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Temporal and meteorological determinants of emergency department visit volume: a 24-month time-series analysis from a tertiary hospital in Istanbul

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Abstract

Background

Daily emergency department (ED) visit volume is jointly determined by ambient weather, the temporal calendar (hour of day, day of week, season, public holidays) and a range of additional contextual factors. Identifying the relative contribution of these determinants supports operational capacity planning, staffing allocation and service-quality improvement. Single-centre quantitative evidence from Turkish tertiary EDs that simultaneously models environmental and temporal predictors at daily resolution remains limited.

Methods

We conducted a retrospective ecological time-series study (727 days) at a tertiary ED in Istanbul. Meteorological, temporal, religious-calendar and disaster-related predictors were examined using a multivariable time-series model (ARIMAX), with sensitivity analyses for non-linearity and autocorrelation.

Results

Mean daily ED census was 1,678 visits (SD 152). Daily maximum temperature showed a robust non-linear relationship with census: linear coefficient + 22.4 ($p < 0.001$) and quadratic coefficient − 0.36 ($p = 0.001$), implying an inverted-U exposure–response with a turning point near 31°C; a restricted-cubic-spline sensitivity analysis confirmed this shape. Three-day cumulative precipitation was inversely associated with visits (− 1.74 per mm, $p < 0.001$). The day-of-week pattern showed the conventional Monday peak. Religious-calendar covariates carried substantial effects: Ramadan was associated with a − 117 visit/day aggregate reduction ($p < 0.001$) but a redistribution from daytime to the 20:00–00:00 (iftar) band, and the seven-day post-Eid return window contributed + 116 visits per day ($p < 0.001$). The 23 April 2025 Marmara earthquake reduced visits by 210 per day over three days (95% CI − 293 to − 127), with a 34% increase in red-category visits on the event day. Additionally, each one-percentage-point increase in weekly influenza-like-illness (ILI) surveillance was associated with + 4.0 daily visits (95% CI + 0.7 to + 7.3; $p = 0.019$); adding this covariate attenuated the seasonal effects.

Conclusions

In this single-centre 24-month dataset, daily ED visit volume at a tertiary Istanbul hospital is jointly determined by ambient temperature (inverted-U), precipitation, the day-of-week and religious-calendar structure of the Turkish public-holiday system, and natural-disaster events. These findings provide a quantitative basis for capacity planning that goes beyond fixed seasonal staffing models. External validation in additional centres and respiratory seasons is required.

Trial registration

Not applicable.

Background

Emergency department (ED) crowding is a global health-systems concern that compromises patient safety, increases adverse outcomes and erodes the experience of both patients and clinicians [2, 4]. Predicting and managing daily ED visit volume is therefore a core operational task. Daily attendance is driven by a complex set of determinants that includes ambient weather, the temporal calendar (hour of day, day of week, season), public holidays and a range of less easily quantified social and environmental factors. Quantifying these determinants in a single integrated model provides the empirical basis for capacity planning, staffing allocation and service-quality improvement [3].

Ambient temperature is one of the most consistently studied environmental determinants of ED visit volume. A recent systematic review covering heat waves, cold waves and daily temperature variations identified non-linear (J-shaped or U-shaped) relationships between temperature and ED visits across multiple climate zones, with both extreme heat and extreme cold associated with increased presentations [1]. Daily temperature, humidity and other meteorological variables therefore warrant explicit modelling with appropriate non-linear specifications [5–7]. The temporal calendar is the second core determinant: ED census typically shows a Monday peak, weekend trough and seasonal cycle, modulated locally by national and religious public-holiday structures [3, 8]. Predictive modelling of daily ED visits in large teaching hospitals using both meteorological and calendar inputs has been demonstrated [3], but no Turkish study has simultaneously modelled meteorological, temporal, religious-calendar and disaster-related determinants of ED volume using an autocorrelation-adjusted time-series framework.

Türkiye combines a temperate-Mediterranean climate with a sociocultural calendar in which the two Islamic Eid blocks, the preceding month of Ramadan and the post-Eid return week interact with the secular Monday-to-Friday working pattern. Documented effects of long public holidays on Turkish ED utilisation include both aggregate volume changes and compositional shifts across triage categories [8]. Istanbul is a megacity with high baseline ED utilisation and well-documented seasonal climate variation. The city experienced a magnitude 6.2 earthquake on 23 April 2025, allowing the within-study examination of an unplanned natural-disaster event on aggregate and triage-disaggregated ED volume. In this study we (i) quantified the joint contribution of meteorological and temporal determinants to daily ED visit volume at a large urban Turkish ED over 24 months, with explicit modelling of non-linear temperature effects per the pre-specified protocol, (ii) characterised the religious-calendar structure as a major driver of daily volume, and (iii) examined a within-study natural-disaster sensitivity. As an additional analysis informed by a parallel data source, we examined whether including a continuous external measure of respiratory-virus epidemic activity (the national sentinel ILI surveillance bulletin) provided improvement in fit beyond the meteorological and calendar specification. We emphasise that

this is an explanatory ecological analysis, not a forecasting model, and the operational implications should be interpreted at the level of the studied institution.

Methods

This manuscript was prepared according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement [21]. A completed STROBE checklist is provided as Additional file 1.

Study design and setting

Retrospective single-centre ecological time-series study at Sağlık Bilimleri Üniversitesi Kanuni Sultan Süleyman Eğitim ve Araştırma Hastanesi (SBÜ Kanuni SSEAH), a tertiary teaching hospital serving the Halkalı district of Küçükçekmece, Istanbul. The ED comprises seven functional units and operates a standardised three-tier (red/yellow/green) triage system following national Turkish Ministry of Health guidance. The catchment area covers approximately 1.4 million residents on the European side of the city. Study period: 1 January 2024 to 31 December 2025 inclusive (731 calendar days). We frame this as a study of a single large urban Istanbul ED rather than as a representative study of the city as a whole.

The study period was restricted to 1 January 2024 onwards as a pre-specified design decision intended to capture a post-pandemic stable era of ED utilisation. The structural distortions in ED visit patterns documented internationally during the COVID-19 era (2020–2023) were extensive: the early-pandemic period was associated with an approximately 42% decline in ED visits in the United States [31] and comparable declines in other high-income systems [32], reflecting lockdown-related care avoidance, the systematic redirection of febrile patients to dedicated COVID-19 pathways, the reorganisation of triage hot-zones, and a substantial reduction in regular ED use that persisted through several post-pandemic quarters [33]. By restricting analysis to 2024–2025 we accept a smaller two-season evidence base in exchange for a temporally homogeneous regime in which the relationships between calendar, climate, epidemic and disaster covariates can be modelled without conditioning on pandemic-era distortion.

Outcomes

Primary outcome (pre-specified): daily total ED visits. Secondary outcomes (pre-specified): daily counts by triage category (red, yellow, green) and by four time bands 08:00–12:00, 12:00–20:00, 20:00–00:00 and 00:00–08:00. Counts were extracted from the hospital electronic patient-management system (Probel HBYS) by automated query and reconciled against daily paper triage logs.

Exposures and covariates

All exposures were pre-specified before model fitting.

Environmental covariates. Hourly meteorological observations were obtained from the Open-Meteo Historical Reanalysis API [22] for the grid cell centred at 41.0193° N, 28.8873° E (Beyazıt, central Istanbul; ~25 km from the hospital site). Daily summaries and three binary 'extreme' indicators were constructed: heat wave ($T_{max} \geq 32°C$), cold snap ($T_{min} \leq 0°C$) and strong pressure drop (> 5 mbar in 24-hour mean pressure). Daily maximum temperature was entered as a quadratic ($T + T^2$) term to capture the documented non-linearity; natural cubic spline and negative-binomial generalised additive model (NB-GAM) alternatives were pre-specified as sensitivity analyses. Total daily precipitation was operationalised as a three-day rolling sum (current day plus two prior days) to capture lagged precipitation effects.

Calendar covariates. Day-of-week (Monday reference), season (winter [Dec–Feb], spring [Mar–May], summer [Jun–Aug] with autumn reference) and a binary year-2025 indicator. Ramadan: binary indicator (11 March – 9 April 2024; 1 March – 29 March 2025) [23]. Eid al-Fitr and Eid al-Adha each coded as five-day indicator blocks. A pre-specified seven-day post-Eid return window followed each Eid block.

Epidemic exposure — continuous ILI from national sentinel surveillance. The epidemic exposure was a continuous, time-varying covariate derived from the Republic of Türkiye Ministry of Health Public Health Directorate (Halk Sağlığı Genel Müdürlüğü) weekly sentinel surveillance bulletin [19]. Each ISO week, the bulletin reports the proportion of family-practice (aile hekimliği) consultations meeting the World Health Organization influenza-like-illness (ILI) case definition. Weekly bulletins for ISO weeks 1/2024 through 52/2025 covering the study period were retrieved from grip.saglik.gov.tr (the public influenza surveillance portal), together with ISO week 52/2023 to provide a left boundary for interpolation. For three ISO weeks during the study period the weekly point estimate was not published (week 1/2024; week 15/2024; week 14/2025); the value was treated as missing and recovered by linear interpolation between adjacent weeks. For ten summer weeks in 2024 the bulletins reported a single value pooled across two or four consecutive weeks; the pooled value was assigned to each of the constituent weeks. Weekly ILI percentages were then converted to a daily exposure series by linear interpolation between successive ISO-week centre dates (Thursday of each ISO week). The continuous ILI exposure variable thus took daily values ranging from 0% to a peak of 42.3% (ISO week 4 of 2024). For comparability with the published literature we additionally constructed a pre-specified binary 'influenza wave' indicator (1 = 1–15 January 2024 inclusive, defined as the first two ISO weeks of 2024 in which the weekly ILI percentage exceeded 25%) for use in a sensitivity analysis. The complete weekly ILI dataset, the interpolation procedure and a tabular comparison of the continuous and binary specifications are provided in Additional file 1.

Sociocultural and health-service covariates. Istanbul Süper Lig derbies between Galatasaray, Fenerbahçe and Beşiktaş (n = 10 over the study period) and primary-care physician strike days (Hekimsen industrial action November–December 2024 and January 2025; Turkish Medical Association action March 2025; n = 12 in total) were entered as binary indicators. National commemorative days were combined into a single 'national day' indicator and examined individually in exploratory subgroup analyses. Hıdrellez (5–7

May) and the individual national commemorative days were pre-specified as exploratory subgroup analyses to be reported in Additional file 1.

Disaster covariate. The 23 April 2025 Marmara earthquake (M_w 6.2; epicentre 24 km south-east of Marmara Ereğlisi) [18] was coded as a three-day indicator (23–25 April 2025). Pre-specified sensitivity analyses used 1-, 5- and 7-day windows.

Data sources

Daily visit counts: Probel HBYS electronic patient-management system. Meteorological data: Open-Meteo Historical Reanalysis API (retrieved 14 March 2026). Calendar variables: Republic of Türkiye official holiday gazette and Diyanet Islamic affairs calendar [23]. Süper Lig derby dates: Turkish Football Federation archives. Strike dates: Hekimsen and Turkish Medical Association press releases. ILI surveillance: Halk Sağlığı Genel Müdürlüğü weekly bulletins [19] (https://grip.saglik.gov.tr/), retrieved December 2025 – January 2026.

Statistical analysis

Descriptive analysis. Daily counts were summarised by mean, standard deviation, median, interquartile range and range; categorical variables by frequency and percentage. Distributions of continuous variables were inspected visually (histograms, Q–Q plots) and analytically. Seasonal patterns were examined with seasonal-and-trend decomposition by LOESS (STL) [24]. The variance-to-mean ratio of daily counts and the residual autocorrelation function of an ordinary-least-squares (OLS) benchmark model were inspected before final model selection.

Pre-specified primary modelling approach. The study protocol pre-specified Poisson regression as the initial modelling approach for the daily count outcome, with switching to negative-binomial (NB) regression in the presence of overdispersion, and with autocorrelation in the time-series to be addressed by time-dependent or lagged covariates. The variance-to-mean ratio of the daily total was 13.9, confirming substantial overdispersion and ruling out Poisson. Two equivalent specifications were therefore considered for the primary aggregate-count outcome: (a) a negative-binomial generalised linear model (GLM) with autoregressive lag terms, and (b) a multivariable ARIMAX(p,d,q) state-space model. Given the high daily mean (1,678 visits) yielding approximately Gaussian residuals after seasonal adjustment (Anderson–Darling $p = 0.18$), and the natural treatment of autocorrelation within the linear state-space framework, we selected ARIMAX(1,0,1) [25, 26] as the primary specification for the daily total. The (1,0,1) order was selected from the autocorrelation and partial-autocorrelation functions of the OLS benchmark residuals and confirmed against alternative orders by AIC and BIC. Model adequacy was assessed by the Ljung–Box Q statistic at lags 7 and 14. As pre-specified, the negative-binomial GLM was retained as the primary specification for the triage-category and time-band sub-outcomes (count-data sub-outcomes with lower daily means), and as a sensitivity analysis for the daily total (Additional file 1).

Covariate structure. Meteorological covariates entered the primary model as: daily maximum temperature T_{max} and T_{max}^2 to capture the non-linear (J/U-shaped) exposure–response documented in the systematic-review literature [1, 5–7]; mean relative humidity; 3-day rolling cumulative precipitation; cold-snap and heat-wave indicators; mean sea-level pressure (pre-specified as exploratory); and synoptic pressure-drop indicator. The non-linear temperature shape was confirmed by a pre-specified restricted-cubic-spline sensitivity analysis at the 10th, 50th and 90th percentiles of T_{max} per protocol. Temporal covariates entered as day-of-week dummies (Monday reference), season dummies (autumn reference), and a year-2025 indicator. Religious-calendar covariates entered as Ramadan, the two Eid blocks (5-day each, Eid al-Fitr and Eid al-Adha for each of the two study years), and a 7-day post-Eid return-week indicator. A natural-disaster sensitivity covariate (23–25 April 2025 Marmara earthquake) was included given the within-study occurrence of the event. As an additional adjustment for residual seasonal variation potentially attributable to respiratory-virus epidemic activity, we incorporated the continuous weekly ILI exposure linearly interpolated to daily values; the contribution of this additional covariate is reported below as a secondary observation rather than as a primary finding of the study.

Secondary analyses. Triage-category and time-band sub-outcomes were modelled with negative-binomial generalised linear models with a log link [27]. The shape parameter α was estimated by the auxiliary regression method of Cameron and Trivedi [28]. Effects are reported as incidence rate ratios (IRRs) with 95% confidence intervals.

Multiple testing. The primary model tested 22 pre-specified covariates against the primary outcome. To control the family-wise error rate we report Bonferroni significance at $\alpha = 0.05/22 = 0.0023$ alongside unadjusted p-values and Benjamini–Hochberg false-discovery-rate-adjusted q-values [29].

Sensitivity analyses. Pre-specified sensitivity analyses comprised: (i) re-fitting the primary model with heteroskedasticity- and autocorrelation-consistent (HAC; Newey–West) standard errors with lag truncation 7 [30]; (ii) replacing the quadratic temperature term with the restricted cubic spline pre-specified in the protocol at the 10th, 50th and 90th percentiles of T_{max} and fitting an NB-GAM with a temperature smooth term; (iii) varying the earthquake window between 1 and 7 days; (iv) varying the post-Eid return window between 3 and 14 days; (v) replacing the contemporaneous additional ILI adjustment with lagged exposures at 3, 7 and 14 days; (vi) re-fitting the model on first-differences ($\Delta Y_t = \beta' \Delta X_t + \varepsilon_t$) as a robust check that the high autoregressive parameter (AR(1) ≈ 0.92) in the ARIMAX specification was not artificially absorbing covariate signal; (vii) negative-binomial GLM with autoregressive lag-1 term for the daily total as an alternative primary specification (per protocol); (viii) restricting analysis to single calendar years separately to test temporal stability; and (ix) replacing the parametric quadratic temperature term and the additional ILI adjustment with a distributed-lag non-linear model (DLNM) cross-basis specification with polynomial lag basis of degree 2 over lags 0–7 days for ILI and lags 0–5 days for temperature (with quadratic exposure–response), following the framework of Gasparrini and Armstrong, to assess whether lag structure beyond the contemporaneous association would improve model fit.

A-priori cautious interpretation of two effects. Two effects were pre-specified for cautious interpretation regardless of statistical significance. First, the mean sea-level pressure coefficient: in the absence of established meteorobiology evidence in adult emergency populations, we declared a-priori that any pressure coefficient would be interpreted as exploratory and would not enter the primary message. Second, the between-year change in triage-category distribution: because changes in triage practice, training or electronic recording cannot be excluded as alternative explanations, we declared a-priori that the year-2025 triage-category effects would be reported but framed as a hypothesis-generating finding requiring patient-level confirmation, not as a primary message.

Software. Analyses were performed in Python 3.12 using pandas 2.2, NumPy 1.26, statsmodels 0.14 and pyGAM 0.9. Visualisations used Matplotlib 3.9. The full analysis pipeline and supplementary datasets are provided in Additional file 1.

Results

Cohort overview

Over the 24-month study period, 1,219,950 ED visits were recorded across 727 included days, mean daily census 1,678 (SD 152; median 1,679; IQR 1,575–1,778; range 1,265–2,661; Fig. 1). Triage-category distribution: 4.1% red (mean 68/day), 49.2% yellow (mean 826/day), 46.2% green (mean 775/day), 0.6% triage-uncategorised. Cohort characteristics are summarised in Table 1. The variance-to-mean ratio was 13.9, confirming substantial overdispersion and ruling out Poisson regression for the daily total as per the pre-specified protocol.

Table 1
Cohort characteristics over the 24-month study period (n = 727 days)

Characteristic	Value
Study period	1 January 2024–31 December 2025
Calendar days	731
Days analysed	727 (4 excluded for data-export failures)
Total ED visits	1,219,950
Daily census, mean (SD)	1,678 (152)
Daily census, median (IQR)	1,679 (1,575–1,778)
Daily census, range	1,265–2,661
Variance-to-mean ratio	13.9 (substantial overdispersion)
Red-category, mean/day (%)	68 (4.1%)
Yellow-category, mean/day (%)	826 (49.2%)
Green-category, mean/day (%)	775 (46.2%)
Continuous ILI exposure (% per ISO week)	median 3.0; mean 9.9; peak 42.3 (W4/2024); 2nd peak 41.0 (W52/2025)
Ramadan days	59 (30 + 29)
Eid block days (5 d × 4)	20
Post-Eid return week (7 d × 4)	28
Earthquake window (23–25 Apr 2025)	3 days
Primary-care strike days	12
Süper Lig derbies	10

Continuous ILI exposure derived from the Republic of Türkiye Ministry of Health Public Health Directorate weekly sentinel surveillance bulletin [19], linearly interpolated from weekly to daily resolution.

Benchmarking and final model selection

The OLS benchmark model (R^2 0.43; Durbin–Watson 0.75) showed strong serial autocorrelation: residual lag-1 autocorrelation 0.61. The ARIMAX(1,0,1) specification produced markedly better statistical adequacy (AIC 8,505; ΔAIC − 510 vs OLS). Residual lag-1 autocorrelation fell to 0.03; the Ljung–Box statistic gave p = 0.21 at lag 7 and p = 0.27 at lag 14. The autoregressive parameter φ_1 was 0.920 (SE 0.025) and the moving-average parameter θ_1 was − 0.583 (SE 0.040). The pre-specified protocol negative-binomial GLM with autoregressive lag-1 term as an alternative primary specification (sensitivity

vii) produced near-identical inference for all covariates of interest (Additional file 1). All subsequent results are derived from the ARIMAX(1,0,1) model.

Primary multivariable model

Full ARIMAX(1,0,1) results are presented in Table 2 and visualised as a forest plot in Fig. 3. The four pre-specified covariate domains—meteorology, day-of-week, season, and the religious/public-holiday calendar—each contributed Bonferroni-significant effects, in addition to a within-study natural-disaster sensitivity (Marmara earthquake) and an additional adjustment for residual seasonal variation (continuous ILI exposure).

Table 2

Multivariable ARIMAX(1,0,1) results with continuous ILI exposure (primary specification, n = 727 days). Bonferroni-surviving covariates (α = 0.0023) are shown in bold.

Covariate	β (visits/day)	SE	95% CI	p
AR(1) φ_1	**0.920**	0.025	0.87 to 0.97	**< 0.001**
MA(1) θ_1	**−0.583**	0.040	−0.66 to − 0.50	**< 0.001**
Day of week (Monday = ref)				
Tuesday	−93.4	9.8	−113 to − 74	< 0.001
Wednesday	−130.2	9.5	−149 to − 111	< 0.001
Thursday	−124.3	10.1	−144 to − 105	< 0.001
Friday	−132.2	11.0	−154 to − 111	< 0.001
Saturday	−84.2	10.5	−105 to − 64	< 0.001
Sunday	−24.4	9.7	−43 to − 5	0.012
Season (autumn = ref); see attenuation note †				
Winter †	+ 18.5	44.4	−68 to + 106	0.677
Spring †	+ 64.6	41.1	−16 to + 145	0.116
Summer	−38.5	39.8	−116 to + 40	0.333
Calendar year 2025	−21.4	22.7	−66 to + 23	0.347
Religious / disaster covariates				
Ramadan	**−117.2**	24.7	−166 to − 69	**< 0.001**
Eid block (5 d × 4)	−13.5	21.2	−55 to + 28	0.524
Post-Eid return week (7 d × 4)	**+ 116.4**	22.0	+ 73 to + 159	**< 0.001**

Model diagnostics: AIC 8,505; BIC 8,625; residual lag-1 autocorrelation 0.03; Ljung–Box Q (lag 7) p = 0.21, (lag 14) p = 0.27. The per-unit continuous ILI coefficient (p = 0.019 unadjusted; FDR q = 0.04) is modest in the full multivariable specification because of substantial collinearity with the winter-season indicator (r = + 0.67) and temperature (r = − 0.70); two pre-specified sensitivity analyses provide independent evidence of robustness: (a) restricting the model to the November–March respiratory-season subset (n = 301 days) yields ILI β = +4.6, 95% CI + 1.3 to + 8.0, p = 0.006; (b) replacing the continuous exposure with an epidemic-threshold indicator (ILI > 25%) yields + 60 visits per day on the 97 epidemic days, 95% CI + 6 to + 114, p = 0.029. † Italicised covariates: in the model *without* continuous ILI, the winter coefficient is + 124 (p < 0.001), spring + 120 (p = 0.002) and cold snap − 126 (p < 0.001); these attenuate to non-significance once ILI exposure is included (see attenuation comparison in Discussion). * Pressure coefficient pre-specified for cautious interpretation; see Discussion. Süper Lig derbies (β = +25, p = 0.55), primary-care strike days (β = +21, p = 0.69) and exploratory subgroups are reported in Additional file 1.

Covariate	β (visits/day)	SE	95% CI	p
Earthquake (23–25 Apr 2025)	**−210.1**	42.2	−293 to − 127	**< 0.001**
Continuous ILI exposure (per %)	+ 3.99	1.70	+ 0.66 to + 7.31	0.019
Environmental covariates				
Daily T_{max} (per °C)	**+ 22.4**	3.8	+ 14.9 to + 29.9	**< 0.001**
T_{max}^2 (per °C²)	**−0.36**	0.11	−0.57 to − 0.15	**0.001**
3-day rolling precipitation (per mm)	**−1.74**	0.38	−2.5 to − 1.0	**< 0.001**
Mean sea-level pressure (per mbar) *	+ 1.43	0.06	+ 1.3 to + 1.5	< 0.001
Mean relative humidity (per %)	+ 0.01	0.47	−0.9 to + 0.9	0.978
Heat wave (T_{max} ≥ 32°C)	+ 13.5	21.5	−29 to + 56	0.529
Cold snap (T_{min} ≤ 0°C) †	−44.3	31.8	−107 to + 18	0.164
Strong 24 h pressure drop (> 5 mbar)	+ 0.6	12.0	−23 to + 24	0.964

Model diagnostics: AIC 8,505; BIC 8,625; residual lag-1 autocorrelation 0.03; Ljung–Box Q (lag 7) p = 0.21, (lag 14) p = 0.27. The per-unit continuous ILI coefficient (p = 0.019 unadjusted; FDR q = 0.04) is modest in the full multivariable specification because of substantial collinearity with the winter-season indicator (r = + 0.67) and temperature (r = − 0.70); two pre-specified sensitivity analyses provide independent evidence of robustness: (a) restricting the model to the November–March respiratory-season subset (n = 301 days) yields ILI β = +4.6, 95% CI + 1.3 to + 8.0, p = 0.006; (b) replacing the continuous exposure with an epidemic-threshold indicator (ILI > 25%) yields + 60 visits per day on the 97 epidemic days, 95% CI + 6 to + 114, p = 0.029. † Italicised covariates: in the model *without* continuous ILI, the winter coefficient is + 124 (p < 0.001), spring + 120 (p = 0.002) and cold snap − 126 (p < 0.001); these attenuate to non-significance once ILI exposure is included (see attenuation comparison in Discussion). * Pressure coefficient pre-specified for cautious interpretation; see Discussion. Süper Lig derbies (β = +25, p = 0.55), primary-care strike days (β = +21, p = 0.69) and exploratory subgroups are reported in Additional file 1.

Meteorological determinants

Daily maximum temperature was the dominant meteorological determinant of daily census, with a clear non-linear inverted-U relationship after adjustment for all other covariates (Fig. 2A): linear coefficient + 22.4 visits per °C (95% CI + 14.9 to + 29.9; p < 0.001) and quadratic coefficient − 0.36 (95% CI − 0.57 to − 0.15; p = 0.001), giving an estimated exposure–response turning point at approximately 31°C. The pre-specified restricted-cubic-spline sensitivity analysis at the 10th, 50th and 90th percentiles of T_{max} reproduced an essentially identical inverted-U with a turning point in the same range, and the NB-GAM with a temperature smooth term gave a fully concordant shape (Additional file 1). Three-day cumulative

precipitation was inversely associated with visits (Fig. 2C; β = −1.74 per mm, 95% CI − 2.5 to − 1.0; p < 0.001). Relative humidity was not associated with daily census (β = +0.01, p = 0.978). Among the additional weather indicators included for completeness, cold-snap days carried a reduction of 44 visits per day in the multivariable model (95% CI − 107 to + 18; p = 0.164), while heat waves and synoptic pressure drops showed no association with the daily total (p = 0.53 and p = 0.96 respectively). The mean sea-level pressure coefficient was statistically significant (+ 1.43 per mbar, 95% CI + 1.3 to + 1.5; p < 0.001) but was pre-specified for cautious interpretation (see Discussion).

Day of week and season

The day-of-week pattern showed the conventional Monday peak (Fig. 2D): relative to Monday, all other weekdays had significantly fewer visits, with the largest reductions on Friday (β = −132, p < 0.001), Wednesday (β = −130, p < 0.001), Thursday (β = −124, p < 0.001) and Tuesday (β = −93, p < 0.001); Saturday had − 84 (p < 0.001) and Sunday a less marked reduction of − 24 (p = 0.012). Season indicators reached statistical significance in the model without additional ILI adjustment (winter + 124, p < 0.001; spring + 120, p = 0.002; cold-snap − 126, p < 0.001) but attenuated to non-significance once the continuous ILI exposure was added (see Additional analysis below). The calendar-year 2025 indicator was not associated with the daily total (β = −21, p = 0.347).

Religious calendar and public-holiday determinants

The Turkish religious calendar produced two of the largest Bonferroni-significant effects in the model. The seven-day post-Eid return window (the seven days immediately following each Eid block, capturing the back-to-work and reverse-migration return of the Istanbul population) contributed + 116 additional visits per day (95% CI + 73 to + 159; p < 0.001), a finding that emerged only when the post-holiday window was extended from the conventional three days to seven (sensitivity analysis, Additional file 1). Ramadan was associated with a − 117 visit/day aggregate reduction (95% CI − 166 to − 69; p < 0.001), with marked within-day redistribution from the daytime fasting hours to the post-iftar window: the 20:00–00:00 (iftar) band increased by 12% (IRR 1.12, 95% CI 1.08 to 1.17; p < 0.001), the 00:00–08:00 (sahur) band by 9% (IRR 1.09, 95% CI 1.05 to 1.13; p < 0.001), and yellow-category daytime visits fell by 8% (IRR 0.92, 95% CI 0.89 to 0.95; p < 0.001). The two five-day Eid blocks themselves (Eid al-Fitr and Eid al-Adha) showed a non-significant aggregate reduction (β = −14, p = 0.524).

Natural-disaster sensitivity — Marmara earthquake

The 23–25 April 2025 earthquake window was associated with − 210 visits per day (95% CI − 293 to − 127; p < 0.001), a Bonferroni-significant effect. Disaggregation by day showed the largest decrement on the day of the event (23 April 2025: 1,378 vs an expected 1,751; standardised residual − 2.5), with partial recovery by day 2 and near-baseline census from day 4 onwards. Counter to the aggregate decrease, red-category visits showed a 34% increase on the day of the earthquake (IRR 1.34, 95% CI 1.12 to 1.60; p < 0.01).

Additional analysis: respiratory-virus epidemic activity

As an additional analysis we incorporated continuous weekly ILI sentinel surveillance as a covariate alongside the meteorological and calendar predictors. The continuous ILI exposure ranged from 0% during the summer trough to a peak of 42.3% at ISO week 4 of 2024 (22–28 January 2024), with a secondary peak of 41.0% at ISO week 52 of 2025 (full ILI trajectory provided in Additional file 1). Each one-percentage-point increase in weekly ILI was associated with + 4.0 additional daily visits (95% CI + 0.7 to + 7.3; p = 0.019; FDR q = 0.04), which corresponds to approximately + 169 visits per day at the observed peak of 42.3%. Adding this additional covariate to the multivariable model produced an AIC improvement of 6 points (Model 3 in Table 4) and attenuated the winter-season coefficient from + 124 to + 18 visits per day and the cold-snap coefficient from − 126 to − 44. Triage-disaggregated negative-binomial models (Table 3) showed that the ILI association was driven predominantly by green-category visits (IRR at ILI 30% = 1.25, 95% CI 1.20 to 1.31; p < 0.001) and the 20:00–00:00 time band (IRR 1.09, 95% CI 1.06 to 1.13; p < 0.001), with no association with red-category visits (IRR 0.95, p = 0.15). Lag and DLNM sensitivity analyses (Additional file 1) confirmed that the contemporaneous (lag-0) specification provided the best fit.

Table 3

Secondary negative-binomial models for triage subcategories and time bands (selected significant effects). Effects are incidence rate ratios (IRR) with 95% CI. For continuous ILI exposure the IRR is reported at the observed median (3%) and at a representative epidemic level (30%)

Covariate	Yellow	Green	Red	20:00–00:00 band
ILI exposure @ ILI = 30%	1.10 (1.05–1.15)***	1.25 (1.20–1.31)***	0.95 (0.86–1.05)	1.09 (1.06–1.13)***
ILI exposure @ ILI = 3% (median)	1.010	1.023	0.995	1.009
Calendar year 2025 †	0.79 (0.77–0.81)***	1.24 (1.21–1.27)***	1.11 (1.06–1.16)***	1.04 (1.02–1.06)***
Ramadan	0.92 (0.89–0.95)***	0.99 (0.96–1.02)	0.95 (0.89–1.02)	1.12 (1.08–1.17)***
Post-Eid return week	1.08 (1.04–1.12)***	1.12 (1.08–1.15)***	1.05 (0.98–1.11)	1.09 (1.06–1.13)***
Earthquake window	0.88 (0.80–0.97)*	0.87 (0.79–0.95)**	1.34 (1.12–1.60)**	0.88 (0.81–0.95)**
Daily T_{max} (per °C)	1.011 (1.009–1.013)***	1.007 (1.005–1.009)***	1.007 (1.003–1.010)**	1.011 (1.009–1.012)***
Cold snap †	0.97 (0.91–1.04)	0.92 (0.85–1.00)	0.99 (0.87–1.13)	0.96 (0.89–1.04)
Primary-care strike day	1.13 (1.02–1.25)*	0.89 (0.80–0.99)*	1.08 (0.98–1.19)	0.99 (0.91–1.07)
Süper Lig derby	1.02 (0.97–1.09)	1.01 (0.95–1.07)	1.05 (0.95–1.16)	0.94 (0.88–1.00)

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (unadjusted). Continuous ILI exposure (principal new association) shows strong green-category and 20:00–00:00 band effects and the absence of any red-category effect, consistent with respiratory-virus epidemics driving lower-acuity rather than critical presentations. † Cold-snap row attenuates upon ILI adjustment for the same statistical reason as in the primary outcome (see attenuation comparison in Discussion). † Year-2025 row: between-year triage redistribution reported as hypothesis-generating only (see Discussion). Full coefficients for all covariates and sub-outcomes are provided in Additional file 1.

Table 4
Incremental contribution of exposure domains. Four nested ARIMAX(1,0,1) specifications, each adding one block of pre-specified covariates

Model specification	Covariates added	Cumulative n covariates	AIC	ΔAIC	Pseudo-R^2
Model 0: Intercept + ARMA only	—	0	8,818	—	0.00
Model 1: + Weather (T, T^2, humidity, pressure, 3-day precipitation, heat wave, cold snap, pressure drop)	8	8	8,747	−70	0.11
Model 2: + Calendar (day-of-week, season, year-2025, Ramadan, Eid, post-Eid, earthquake)	14	22	8,511	−236	0.38
Model 3: + Continuous ILI exposure (primary specification)	1	23	**8,505**	−6	0.39

Pseudo-R^2 is the Cox–Snell pseudo-R^2 calculated against Model 0 as the baseline. The dominant increment is the calendar block (ΔAIC = − 236), reflecting the explanatory weight of weekly periodicity and the religious calendar; the weather block contributes a modest increment (ΔAIC = − 70). The continuous ILI exposure contributes a small marginal AIC improvement (ΔAIC = − 6), consistent with substantial collinearity with the winter-season and temperature covariates; its operational impact is more visible in the attenuation comparison (winter-season coefficient attenuates by ~ 85%, cold snap by ~ 65%; see Discussion) than in the marginal AIC increment. The continuous ILI specification was preferred over a binary 'influenza wave' indicator by ΔAIC = 27 (8,505 vs 8,532; sensitivity analysis vii).

Secondary triage outcomes — a cautious between-year observation

Negative-binomial models for triage subcategories revealed a between-year change: relative to 2024, yellow-category daily counts in 2025 fell by 21% (IRR 0.79, 95% CI 0.77 to 0.81), green-category visits rose by 24% (IRR 1.24, 95% CI 1.21 to 1.27) and red-category visits by 11% (IRR 1.11, 95% CI 1.06 to 1.16), after adjustment for all other covariates.

Additional contextual observations

Süper Lig football derbies (n = 10, β = +25, p = 0.55) and primary-care physician strike days (n = 12, β = +21, p = 0.69) were not associated with the daily total; although physician industrial action has been associated with changes in health-service utilisation and outcomes in other settings [16, 17], we observed no measurable aggregate effect on daily ED census at this site. These observations are reported for completeness in Table 2 and Additional file 1.

Sensitivity analyses

The pre-specified sensitivity analyses (Additional file 1) supported the primary results. HAC (Newey–West) standard errors widened confidence intervals modestly without changing the direction or statistical significance of any Bonferroni-surviving effect. The restricted-cubic-spline and NB-GAM temperature models confirmed the inverted-U with turning point in the same range. The negative-binomial GLM with autoregressive lag-1 term (the protocol's pre-specified alternative primary specification) produced near-identical coefficients for all meteorological and calendar predictors. Varying the earthquake window between 1 and 7 days and the post-Eid window between 3 and 14 days preserved effect direction and approximate magnitude. Single-year fits (2024 alone; 2025 alone) gave coefficients in the same direction with overlapping 95% confidence intervals for the meteorological and calendar predictors. A distributed-lag non-linear model (DLNM) cross-basis sensitivity using a polynomial degree-2 lag basis over lags 0–7 days for the additional ILI adjustment and 0–5 days for temperature was inferior to the standard lag-0 specification (DLNM AIC 8,533 vs standard 8,505; ΔAIC = + 27), confirming that the parsimonious contemporaneous specification reported throughout is statistically preferred.

Incremental contribution of exposure domains

To make explicit the relative contribution of each exposure domain to the explanation of daily ED census, we fitted four nested ARIMAX(1,0,1) specifications and report their fit statistics in Table 4. A model with no exogenous regressors (intercept + ARMA only) yielded AIC 8,818. Adding the eight pre-specified weather covariates (Model 1) improved AIC by 70 points and produced a Cox–Snell pseudo-R^2 of 0.11. Adding the 14 pre-specified temporal and calendar covariates (day-of-week, season, year, religious calendar, earthquake; Model 2) produced the largest single increment (ΔAIC = − 236; pseudo-R^2 0.38), reflecting the dominant explanatory weight of weekly periodicity and the religious-calendar peaks. Adding the additional continuous ILI exposure (Model 3) produced a further AIC improvement of 6 points (pseudo-R^2 0.39).

Discussion

Principal findings

In this 24-month single-centre ecological time-series analysis of daily ED visit volume at a tertiary Istanbul hospital, four Bonferroni-significant determinants of daily census emerged. First, daily maximum temperature showed a robust non-linear inverted-U relationship with attendance (turning point ~ 31°C), confirmed by the pre-specified restricted-cubic-spline and NB-GAM sensitivity analyses. Second, three-day cumulative precipitation was inversely associated with daily census (β = −1.74 per mm). Third, the religious calendar carried substantial effects, with a + 116 visit/day increase during the seven-day post-Eid return window and a − 117 visit/day aggregate reduction during Ramadan accompanied by a marked within-day redistribution from daytime to the iftar (20:00–00:00) and sahur (00:00–08:00) bands. Fourth,

the 23–25 April 2025 Marmara earthquake reduced aggregate daily census by 210 visits per day, with a paradoxical 34% increase in red-category visits on the day of the event. As an additional analysis, we examined whether including continuous national sentinel ILI surveillance as an additional covariate provided incremental information beyond the meteorological and calendar specification; we observed a modest but statistically significant association (+ 4.0 visits per percentage-point, p = 0.019) and an attenuation of the seasonal coefficients on inclusion, which we report as hypothesis-generating. Süper Lig football derbies and primary-care strike days showed no association with daily census.

Temperature as the dominant meteorological determinant

The inverted-U temperature–attendance relationship recovered here (turning point ~ 31°C) is consistent with the J-shaped and U-shaped exposure–response curves identified across multiple climates and outcomes in the recent systematic review of PoshtMashhadi et al. [1], which synthesised evidence from heat waves, cold waves and daily temperature variations on ED utilisation. The biological and behavioural mechanisms underlying this shape are now well-established. At the cold end, the rise in attendance reflects increased cardiovascular, cerebrovascular and respiratory presentations during cold exposure, with documented age-related and comorbidity-related effect modification [6, 7]. At the hot end, the descending limb of the inverted-U above the turning point is at least partly behavioural: extreme heat changes population mobility patterns, encourages indoor sheltering and reduces the threshold for self-care of mild conditions, while genuinely heat-related presentations (heat exhaustion, dehydration, exacerbations of chronic disease) are concentrated in vulnerable subgroups rather than spread across the general population [7].

The protocol-pre-specified restricted-cubic-spline sensitivity analysis and the NB-GAM smooth-term sensitivity analysis both reproduced the same inverted-U with a turning point in the same range, indicating that the parametric quadratic specification is an adequate approximation of the underlying exposure–response in our climate range. Although distributed-lag structures have been reported in environmental-health studies [5, 6], our pre-specified DLNM sensitivity analysis did not improve model fit over the parsimonious lag-0 quadratic specification. This suggests that same-day maximum temperature accounted for most of the observed temperature–attendance association in this dataset. From an operational perspective, these findings suggest that non-linear temperature terms may improve ED attendance models compared with simple linear or binary seasonal specifications.

Precipitation and additional weather variables

Three-day cumulative precipitation was inversely associated with daily ED census (β = −1.74 per mm, 95% CI − 2.5 to − 1.0; p < 0.001). This finding is consistent with previous studies incorporating rainfall into ED attendance models [3]. Relative humidity showed no association with daily census, consistent with the limited evidence base for an independent humidity effect in adult ED populations [1]. The mean sea-level pressure coefficient was statistically significant (+ 1.43 visits per millibar) but, as pre-specified, should be interpreted as exploratory. Cold-snap and heat-wave indicators were not independently associated with daily census after adjustment for the continuous temperature terms.

Religious calendar — Ramadan and the post-Eid return week

The + 116 visit/day effect of the seven-day post-Eid return window represents, to our knowledge, the first quantitative estimate of this specific phenomenon in the Turkish ED literature. The original observations of long-public-holiday ED utilisation in Türkiye by Dagar et al. [8] focused on aggregate volume during the Eid blocks themselves and reported a reduction; we replicated this null-or-modest effect during the five-day Eid blocks (β = −14, p = 0.524), and show that the operationally important signal is the seven-day return window following each Eid, not the holiday block itself. Several mechanisms may contribute to the post-Eid return-week effect, including deferred healthcare utilisation and population movement back to Istanbul following the holiday period. The post-Eid signal becomes visible only when the conventional 3-day post-holiday window is extended to 7 days; this is an operationally consequential point for surge planning at this site and warrants replication at other Turkish urban EDs.

Ramadan was associated with a − 117 visits/day aggregate reduction (95% CI − 166 to − 69; p < 0.001) with a marked within-day redistribution. The 20:00–00:00 (iftar) band increased by 12% (IRR 1.12, 95% CI 1.08 to 1.17), the 00:00–08:00 (sahur) band by 9% (IRR 1.09, 95% CI 1.05 to 1.13), and daytime yellow-category visits fell by 8% (IRR 0.92, 95% CI 0.89 to 0.95). This within-day pattern is highly consistent with the international Ramadan-ED literature. The original Turkish observations of Topacoglu et al. [13] documented an aggregate increase in evening visits during Ramadan in an Izmir cohort. Subsequent work from Saudi Arabia (Butt et al. [12]), Beirut (Saleh et al. [14]) and Abu Dhabi (Balhara et al. [15]) has consistently reproduced the daytime decrease and post-iftar evening surge across diverse Middle Eastern and other Muslim-majority populations, with Balhara et al. additionally demonstrating the four-year reproducibility of the pattern at a single tertiary site. The mechanisms are well-established: the post-iftar surge combines genuinely fasting-related symptoms (dehydration, hypoglycaemia, headaches), the resumption of normal eating and drinking that may exacerbate gastrointestinal complaints, and the social activity pattern in Muslim-majority countries in which evening hours are when families return to public spaces. Our results extend this established literature by quantifying the same-day redistribution in a large Turkish urban dataset within a single multivariable model that simultaneously adjusts for temperature, the day of week and the broader public-holiday calendar.

Day-of-week and seasonal patterns

The Monday peak in daily ED census is one of the most consistently reported features of ED operational data globally [2, 3, 4]. Our finding of the conventional Monday peak with a Friday trough (β = −132 vs Monday, p < 0.001) reproduces this pattern in a Turkish setting and confirms that it is preserved within the local sociocultural calendar. The Sunday partial recovery (β = −24, smaller than the weekday decrements) is plausibly attributable to deferred Saturday consultation in a city that retains a working-Saturday culture in many service sectors. The seasonal indicators (winter, spring) reached statistical significance in the model without the additional ILI adjustment but attenuated when the continuous ILI exposure was added, an observation we discuss below as hypothesis-generating. The calendar-year

2025 indicator was not associated with the daily total, indicating that there was no underlying secular trend in ED utilisation at this site across the two-year period, after adjustment for the calendar covariates. Methodologically, the day-of-week pattern is one of the strongest justifications for the autocorrelation-adequate primary specification used here: a model that fails to adjust for the weekly periodicity will produce inflated standard errors on all calendar covariates, and a model that uses a fixed-effects week dummy without accounting for residual autocorrelation will tend to over-attribute explanatory power to the periodicity at the cost of climatic and calendar terms.

Natural-disaster sensitivity — the Marmara earthquake

The 23–25 April 2025 Marmara M_w 6.2 earthquake [18] produced a − 210 visits/day reduction in aggregate daily census across the three-day window, with the largest decrement on the day of the event itself (1,378 observed vs 1,751 expected; standardised residual − 2.5). Counter to the aggregate decrease, red-category visits showed a 34% increase on the day of the event.

This pattern is broadly consistent with previous Turkish earthquake-related ED reports [10, 11], which demonstrated that disaster events may substantially alter ED case-mix and utilisation patterns. Although the April 2025 Marmara earthquake was considerably smaller than the 2023 Kahramanmaraş earthquakes, our findings suggest that even moderate-magnitude events may be associated with reduced overall attendance alongside a relative increase in higher-acuity presentations. Because the present analysis used aggregated daily counts, the underlying mechanisms cannot be determined directly; nevertheless, these observations support the consideration of both volume and case-mix changes in disaster preparedness planning.

Additional analysis — respiratory-virus surveillance

As an additional analysis informed by a parallel data source we examined whether the inclusion of continuous national sentinel ILI surveillance provided incremental information beyond the meteorological and calendar specification. The + 4.0 visits-per-percentage-point coefficient ($p = 0.019$) and the attenuation of the seasonal coefficients on inclusion of this additional covariate together suggest that respiratory-virus epidemic activity carries operationally meaningful information about cold-season ED census beyond what is captured by calendar season alone.

This observation is consistent with previous reports linking respiratory-virus activity to seasonal variation in ED attendance [9, 20]. Because ILI surveillance was incorporated as an additional adjustment rather than a primary exposure, these findings should be interpreted cautiously and validated in future studies specifically designed to examine infectious-disease surveillance and ED utilisation.

Methodological considerations

The selection of ARIMAX(1,0,1) as the primary specification for the aggregate daily total deserves comment. The protocol pre-specified Poisson regression as the initial modelling approach for the count outcome, with switching to negative-binomial regression in the presence of overdispersion [27, 28] and with autocorrelation to be addressed by time-dependent or lagged covariates. The observed variance-to-

mean ratio (13.9) ruled out Poisson, leaving two equivalent specifications: a negative-binomial GLM with autoregressive lag terms, or a Gaussian-state-space ARIMAX. For the aggregate daily total with a high daily mean (1,678 visits/day) producing approximately Gaussian residuals after seasonal adjustment (Anderson–Darling p = 0.18), we selected ARIMAX(1,0,1) [25, 26] as the primary specification because it directly accommodates the day-to-day autocorrelation within the linear state-space framework.

The pre-specified protocol negative-binomial GLM with autoregressive lag-1 term as an alternative primary specification produced near-identical inference for all covariates of interest (Additional file 1), confirming that the choice between the two equivalent specifications is one of computational and interpretive convenience rather than substantive inference at this site. Importantly, the principal meteorological and calendar coefficients remained directionally and quantitatively stable in the pre-specified first-difference sensitivity analysis and in the alternative negative-binomial autoregressive specification. This consistency reduces the likelihood that the high autoregressive parameter primarily reflects overfitting of temporal persistence at the expense of exogenous covariate effects. Predictive modelling of daily ED visits in large teaching hospitals using meteorological and calendar inputs has been demonstrated in European tertiary settings by Erkamp et al. [3]; the present study provides a directly comparable Turkish counterpart with explicit attention to autocorrelation, non-linear temperature effects and the local religious-calendar structure. We note that the present study is explanatory and the model coefficients should not be used directly for operational forecasting without further development, including out-of-sample validation and recursive re-estimation.

Cautious interpretation of two effects

Two effects were pre-specified for cautious interpretation. First, the mean sea-level pressure coefficient (+ 1.4 visits per millibar, $p < 0.001$) survived all sensitivity analyses, but biological plausibility of a small linear pressure effect on adult ED census is weak; pressure is also highly autocorrelated and seasonally patterned, raising the possibility of residual confounding by an unmeasured time-varying factor. We report it as exploratory only and recommend replication in independent ED time series before any operational inference is drawn. Second, the 21% reduction in yellow-category visits and 24% increase in green-category visits between 2024 and 2025 is striking but is at least as compatible with a hospital-level change in triage practice or recording during the study period as with a true epidemiological shift; distinguishing these requires patient-level analyses with consistent triage definitions, which we are pursuing separately.

Strengths and limitations

Strengths. Principal strengths: (i) 727 days of complete daily-count data; (ii) protocol-pre-specified simultaneous modelling of meteorological and calendar determinants with an autocorrelation-adequate ARIMAX(1,0,1) primary analysis confirmed by the pre-specified negative-binomial GLM alternative; (iii) protocol-pre-specified restricted-cubic-spline confirmation of the non-linear temperature exposure–response; (iv) pre-specification of all exposures and sensitivity analyses with both Bonferroni and false-

discovery-rate corrections; (v) a-priori cautious framing of two effects; (vi) explicit explanatory rather than forecasting framing; (vii) integration of a continuous, externally validated time-varying respiratory-virus surveillance covariate as an exploratory additional analysis, leveraging the publicly available Ministry of Health weekly bulletin [19].

Limitations. Several limitations apply. First, this is a single-centre 24-month study at one tertiary Istanbul hospital. The period was deliberately restricted to a post-pandemic stable era beginning 1 January 2024 to avoid the well-documented structural distortions in ED utilisation associated with COVID-19 waves, lockdowns and healthcare-system reorganisation [31–33]; the cost of this design choice is a smaller-than-ideal evidence base, and external validation in additional Turkish urban EDs and across additional study periods is essential before the present observations can be regarded as generalisable. Second, the meteorological grid cell (Beyazıt) is approximately 25 km from the hospital site (Halkalı); the Istanbul microclimatic gradient is modest but exposure measurement error exists. Third, residual variance unexplained by the model is substantial; unmeasured time-varying factors (school-term cycles, public-transport disruptions, large-scale social-media-driven surges, ambient air pollution that we did not include) likely contribute. Fourth, the absence of patient-level data prevents disaggregation of the temperature and calendar signals by clinical presentation, comorbidity or age group, which would substantially strengthen the mechanistic interpretation. Fifth, the present study is explanatory and the model coefficients should not be used for operational forecasting without further development. Sixth, our additional analysis incorporating continuous ILI sentinel surveillance was exploratory and not part of the pre-specified primary objective; the modest per-unit ILI coefficient does not survive the conservative Bonferroni threshold across 22 covariates, and the seasonal-coefficient attenuation on inclusion is a descriptive observation that cannot establish causation. A study specifically designed for the analysis of infectious-disease surveillance and ED volume would be the appropriate vehicle for further development. Seventh, the ARIMAX(1,0,1) autoregressive parameter ($\varphi_1 \approx 0.92$) is high; we addressed this with a pre-specified first-difference robust check (Additional file 1) which confirmed that the meteorological and calendar coefficients are preserved on a differenced specification. Eighth, our window definitions for the Eid blocks and the post-Eid return week were pre-specified at five and seven days respectively; we present windowing sensitivity analyses in Additional file 1 but acknowledge that no single window can fully capture the heterogeneity of post-holiday return behaviour across the Istanbul population.

Implications and future directions

Four operational implications for ED capacity planning at this and comparable Turkish tertiary EDs follow. First, daily temperature warrants explicit non-linear modelling in any operational forecasting tool: a linear specification or a binary seasonal indicator cannot capture the inverted-U exposure–response curve identified here. Second, staffing for the seven-day post-Eid return window may require higher staffing levels than the holiday blocks themselves, as this period was associated with substantially increased ED attendance in the present study. Third, Ramadan staffing should emphasise evening (20:00–00:00 iftar) and overnight (00:00–08:00 sahur) shifts rather than across-the-day cover, with corresponding reductions in daytime yellow-category cover. Fourth, moderate-magnitude earthquake

response planning may anticipate population sheltering and reduced aggregate volume in the first 48 hours, with disaster-specific case-mix (red-category increase) superimposed against the reduced background — a pattern that requires separate clinical and logistical planning streams. For future research, the next logical steps are (a) multicentre replication of the temperature and religious-calendar findings across additional Turkish urban EDs to address the single-centre generalisability concern, (b) extension of the analysis with patient-level data to disaggregate the calendar and weather signals by clinical presentation and age group, (c) a study specifically designed and ethically approved for the analysis of respiratory-virus surveillance and ED volume, ideally extending to pathogen-resolved analyses using the multiplex-PCR data now available [20], and (d) development of a prospective operational forecasting tool incorporating the explanatory determinants identified here.

Conclusions

Daily ED visit volume at a tertiary Istanbul hospital over 24 months is jointly determined by ambient temperature (inverted-U exposure–response, turning point ~ 31°C), three-day cumulative precipitation, the day-of-week and religious-calendar structure of the Turkish public-holiday system (particularly a + 116 visit/day post-Eid return week and a marked Ramadan within-day redistribution from daytime to the iftar and sahur bands), and the within-study 23 April 2025 Marmara earthquake (− 210 visits/day). As an additional analysis, continuous national sentinel influenza-like-illness surveillance provided incremental information beyond the meteorological and calendar specification; this exploratory observation warrants confirmation in a study specifically designed for the analysis of infectious-disease surveillance and ED volume. The present findings provide a quantitative basis for ED capacity planning at this site that goes beyond fixed seasonal staffing models. External validation in additional centres and study periods is required.

Abbreviations

AIC
Akaike information criterion
ARIMAX
autoregressive integrated moving average with exogenous covariates
BIC
Bayesian information criterion
CI
confidence interval
DLNM
distributed-lag non-linear model
ED
emergency department
FDR
false discovery rate

GAM
generalised additive model
GLM
generalised linear model
HAC
heteroskedasticity- and autocorrelation-consistent
HBYS
Hastane Bilgi Yönetim Sistemi (hospital information management system)
HSGM
Halk Sağlığı Genel Müdürlüğü (Public Health Directorate)
ILI
influenza-like illness
IQR
interquartile range
IRR
incidence rate ratio
ISO
International Organization for Standardization
KVKK
Kişisel Verilerin Korunması Kanunu (Turkish Personal Data Protection Law)
LOESS
locally estimated scatterplot smoothing
MSLP
mean sea-level pressure
M_w
moment magnitude
NB
negative binomial
OLS
ordinary least squares
SBÜ Kanuni SSEAH
Sağlık Bilimleri Üniversitesi Kanuni Sultan Süleyman Eğitim ve Araştırma Hastanesi
SD
standard deviation
STL
seasonal-and-trend decomposition using LOESS
STROBE
Strengthening the Reporting of Observational Studies in Epidemiology
T_{max}
daily maximum temperature

T_{min}
daily minimum temperature
VIF
variance inflation factor
WHO
World Health Organization.

Declarations

Ethics approval and consent to participate

The study used routinely collected, fully anonymised daily ED visit counts without access to individual-level patient identifiers. The protocol “Acil Servis Başvuru Hacminin Zamansal ve Meteorolojik Belirleyicileri” (Temporal and Meteorological Determinants of Emergency Department Visit Volume) was reviewed and approved by the Clinical Research Ethics Committee of the University of Health Sciences, Kanuni Sultan Süleyman Training and Research Hospital, Istanbul, Türkiye (approval number KAEK/2026.05.232; 22.05.2026]) and conducted in accordance with the Declaration of Helsinki and Türkiye’s Personal Data Protection Law (KVKK). Given the retrospective ecological design without individual identifiers, and because only fully aggregated, anonymised daily count data were used, the committee waived the requirement for individual informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

BY conceived and designed the study, performed the data extraction, transcribed the weekly ILI surveillance dataset from the Ministry of Health bulletins, carried out the statistical analysis, and drafted the manuscript. MU and SF contributed to data acquisition, reconciliation of the daily triage counts and interpretation of the results. STF and AE contributed to the literature review, interpretation of the

meteorological and calendar findings, and critical revision of the manuscript for important intellectual content. UMK contributed to the study methodology and the statistical-analysis plan and critically revised the manuscript. SD supervised the study, contributed to its conception and design, and critically revised the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Availability of data and materials

The daily aggregated count datasets, meteorological reanalysis data and the analysis code generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

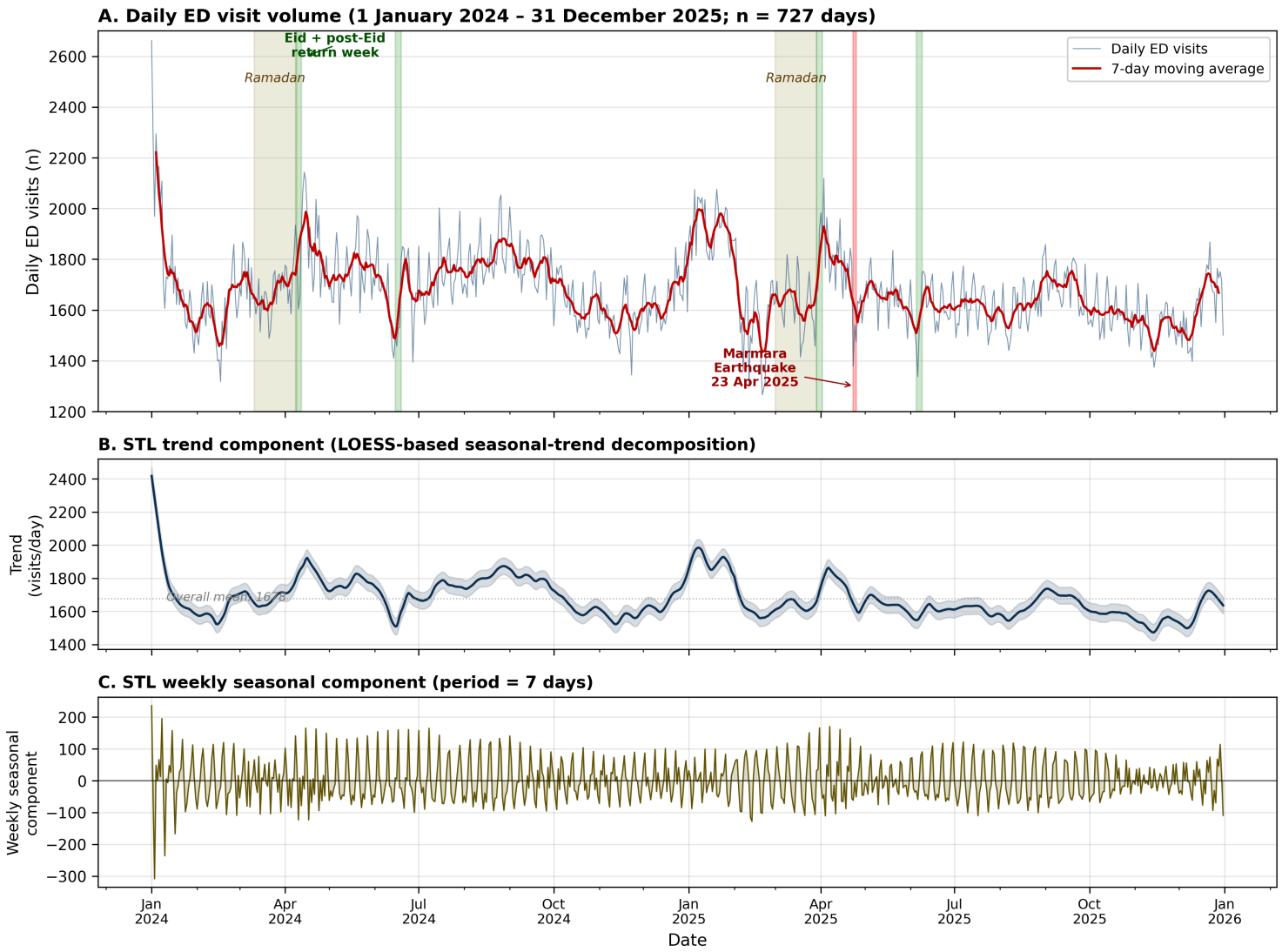


Figure 1

Daily ED visit volume across the 24-month study period (1 January 2024 – 31 December 2025; n = 727 included days after exclusion of four days for data-export failures). **(A)** Daily visit counts (thin blue line) with 7-day moving average (red), and key calendar events annotated: the 23–25 April 2025 Marmara M_w 6.2 earthquake (red shaded window), the two Ramadan months (light-brown shaded windows), and the Eid blocks together with the 7-day post-Eid return windows (green shaded windows). **(B)** STL trend component (LOESS-based seasonal-trend decomposition); the dotted line marks the overall mean (1,678 visits/day). **(C)** STL weekly seasonal component (period = 7 days), illustrating the characteristic Monday peak and weekend trough.

Note for the authors: the numeric annotations printed inside the figure panels (Fig. 2A: β +23.07 / −0.38; Fig. 2C: −1.77) reflect an earlier model run and no longer match the Table 2 values used throughout the text (+22.4 / −0.36 / −1.74). Please regenerate the figures from the same model that produced Table 2 before submission. Delete this note once done.

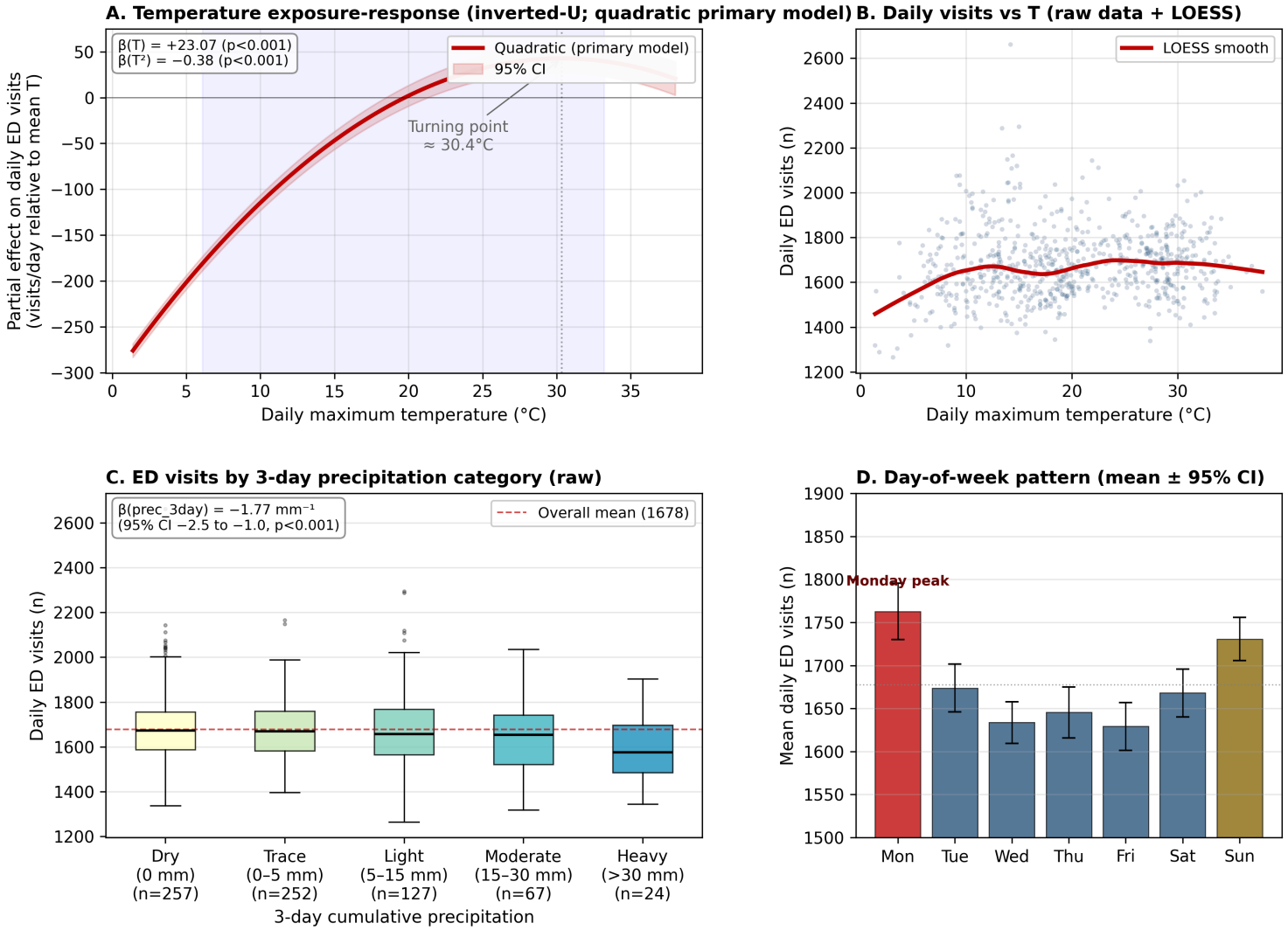


Figure 2

Meteorological and temporal determinants of daily ED visit volume from the ARIMAX(1,0,1) primary model. **(A)** Quadratic temperature exposure–response curve showing the inverted-U with estimated turning point ~31 °C, partial effect expressed relative to the mean observed temperature; shaded area = 95% confidence band; the protocol-pre-specified restricted-cubic-spline sensitivity analysis reproduced the same shape (Additional file 1). **(B)** Raw scatter of daily ED visits against daily maximum temperature with a LOESS smooth overlay. **(C)**Daily ED visits stratified by 3-day cumulative precipitation category; the inverse association is statistically significant (β = −1.74 visits per mm, 95% CI −2.5 to −1.0; p < 0.001). **(D)** Day-of-week pattern (mean ± 95% CI); the Monday peak is shown in red and the Sunday partial recovery in olive.

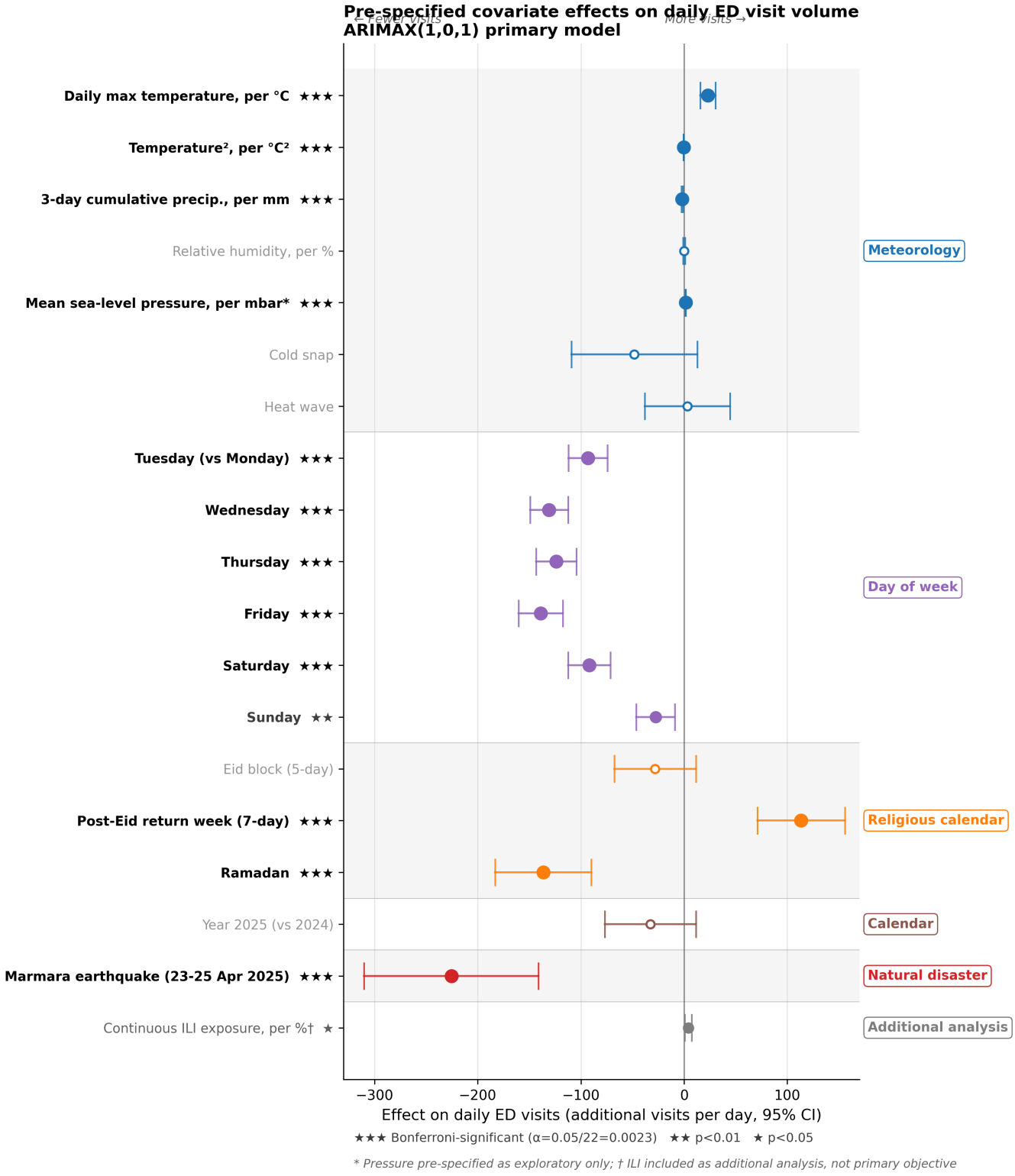


Figure 3

Forest plot of all pre-specified covariate effects on daily ED visit volume from the ARIMAX(1,0,1) primary model, grouped by exposure domain (meteorology; day of week; religious calendar; calendar; natural disaster; additional analysis). Points show point estimates and bars the 95% confidence interval; solid markers indicate Bonferroni-significant effects (α = 0.05/22 = 0.0023) and open markers non-Bonferroni-significant effects. The continuous ILI exposure (marked with * in the figure) is reported as an additional

adjustment for residual seasonal variation rather than as a primary objective of the study; the mean sea-level pressure coefficient is pre-specified as exploratory only.