutant accumulation and dispersion across the Nile Delta.

Future studies should also assess how projected changes in large-scale circulation may influence stagnation regimes under continued climate warming. Climate projection frameworks such as CMIP6 provide a suitable basis for evaluating potential modifications in

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Mediterranean pressure gradients, regional wind regimes, and seasonal atmospheric stability under emission scenarios such as SSP2-4.5 and SSP5-8.5.

Urban expansion across the Nile Delta represents another factor that warrants further investigation. Changes in surface roughness, thermal properties, and land-surface energy exchange influence boundary-layer development and local ventilation efficiency. High-resolution urban climate simulations could therefore clarify how urban growth affects turbulent mixing and air-mass renewal within major Delta cities.

Integrating stagnation diagnostics into air-quality early-warning systems and urban planning frameworks may also provide practical benefits. Incorporating atmospheric ventilation considerations into urban design could improve natural air exchange and reduce environmental impacts associated with persistent stagnation conditions in rapidly expanding Delta cities.

9 Conclusion

This study provides a quantitative climatological assessment of the spatial and temporal characteristics of air stagnation across the Nile Delta during the period 1980–2020 using high-resolution reanalysis datasets and spatial statistical analysis. The results demonstrate that atmospheric stagnation over the region represents a persistent climatic feature rather than an isolated meteorological occurrence. Clear spatial and seasonal patterns were identified, with stagnation reaching its highest frequency during summer when weakened pressure gradients and the eastward extension of the subtropical high reduce horizontal ventilation and promote stable boundary-layer conditions.

The analysis further indicates a gradual increase in stagnation frequency over the study period, particularly across the central and southern sectors of the Delta where urban expansion is most pronounced. This tendency reflects the combined influence of declining near-surface wind speeds, enhanced boundary-layer stability, and regional warming. The strong inverse relationship identified between stagnation frequency and surface wind speed highlights the dominant role of horizontal ventilation in regulating stagnation variability across the region.

Spatial contrasts between coastal and inland areas further illustrate the influence of regional circulation processes. Coastal locations benefit from persistent marine ventilation associated

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with Mediterranean sea-breeze circulation, while inland sectors experience weaker ventilation and more frequent stagnation conditions. These differences emphasize the importance of mesoscale atmospheric processes in shaping the regional distribution of stagnation events across the Delta.

From a methodological perspective, the study demonstrates the value of combining high-resolution reanalysis datasets such as ERA5 and ERA5-Land with spatial analytical techniques for diagnosing mesoscale atmospheric variability. This integrated framework enables the identification of regional stagnation patterns and their relationship to boundary-layer processes and surface wind regimes.

Overall, the findings indicate that the Nile Delta represents a region of increasing sensitivity to atmospheric stagnation under ongoing climatic and environmental change. Understanding the dynamics that control ventilation efficiency and boundary-layer stability over the Delta is therefore essential for assessing future environmental conditions in this densely populated coastal region.

Declarations

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