Supplementary Materials

The Effects of Temporal Averaging of AIS-Based Ship Emissions on $PM_{2.5}$ Hotspot Representation Under Idealized Sea–Land Breeze Conditions

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Abbreviations, scenario names and metrics follow the main text. Baseline refers to the hourly-inventory simulation. Unless stated otherwise, every averaged concentration field retains its normalization to the baseline 96 h emission mass of 685.915 kg, while the primary evaluation covers the final 72 h (Days 2–4). P95, P99 and P99.9 for the original baseline are the area-time-weighted percentiles of that 72 h field: 0.826, 1.447 and 2.319 μg m^{-3}. By default, concentration metrics refer to these 72 h, the 2 m output height and the Incheon mainland analysis area. Sections S9, S10, S12 and S16 define the corresponding reference thresholds for the additional stability, seed, circulation and emission-week comparisons.

The following abbreviations occur only in the Supplementary Materials: AGL, above ground level; CORINE, Coordination of Information on the Environment (land-cover classes); EPSG, European Petroleum Survey Group (coordinate reference system code); GUI, graphical user interface; NO_x, nitrogen oxides; PM_{10}, particulate matter with an aerodynamic diameter of 10 μm or less; Ro-Pax, roll-on/roll-off passenger (ferry); SO_2, sulfur dioxide; WRF, Weather Research and Forecasting model.

S1. Emission Period and Inventory Coverage

During the episode (18–21 June 2024), the Incheon weather station of the Korea Meteorological Administration recorded no precipitation and 10.4–13.3 h of sunshine per day. The inventory contained files and AIS messages for every hour of the episode, the surrounding averaging windows and June 2024. Among the 50 complete Tuesday–Friday windows of 2024, the episode lay at the 82nd percentile of the daytime emission share (58.3%; median: 55.8%) and at the 96th percentile of the in-domain mass. Annual emission statistics for 2024 were calculated for the 8516 hours with collected AIS data out of the 8784 hours in the year. The Year input averages the 8658 hours of 2024 with an inventory file; 142 of these hours had no AIS messages and retained only stationary emissions.

The inventory assumes a fuel sulfur content of 0.1% in the emission control area and 0.5% elsewhere. Across the inventory grid cells, $PM_{2.5}$ was consistently 0.92 of PM_{10}, the fraction that the EPA port guidance gives for Category 3 engines [42]. For each interval between consecutive AIS records of a vessel, main-engine load was estimated from the reported speed relative to the vessel's maximum speed, auxiliary-engine power from ship-type ratios of auxiliary to main installed power and mode-specific load factors, and boiler power from fixed values by vessel type and operating mode. Brake-specific fuel consumption, the low-load adjustment and the sulfur-dependent PM emission factor follow the same guidance [42]; emission is power × interval duration × emission factor, summed over the inventory cell and hour. The inventory cells lie on a geographic lattice

of 0.0045° × 0.00565° (about 500 m) and were reprojected to EPSG:5181. Inventory cells were retained only if their centers lay strictly inside the union of the VTS polygons; the retained cells held 83.2% of the 2406.7 kg of $PM_{2.5}$ emitted over the 96 h in the area for which the inventory was processed. Retained cells inside the GRAL domain held 28.5% of the 2406.7 kg (28.8% without the VTS selection); emissions outside the union or the domain were not simulated. Inside the domain, the selection removed 6.7 kg (1.0%) of the 96 h mass, mainly in a western lane (126.20–126.31° E, 37.33–37.35° N) and a northern port approach (126.58–126.61° E, 37.51–37.56° N).

Each projected inventory cell was represented by 200 m × 200 m area-source elements (hereafter, source elements), and its emissions were divided equally among them before domain clipping. A source element was retained only if its full horizontal extent lay strictly inside the GRAL domain; the mass of excluded elements was not reassigned to retained elements. The retained set was therefore the same in every hour.

The hourly inventory grids extend beyond the Incheon, Pyeongtaek–Dangjin and Daesan VTS areas. Relative to Lee et al. [12], the inventory includes boiler emissions, distinguishes anchoring from hoteling and is limited to vessels with the specifications required for emission calculation.

During the episode, 178 inventory vessels emitted in the GRAL domain, a median of 61 per hour (range: 51–71). In their vessel-level records, container ships emitted 20.9% of the episode $PM_{2.5}$, oil and product tankers 18.9%, bulk carriers 16.8%, liquefied gas tankers 12.4%, tugs 8.7%, Ro-Pax ferries 8.3%, general cargo ships 5.7%, passenger ferries 4.5%, vehicle carriers 2.8% and other types 1.1%; none were fishing vessels or pleasure craft.

The mainland population was calculated from the October 2022 National Geographic Information Institute 1 km total-population grid for Incheon [41]. Of 1703 grid records, 1094 contained nonnegative population values, totaling 2,835,265 people; 609 records had no reported value and were excluded without imputation. Assigning each population cell by its center to the union of positive-weight 500 m analysis cells placed 2,491,897 people (87.9% of the reported total) in the mainland analysis area. Counting only fully contained population cells gave 82.3%, while counting every intersecting cell gave 89.3%. These percentages reflect the boundary assignment of the 1 km population cells. Concentration statistics use land-area weights.

S2. SMOKE Temporal Profiles and AIS-Based Hourly Ship Inventories

The comparison uses the profiles and inventories of the EPA 2022v2 emissions modeling platform package, which requires SMOKE version 5.2.1 [19]; the main text cites the SMOKE release 5.3 manual [9] only for the general allocation framework and the hour-specific input option. The one-week hourly series of on-road activity and industrial point sources (Monday to Sunday, without holidays) were built from the platform's day-of-week and hour-of-day profiles (Table S1). On-road profiles were weighted by the vehicle miles traveled in 3050 counties in July 2022; California is processed as a separate sector [18] and is not in this activity file. Industrial profiles are those of the industrial point sector without rail yards; power plants, industrial units with hourly emission records, oil and gas point sources, and airports are separate sectors of the platform [18].

The day-to-day r is a leave-one-out correlation (Section 2.2 of the main text). For the two SMOKE series, the days are the seven day types of the week. For the four-day Incheon episode, including each day in its reference mean profile raises r from the leave-one-out value of 0.42 to 0.69.

Upper bounds of M for on-road activity and industrial point sources follow from the spatial allocation in SMOKE. Within a county, on-road activity lies on two fixed road surrogates [18], so M cannot exceed the deviation of the hourly activity share of one surrogate from its mean; for industrial sources, groups of stacks with different hourly profiles

were treated as separate fixed maps. Table S1 gives these within-county bounds for the median county, weighted by vehicle miles traveled for on-road activity and by annual $PM_{2.5}$ emissions for industrial point sources, and, in parentheses, for the 95th percentile of counties. The ship M of the main text instead refers to the whole GRAL domain. With all U.S. industrial point sources taken as one domain, the bound is 7.9%.

The temporal cross-reference file of the platform package (ge_dat/temporal/tref_general_2022platform_31may2025_nf_v4) assigns all 299 national ship source codes (commercial marine vessels) the uniform hourly profile (code 24) and the uniform weekly profile (code 7) [19]. Section 3.3.11 of the platform's technical support document states that most areas use hourly commercial marine vessel inventories derived from 5 min AIS data [18]. These AIS-based hourly ship $PM_{2.5}$ emissions cover Category 1/2 and Category 3 vessels, including harbor craft [18]. The Incheon inventory includes tugs and ferries as well (Section S1).

A port complex combines the named port records with the underway grid cells within 20 km of its emission-weighted centroid (25 km for Houston). The 20 largest ports are the named port records with the largest annual $PM_{2.5}$ emissions; they contain only in-port emissions, which account for 3.0% of the U.S. ship $PM_{2.5}$. The U.S. series use the hour bins of the inventory files, whose clock convention is not documented.

Table S1. SMOKE temporal profiles by source class in the EPA 2022v2 platform.

Source class	Temporal allocation in the platform	Share or count with a uniform hourly profile	Diurnal CV (%)	Day-to-day r	Upper bound of M (%)
On-road activity	Activity profiles by county, road type, vehicle class and day of the week	0 of 271,152 profiles	64.6	0.97	5.7 (9.6)
Industrial point sources	One monthly, weekly and hourly profile per source classification code	88.9% of $PM_{2.5}$ emissions	8.6	1.00	2.8 (27.8)
Power plants	Hourly monitor records (NO_x, SO_2 and activity) for units with 86.6% of $PM_{2.5}$ emissions; heat-input profiles for other units	–	–	–	–
Ships, default profiles	Uniform over the day and the week; for most areas the platform reads AIS-based hourly inventories instead (Table S2)	299 of 299 ship source codes	0	–	0

Diurnal CV and r refer to one week built from the profiles (r as in Section 2.2 of the main text); r is high by construction because the profiles repeat by day type. Upper bound of M within one county, median county (95th percentile). For the ship default, $M = 0$ because a single fixed map multiplied by one spatially common temporal profile is compared with itself. –, not applicable.

Table S2 summarizes the hourly inventory comparisons.

Table S2. Variability of AIS-based hourly ship $PM_{2.5}$ emissions and NMAE of monthly and annual means for Incheon, the U.S. total and selected U.S. ports. For the EPA 2022v2 inventory, variability covers July 2022 and NMAE covers all of 2022.

Series	Diurnal CV (%)	Hourly CV (%)	Day-to-day r	NMAE, monthly mean (%)	NMAE, annual mean (%)
U.S. total	1.5	5.9	0.30	4.7	5.3
San Pedro Bay complex	13.8	20.8	0.74	15.2	29.3
Houston complex	4.0	11.0	0.41	7.4	8.2
New York/New Jersey complex	26.5	32.7	0.86	24.6	26.6
20 largest U.S. ports, median	11.8	34.5	0.35	22.7	23.8
(IQR)	(5.0–22.0)	(23.6–48.1)	(0.21–0.56)	(20.0–36.7)	(21.2–38.9)
Incheon, June 2024	18.1	35.2	0.57	27.0	–
Incheon, 2024	15.3	35.1	0.50	26.5	27.2

CV, coefficient of variation; hourly CV, computed across all hourly values of the period; r, day-to-day correlation; NMAE, normalized mean absolute error of hourly emissions; IQR, interquartile range; ports, in-port emissions only; –, not computed. The U.S. NMAE values include late March to late June 2022, for which EPA substituted its 2021 inventory for ship emissions [18].

S3. Scenario Set and Emission Input

The moving averages are centered, and windows with an even number of hours are centered half an hour later than hour t (Equation (2) of the main text). Because each inventory-cell emission was divided equally among a fixed set of source elements (Section S1), averaging per inventory cell or per source element gives identical element emissions. The moving average is linear, so the sums of the averaged elements centered in a 500 m cell equal the moving average of the cell sum (Equation (2) of the main text). The weekly, monthly and annual means use the inventories for 17–23 June, June 2024 and the year 2024, respectively (Section S1).

The inventory mass of the moving averages differs from the baseline mass because their windows include hours outside the episode, whereas block means conserve the mass (Table S3). Because the rescaling equalizes only the 96 h total and a constant emission gives equal daily totals, the constant-rate inputs (Week, Month and Year after rescaling, and BK96, which conserves the 96 h mass by construction; Section S10) emitted 15.5% more mass than the baseline on Day 1 and 4.3% less on Days 2–4. Equating the final-72 h mass instead multiplies all four by a further factor of 1.044685 (Sections S8 and S10), which raises their Day 1 emissions by 20.6% and their 96 h total by 4.5% relative to the baseline.

Cruising, maneuvering, anchoring and hoteling modes accounted for 39.4%, 10.2%, 12.4% and 38.0% of the episode mass. Of these amounts, 66.9%, 63.9%, 52.0% and 50.0% were emitted in daytime.

Table S3. In-domain scenario emissions and mass rescaling over the 96 h episode, relative to the hourly inventory.

Scenario	Definition	Inventory mass (kg)	Mass factor	Spin-up mass change (%)	Emission NMAE (%)	NMAE of hourly totals (%)	Cancellation share
Baseline (1 h)	Hourly inventory	685.915	1.000000	–	–	–	–
MA2	Moving average, 2 h	686.269	0.999483	−3.25	40.0	10.7	0.73
MA3	Moving average, 3 h	684.803	1.001624	−0.18	48.1	10.8	0.78
MA4	Moving average, 4 h	685.353	1.000820	−2.29	54.9	13.3	0.76
MA6	Moving average, 6 h	685.005	1.001328	−2.38	62.3	14.0	0.78
MA12	Moving average, 12 h	685.024	1.001300	−3.82	74.6	15.5	0.79
MA24	Moving average, 24 h	683.617	1.003361	−4.46	83.4	21.8	0.74
MA48	Moving average, 48 h	682.355	1.005217	−1.36	91.5	22.3	0.76
BK6	Block mean, 6 h	685.915	1.000000	0.00	65.8	16.1	0.76
BK12	Block mean, 12 h	685.915	1.000000	0.00	77.1	19.8	0.74
BK24	Block mean, 24 h	685.915	1.000000	−1.09	86.5	22.2	0.74
Week	Mean of 17–23 June 2024	661.156	1.037448	+10.90	102.9	22.3	0.78
Month	Mean of June 2024	565.054	1.213893	+10.90	109.1	22.3	0.80
Year	Mean of 2024	544.469	1.259786	+10.90	114.1	22.3	0.81

Mass factor, baseline mass / inventory mass. Spin-up mass change, change in the 12 h spin-up mass after rescaling, relative to the baseline. Emission NMAE (200 m source elements) and NMAE of hourly totals as in Section 2.3 of the main text. With equal hourly totals on the same grid, emission NMAE equals twice the emission-weighted mean of M (Equation (1) of the main text). Cancellation share, 1 − NMAE of hourly totals / emission NMAE (both unrounded), the share of the absolute source-element difference that cancels in the hourly totals. –, not applicable.

S4. Model Configuration and Meteorological Forcing

The simulations used GRAL V26.01 and a version of GRAMM V26.01 modified for continuous simulation [43,44]. The modified GRAMM initializes once and advances through a single integration loop, writing intermediate outputs each hour. Wind, atmospheric temperature and soil/surface temperature states carry forward across hourly output boundaries without reinitialization. The solar clock repeats the fixed 18 June date. GRAL receives the mean of successive start- and end-of-hour wind fields and the stability class at the start of the hour. The 24 pairs from model hours 42–66 form the repeated third-

day forcing (Section S7.2). Initial conditions used episode-mean water temperature at four National Institute of Fisheries Science coastal stations and the 06:00 atmospheric and soil state at the Incheon weather station (Table S4).

Over Incheon land and at the sources, the stability class was 4–7 from 20:00 to 21:59, 6–7 from 22:00 to 05:59, mostly 4 at 06:00, 1–4 from 07:00 to 18:59 and mostly 4 at 19:00. From 00:00 to 06:59, the scalar wind speed, weighted by the 96 h mean baseline emission map, was 0.14–0.41 m s^{-1} at 10 m and 0.66–1.57 m s^{-1} at 36 m. Figure 2b of the main text uses the same weights for the eastward component at 36 m. The onshore flow weakened from 20:00 to 07:00 without reversing (Figure 2b of the main text; Figure S1a,b); at night, the eastward 10 m component was below −0.5 m s^{-1} in at most 1.6% of the coastal land cells.

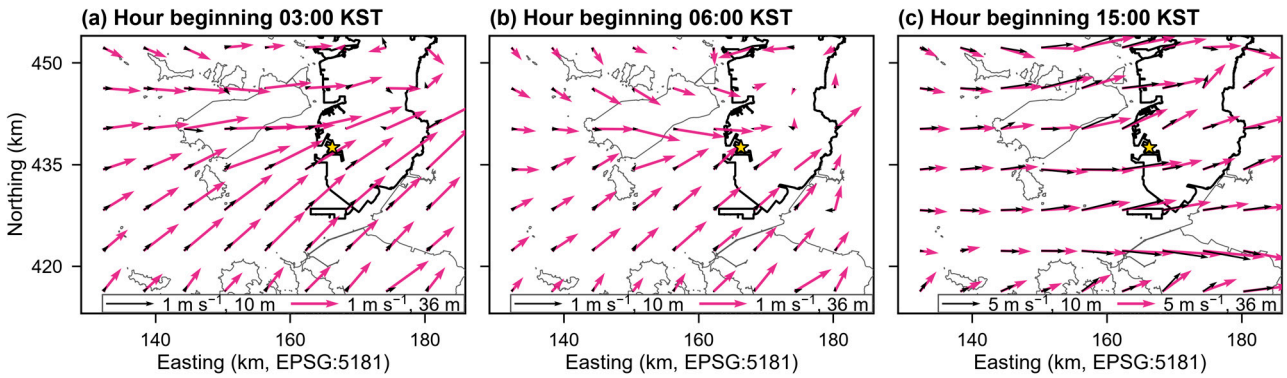

Figure S1. Wind maps at 10 and 36 m on the representative day. Panel times are nominal clock hours (Section S15.1). Short 10 m arrows in (a,b) indicate weak winds. The bold outline marks the Incheon mainland and the star marks the centroid of the Port of Incheon's port areas.

Table S4. GRAMM and GRAL inputs and settings that complement Table 1 of the main text. Values are from the model input files.

Model	Setting	Value
GRAMM	Domain (EPSG:5181)	99,000–223,000 m east, 401,000–460,500 m north
GRAMM	Terrain and land cover	National digital elevation model (National Geographic Information Institute) on a 100 m grid; land-cover map of the Korean Ministry of Environment (2022) reclassified to CORINE classes, 500 m
GRAMM	Latitude	37.478° N
GRAMM	Integration	06:00 start; 72 h; hourly fields
GRAMM	Representative day	Model hours 42–65 start the 24 input hours of the third day; hour 66 supplies the final end field
GRAMM	Initial state, Incheon station at 06:00 KST	Air: 21.4 °C, relative humidity: 83%, surface: 20.5 °C, soil at 1 m depth: 21.4 °C; sea-level input values: air: 294.703 K, surface: 293.778 K, soil: 294.692 K; water: 19.6 °C
GRAMM	Initial wind and temperature profile	0 m s^{-1}; −6.5 K km^{-1} up to the model level at 4.3 km (input height 5 km above ground), −3 K km^{-1} above
GRAMM	Time step	1.5 s (maximum input value 6 s)
GRAMM	Under-relaxation (velocity; scalars)	0.4; 0.4, constant during the integration (adaptive reduction of time step and relaxation disabled)
GRAMM	Lateral boundary relaxation	16 cells at west/east and 12 at south/north; coefficient 0.2 at the boundary, decreasing inward with exponent 2, scaled to the time step (reference 2.5 s)
GRAMM	Radiation update	Every 750 s
GRAMM	Diagnostic boundary exclusion	16 cells at west/east and 12 at south/north lateral boundaries; 20 and 16 cells for coastal bands
GRAL	Domain (EPSG:5181)	129,000–186,000 m east, 413,000–454,000 m north
GRAL	Meteorological input	24 hourly wind fields of the representative day, each the mean of the fields at the start and the end of the hour; stability class of each cell at the start of the hour
GRAL	Flow-field grid	500 m cells; lowest cell 2 m high, growing by a factor of 1.01 per cell
GRAL	Roughness length; wind meandering	Per cell from the GRAMM land-use file; on
GRAL	Roughness length over water	0.0001 m [44]

Model	Setting	Value
GRAL	Dispersion time; spin-up	3600 s per hour; 12 h from 12:00 KST on 17 June 2024
GRAL	Transient concentration threshold	0.001 μg m^{-3}
GRAL	Boundary-layer height	Spatially uniform within each hour, 478–573 m; limits vertical mixing in unstable cells only
GRAL	Concentration slices	Nine slices of 4 m thickness, centered at 2, 6, 10, 15, 20, 30, 50, 75 and 100 m (Section S8)
Both	Vertical geometry	GRAMM 28 layer centers and GRAL vertical specifications: Section S8

KST, Korea Standard Time. Coastal bands, land cells within 2.5 km of water over which the wind diagnostics were averaged. The initial water input was 1.942 K below the soil value.

In transient mode, the end-of-hour three-dimensional concentration field supplies particles for the next hour [43]. Table S4 and Section S13 list the concentration threshold and particle settings. GRAL's passive-tracer concentration estimator sums particle mass times residence time over the sampling volume and period [43, Equation (77)]. With the transport field fixed, the estimator scales in proportion to particle mass. The normalization factors were applied uniformly to the stored concentration fields, preserving the transient particle-removal history of each original integration. Because the transient threshold is an absolute concentration and is not rescaled, the normalization departs from a rerun with scaled emissions only for residual material near that threshold; Section S14 reports direct simulations of this departure. Over the original 96 h baseline episode, releases at least 12 h old supplied 0.12% of the domain concentration sum; releases 24 h or older supplied none.

S5. Concentration Changes over the Final 72 Hours and the Full Episode

The final 72 h exclude the first emission day from evaluation while retaining the original simulation history. Release-group accounting found zero spin-up contribution in this window for all analyzed scenarios. Day 1 releases in the baseline still supplied 6.73% of the mean concentration and were retained, although baseline releases before 16:00 KST on Day 1 contributed nothing to the mainland concentrations of Days 2–4. Table S5 compares the 72 h and 96 h land means and gives the daily changes on Days 2–4. All entries retain the 96 h emission-mass normalization. Section S8 separately reports a uniform post hoc rescaling to equal final-72 h emission mass, and Table 5 of the main text extends it to exceedance area-time and J. Source elements centered in cells with a positive mainland area accounted for 21.3% of final-72 h baseline emissions, compared with 21.5% for MA24 and 23.5%, 25.3% and 26.6% for Week, Month and Year. Their composition reflects both the averaging period and the recorded vessel population.

Table S5. Mainland concentration changes over the final 72 h and the full 96 h episode. Daily changes use the baseline for the same day.

Scenario	72 h mean (%)	96 h mean (%)	Night share (%)	Day 2 mean / max (%)	Day 3 mean / max (%)	Day 4 mean / max (%)
MA2	−0.9	−0.7	115.5	−0.8 / −2.8	−1.0 / +0.6	−1.0 / +3.5
MA3	+0.3	+0.4	78.5	−0.5 / +0.5	+0.2 / +1.5	+1.0 / +2.2
MA4	−0.5	−0.2	138.2	−1.0 / −2.5	−0.5 / −0.3	+0.0 / +4.4
MA6	−0.1	+0.4	462.4	−1.2 / −0.9	−0.4 / +1.7	+1.3 / +4.9
MA12	+1.6	+2.7	62.8	−1.7 / −7.9	+0.9 / +7.1	+5.6 / +0.5
MA24	+8.7	+10.5	87.3	+1.0 / −26.6	+10.4 / +8.4	+14.8 / +6.1
MA48	+8.7	+11.1	87.7	−0.3 / −30.8	+17.8 / +14.5	+9.2 / −0.6
BK6	+1.4	+2.2	82.2	−2.6 / −2.6	+1.2 / +1.6	+5.8 / +7.8
BK12	+8.3	+10.1	97.6	+4.1 / +4.0	+8.2 / +5.3	+12.7 / +2.2
BK24	+9.1	+10.8	87.9	+0.6 / −31.4	+19.6 / +15.6	+7.9 / −1.5

Scenario	72 h mean (%)	96 h mean (%)	Night share (%)	Day 2 mean / max (%)	Day 3 mean / max (%)	Day 4 mean / max (%)
Week	+9.5	+14.5	85.1	+6.3 / −28.7	+15.4 / +9.3	+7.3 / −4.9
Month	+11.9	+17.0	81.7	+8.6 / −25.3	+17.9 / +15.4	+9.6 / +0.3
Year	+13.7	+18.9	82.3	+10.4 / −22.3	+19.9 / +19.2	+11.4 / +4.2

The 72 h and 96 h columns use their respective baseline means; both retain equal 96 h episode emission mass. Night share is the contribution of 20:00–07:59 hours to the final-72 h mean difference. A negative share or a share above 100% can occur when daytime and nighttime changes oppose each other. Daily baseline maxima on Days 2–4 were 4.44, 2.87 and 3.28 μg m^{-3}.

S6. Hotspot Extent, Location and Timing

The 72 h baseline contains 96,408 mainland cell-hours with positive area weights, totaling 22,644.9 km^2 h. Each percentile is the lowest concentration at which cumulative area-time, summed in ascending concentration order, reaches its specified fraction, without interpolation. Classifications use unrounded thresholds and strict exceedance. Baseline exceedance area-times are 1132.2125, 226.4400 and 22.4575 km^2 h at P95, P99 and P99.9. Area-time divided by 0.25 km^2 h gives full-cell equivalents.

A space–time cluster links exceeding cell-hours that are adjacent, including diagonally, in the same hour or that occupy the same cell in consecutive hours. Within the final 72 h, the baseline P99 set contains 995 exceeding cell-hours in 192 distinct cells and 35 hours, forming 44 clusters. Its exceedances occur between 22:00 and 09:59. The P99.9 set contains 101 exceeding cell-hours in 32 cells and 21 hours, forming 17 clusters, all between 00:00 and 08:59. Days 2, 3 and 4 contribute 55.1%, 13.2% and 31.7% of the P99.9 area-time, respectively.

With A_i the area of cell i inside the mainland analysis area, the concentration NMAE of a scenario field, C_s, against the baseline field, C_1, is

$$\mathrm{NMAE}_s = 100\,\frac{\sum_{t,i} A_i |C_s(t,i) - C_1(t,i)|}{\sum_{t,i} A_i\, C_1(t,i)}. \tag{S1}$$

The hourly footprint is the fixed fraction of the land area (1%, 5% or 10%) with the highest concentration in each hour; the cell at the cutoff contributes a fractional area. The 5% share has also been used for hotspot cells of ship emissions [37]. The footprint overlap is the Jaccard index of the scenario and baseline footprints of the same hour.

The baseline final-72 h maximum occurs at 08:00 on Day 2. The maxima of MA24, MA48, BK24 and Week occur at the MA24-maximum cell, 8.5 km south-southeast of the baseline-maximum cell. Table S6 describes those two cells and the two port cells shown in Figure 7.

In Table S7, the hit rate is the fraction of baseline exceedance area-time also exceeded by a scenario; the false-alarm ratio (FAR) is the fraction of scenario exceedance area-time absent from the baseline. Own-percentile comparisons cut each scenario at its own P95, P99 or P99.9, giving approximately equal exceedance area-times. Table S8 reports the median distance between concentration-weighted centroids of the two hourly 5% footprints. A 1% footprint holds about 13 full-cell equivalents (3.1 km^2), so its overlap can change appreciably when only a few cells differ. For two equal-area sets, J = 0.70 corresponds to 82.4% shared area.

Table S6. Final-72 h $PM_{2.5}$ at the four cells of Figure 7. Day and hour identify the concentration maximum. Exceedance hours use the common baseline P99 and P99.9.

Cell	Scenario	Mean (μg m^{-3})	Maximum (μg m^{-3})	Day / hour	P99 hours	P99.9 hours
Port of Incheon	Baseline	0.383	1.385	4 / 07	0	0
Incheon New Port	Baseline	0.575	1.627	4 / 07	2	0
Baseline maximum	Baseline	0.423	4.436	2 / 08	5	2

Cell	Scenario	Mean (μg m⁻³)	Maximum (μg m⁻³)	Day / hour	P99 hours	P99.9 hours
MA24 maximum	Baseline	0.513	2.486	3 / 06	11	2
Port of Incheon	MA24	0.485	1.803	4 / 07	3	0
Incheon New Port	MA24	0.582	1.787	4 / 07	2	0
Baseline maximum	MA24	0.420	3.255	2 / 08	5	2
MA24 maximum	MA24	0.696	3.486	4 / 06	15	9
Port of Incheon	Month	0.568	1.787	3 / 07	8	0
Incheon New Port	Month	0.392	1.109	3 / 07	0	0
Baseline maximum	Month	0.563	3.245	2 / 08	6	6
MA24 maximum	Month	0.727	3.303	2 / 06	15	9
Port of Incheon	Year	0.586	1.782	3 / 07	9	0
Incheon New Port	Year	0.398	1.103	3 / 07	0	0
Baseline maximum	Year	0.740	3.182	4 / 08	9	6
MA24 maximum	Year	0.666	3.123	2 / 06	15	9

Cell centers (° E, ° N): Port of Incheon, 126.619, 37.439; Incheon New Port, 126.630, 37.344; baseline maximum, 126.624, 37.502; MA24 maximum, 126.670, 37.434. All four cells lie in the mainland analysis area. Final-72 h source mass within 3 km of the Port of Incheon and Incheon New Port cells was 58.9 and 61.5 kg (baseline), 59.7 and 60.6 kg (MA24), 74.4 and 42.2 kg (Month) and 79.6 and 43.4 kg (Year) after 96 h normalization. Within 5 km in the ±30° sector west of each cell, the night share of emissions was 38% and 50% (baseline) and 50% and 50% (MA24). Hour denotes the beginning of the one-hour concentration period. Month and Year have constant emission rates under the repeated daily forcing.

Table S7. Final-72 h exceedance area-time and overlap at P95, P99 and P99.9. Common thresholds come from the baseline. The final column compares the scenario and baseline at their respective percentiles.

Scenario	Threshold	Area-time (km² h)	Change (%)	*J*	Hit rate	FAR	Own-percentile *J*
Baseline	P95	1132.21	+0.0	1.000	1.000	0.000	1.000
Baseline	P99	226.44	+0.0	1.000	1.000	0.000	1.000
Baseline	P99.9	22.46	+0.0	1.000	1.000	0.000	1.000
MA2	P95	1088.47	−3.9	0.906	0.932	0.030	0.913
MA2	P99	223.69	−1.2	0.854	0.916	0.073	0.857
MA2	P99.9	22.44	−0.1	0.838	0.912	0.088	0.838
MA3	P95	1132.43	+0.0	0.915	0.956	0.045	0.914
MA3	P99	229.95	+1.5	0.878	0.942	0.072	0.881
MA3	P99.9	22.40	−0.3	0.883	0.937	0.061	0.883
MA4	P95	1098.70	−3.0	0.891	0.928	0.043	0.894
MA4	P99	223.67	−1.2	0.822	0.897	0.092	0.819
MA4	P99.9	21.67	−3.5	0.866	0.912	0.055	0.850
MA6	P95	1117.74	−1.3	0.868	0.923	0.065	0.868
MA6	P99	227.04	+0.3	0.793	0.885	0.117	0.791
MA6	P99.9	19.68	−12.4	0.791	0.829	0.054	0.777
MA12	P95	1179.46	+4.2	0.804	0.910	0.127	0.803
MA12	P99	247.51	+9.3	0.696	0.859	0.214	0.705
MA12	P99.9	17.91	−20.2	0.530	0.623	0.219	0.556
MA24	P95	1356.84	+19.8	0.677	0.887	0.260	0.690
MA24	P99	320.84	+41.7	0.465	0.767	0.458	0.487
MA24	P99.9	36.97	+64.6	0.217	0.472	0.713	0.247
MA48	P95	1353.05	+19.5	0.614	0.835	0.301	0.638
MA48	P99	306.21	+35.2	0.401	0.674	0.502	0.421
MA48	P99.9	30.32	+35.0	0.148	0.303	0.775	0.140
BK6	P95	1186.62	+4.8	0.821	0.923	0.119	0.823
BK6	P99	246.15	+8.7	0.759	0.900	0.172	0.762
BK6	P99.9	22.42	−0.2	0.722	0.838	0.161	0.722
BK12	P95	1362.94	+20.4	0.726	0.927	0.230	0.745
BK12	P99	312.19	+37.9	0.587	0.880	0.362	0.606
BK12	P99.9	27.34	+21.8	0.477	0.716	0.412	0.485
BK24	P95	1377.47	+21.7	0.617	0.846	0.305	0.650
BK24	P99	325.33	+43.7	0.412	0.711	0.505	0.441
BK24	P99.9	36.46	+62.3	0.194	0.426	0.738	0.151
Week	P95	1372.68	+21.2	0.581	0.813	0.329	0.583

Scenario	Threshold	Area-time (km² h)	Change (%)	J	Hit rate	FAR	Own-percentile J
Week	P99	289.60	+27.9	0.308	0.537	0.580	0.317
Week	P99.9	24.90	+10.9	0.101	0.194	0.825	0.101
Month	P95	1374.24	+21.4	0.525	0.762	0.372	0.529
Month	P99	319.99	+41.3	0.286	0.537	0.620	0.288
Month	P99.9	34.76	+54.8	0.153	0.339	0.781	0.146
Year	P95	1449.15	+28.0	0.532	0.792	0.382	0.536
Year	P99	339.74	+50.0	0.305	0.584	0.611	0.307
Year	P99.9	27.88	+24.2	0.159	0.307	0.752	0.166

Hit rate is the fraction of baseline exceedance area-time also exceeded by a scenario; false-alarm ratio (FAR) is the fraction of scenario exceedance area-time absent from the baseline. Own-percentile comparisons give approximately equal exceedance area-times. Percentile classification and $J > 0.70$ comparisons use unrounded values.

Table S8. Final-72 h hourly footprint overlap and spatial diagnostics. Footprints cover the highest-concentration 1%, 5% or 10% of mainland area in each hour. Each pair gives median J and the percentage of hours with $J > 0.70$.

Scenario	1%: J / hours (%)	5%: J / hours (%)	10%: J / hours (%)	5% centroid displacement (km)	NMAE (%)	Time-collapsed J
MA2	0.860 / 88.9	0.872 / 95.8	0.884 / 97.2	0.36	4.9	0.949
MA3	0.857 / 90.3	0.870 / 97.2	0.888 / 98.6	0.25	4.5	0.954
MA4	0.848 / 87.5	0.848 / 91.7	0.868 / 91.7	0.44	6.0	0.922
MA6	0.778 / 76.4	0.813 / 87.5	0.825 / 81.9	0.57	7.6	0.881
MA12	0.676 / 47.2	0.739 / 66.7	0.760 / 70.8	0.95	11.7	0.802
MA24	0.572 / 26.4	0.631 / 26.4	0.643 / 40.3	1.53	20.7	0.574
MA48	0.479 / 8.3	0.583 / 11.1	0.607 / 22.2	1.68	25.8	0.554
BK6	0.756 / 63.9	0.746 / 76.4	0.790 / 75.0	0.94	10.1	0.850
BK12	0.695 / 50.0	0.689 / 44.4	0.705 / 50.0	1.10	17.1	0.735
BK24	0.505 / 19.4	0.586 / 12.5	0.618 / 27.8	1.79	25.7	0.563
Week	0.340 / 2.8	0.481 / 4.2	0.532 / 8.3	2.28	27.6	0.474
Month	0.271 / 0.0	0.442 / 2.8	0.494 / 4.2	2.72	31.3	0.464
Year	0.248 / 1.4	0.422 / 1.4	0.463 / 2.8	3.35	31.9	0.498

The centroid displacement is the median distance between concentration-weighted centroids of the two 5% footprints. NMAE compares concentration fields by Equation (S1). Time-collapsed J compares the areas of cells exceeding the common P99 in at least one of the 72 h, with time ignored.

The timing metrics are summarized in Table S9.

Table S9. Final-72 h timing of P99 exceedances. Timing shares use each simulation's total P99 exceedance area-time.

Scenario	Night 20–07 (%)	20–01 (%)	02–05 (%)	06–09 (%)	Circular mean (h)	Duration (h)	Hit rate ±1 h	FAR ±1 h	Temporal J
Baseline	94.0	12.3	46.6	41.1	4.58	2.45	–	–	–
MA2	94.2	12.2	46.8	41.0	4.59	2.55	0.965	0.017	0.831
MA3	94.5	11.6	48.3	40.1	4.56	2.60	0.975	0.017	0.863
MA4	94.4	11.5	49.2	39.3	4.56	2.67	0.943	0.030	0.803
MA6	94.7	10.7	49.9	39.4	4.59	2.69	0.931	0.048	0.780
MA12	95.1	9.9	48.1	42.0	4.73	2.70	0.910	0.090	0.699
MA24	96.5	7.5	51.5	41.1	4.77	2.86	0.831	0.287	0.561
MA48	96.7	6.3	51.8	41.9	4.87	2.74	0.759	0.330	0.498
BK6	94.7	11.2	49.5	39.2	4.57	2.69	0.937	0.070	0.751
BK12	95.6	9.6	50.1	40.3	4.67	2.73	0.927	0.210	0.650
BK24	96.6	6.8	52.2	41.0	4.80	2.79	0.785	0.330	0.505

Scenario	Night 20–07 (%)	20–01 (%)	02–05 (%)	06–09 (%)	Circular mean (h)	Duration (h)	Hit rate ±1 h	FAR ±1 h	Temporal J
Week	95.9	5.4	49.8	44.7	5.00	2.69	0.636	0.406	0.406
Month	95.5	5.2	50.5	44.2	4.97	2.79	0.612	0.456	0.405
Year	95.3	5.3	48.9	45.9	5.02	2.74	0.665	0.454	0.398

Circular mean hour is the area-time-weighted mean on a 24 h circle; each hour hh:00–hh:59 is placed at hh, so midpoint coordinates would be 0.5 h later. Exceedance duration is the area-weighted mean length of uninterrupted exceedance runs in a cell, clipped at the 72 h evaluation boundaries. The ±1 h tolerance matches exceedances in the same cell within one hour inside the 72 h evaluation window. Temporal J is the area-weighted mean of per-cell temporal J across cells that exceed in both simulations. All metrics use the common baseline P99.

Table S10 gives the daily shares of each simulation's final-72 h P99 exceedance area-time and its daily J against the baseline (Figure S2b).

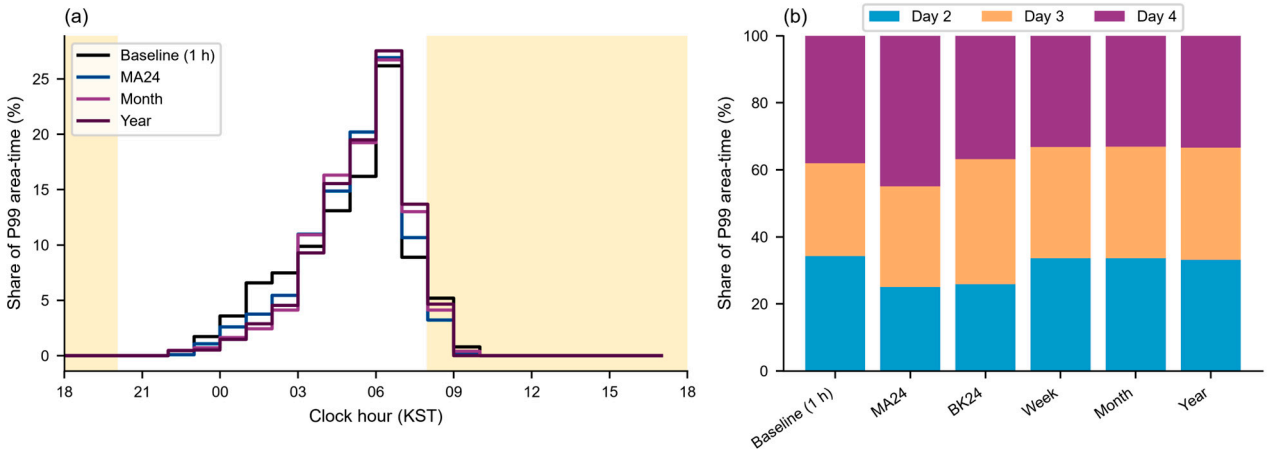

Figure S2. Timing of P99 exceedances within the final 72 h. Share of each simulation's exceedance area-time (a) by clock hour and (b) by day. Shading marks daytime (08:00–19:59 KST).

Table S10. Daily P99 exceedance area-time, its share of the final-72 h total, and daily J against the baseline at P99 and P99.9.

Scenario	Day	P99 area-time (km² h)	Share of 72 h (%)	J (P99)	J (P99.9)
Baseline	2	77.51	34.2	1.000	1.000
Baseline	3	62.77	27.7	1.000	1.000
Baseline	4	86.16	38.0	1.000	1.000
MA2	2	77.42	34.6	0.872	0.900
MA2	3	64.32	28.8	0.787	0.686
MA2	4	81.96	36.6	0.890	0.806
MA3	2	77.15	33.6	0.895	0.953
MA3	3	64.36	28.0	0.797	0.690
MA3	4	88.44	38.5	0.927	0.841
MA4	2	76.88	34.4	0.835	0.889
MA4	3	64.15	28.7	0.769	0.690
MA4	4	82.64	36.9	0.852	0.895
MA6	2	77.48	34.1	0.797	0.860
MA6	3	62.38	27.5	0.729	0.468
MA6	4	87.19	38.4	0.838	0.795
MA12	2	83.07	33.6	0.680	0.519
MA12	3	59.88	24.2	0.698	0.476
MA12	4	104.56	42.2	0.709	0.570
MA24	2	80.25	25.0	0.402	0.212
MA24	3	96.41	30.0	0.513	0.184
MA24	4	144.18	44.9	0.478	0.236
MA48	2	73.91	24.1	0.276	0.025
MA48	3	113.57	37.1	0.441	0.196
MA48	4	118.73	38.8	0.473	0.248
BK6	2	76.42	31.0	0.796	0.833

Scenario	Day	P99 area-time (km² h)	Share of 72 h (%)	J (P99)	J (P99.9)
BK6	3	67.93	27.6	0.703	0.533
BK6	4	101.80	41.4	0.770	0.641
BK12	2	98.17	31.4	0.628	0.688
BK12	3	84.26	27.0	0.611	0.320
BK12	4	129.76	41.6	0.540	0.318
BK24	2	84.28	25.9	0.329	0.182
BK24	3	121.05	37.2	0.434	0.157
BK24	4	120.00	36.9	0.465	0.246
Week	2	97.32	33.6	0.228	0.104
Week	3	95.99	33.1	0.342	0.079
Week	4	96.28	33.2	0.365	0.116
Month	2	107.60	33.6	0.233	0.215
Month	3	106.29	33.2	0.275	0.065
Month	4	106.09	33.2	0.353	0.151
Year	2	112.55	33.1	0.272	0.247
Year	3	113.77	33.5	0.273	0.059
Year	4	113.42	33.4	0.369	0.136

Daily J compares the 24 h scenario and baseline cell-hour sets using the common final-72 h baseline thresholds. All fields retain the 96 h emission-mass normalization. The three baseline day pairs aligned by clock hour under the repeated forcing give P99 J = 0.257, 0.341 and 0.449 (Days 2–3, 2–4 and 3–4; mean: 0.349).

S7. Surface Parameters and Forcing Diagnostics

S7.1. Land-Surface Parameters

Table S11 groups the land-cover classes present in the meteorological (GRAMM) grid. Default refers to the land-use table of the GRAL GUI (Version 20.01). For built-up, vegetated and bare-rock classes, its conductivities differ from those in the land-use table of the GRAMM documentation [44]. GRAMM fixes the specific heat capacity of the soil, CPBOD, at 900 J kg^{-1} K^{-1} and uses CPBOD × RHOB for heat storage [44]. RHOB was set to conductivity/(target diffusivity × 900), rounded; it is therefore an effective heat-storage parameter.

Table S11. Thermal input parameters used in GRAMM, by land-cover group.

Land-cover group (CORINE classes)	Thermal conductivity, default → study (lambda; W m^{-1} K^{-1})	Target thermal diffusivity (10^{-6} m^2 s^{-1})	Effective heat-storage parameter (RHOB; kg m^{-3})	Volumetric heat capacity (CPBOD × RHOB; MJ m^{-3} K^{-1})
Built-up: 112, 121, 122, 123, 124, 131, 133	1.0 → 0.834	0.441	2101	1.8909
Green/crop/forest/grass: 141, 142, 211, 222, 311, 312, 313, 321	0.2 → 1.62	0.600	3000	2.7000
Paddy: 213	2.0 → 2.0	0.700	3175	2.8575
Wetland/salt pan/tidal flat: 411, 422, 423	20.0 → 1.8	0.500	4000	3.6000
Water: 511, 512, 523	100 → 100	1.000	111,111	99.9999
Beach/sand: 331	0.3 → 0.3	1.000	333	0.2997
Bare rock: 332	1.0 → 1.0	1.000	1111	0.9999

Conductivity 1.62 W m^{-1} K^{-1} is the upper end of the 0.85–1.62 range measured on saturated soil samples from 16 Korean weather stations [45]. The target diffusivity 0.60 × 10^{-6} m^2 s^{-1} is the mean for the upper 1 m at 56 Korean stations [46]. The wetland pair 1.8 W m^{-1} K^{-1} and 0.5 × 10^{-6} m^2 s^{-1} was selected using Baeksu tidal-flat measurements [47]. Built-up values were derived from the heat capacity (1.89 MJ m^{-3} K^{-1}) and thermal inertia listed for urban land in the WRF land-use table (LANDUSE.TBL).

Besides conductivity, the following parameters were changed from the same default table: for urban classes 112/121/122, albedo changed from 0.25 to 0.13, soil-moisture parameter FW from 0.03 to 0.10 and roughness length from 0.3–0.5 to 1.0 m; FW changed from 0.10 to 0.30 for classes 141/142/211/222, from 0.10 to 0.15 for 321 and from 0.50 to 0.85

for paddy class 213; and, for tidal-flat class 423, albedo changed from 0.14 to 0.15, the summer mean albedo estimated for the same tidal flat [47]. Emissivity was unchanged.

S7.2. Repeated Meteorological Forcing

The solar-date input is 18 June with a 06:00 start; in this integration, the model code wraps the solar clock each day without advancing the date. Each of the 24 hourly wind inputs averages two successive hourly fields from model hours 42–66, and stability uses the field at the start of each hour (model hours 42–65). The repeated transition therefore goes from the mean of the fields at model hours 65 and 66 to the mean of those at hours 42 and 43 (23:30 to 00:30). In the natural continuation, the next field is the mean of the fields at hours 66 and 67; Table S12 compares both transitions. Coastal wind strength did not converge across the tested GRAMM under-relaxation factors: in 48 h tests on a smaller grid at a 2.5 s time step, the first-model-day mean eastward 10 m wind over the coastal band (hourly fields 11:00–17:00) rose from 1.94 to 2.91 m s^{-1} as the factor increased from 0.1 to 0.8. We used a factor of 0.4 with a 1.5 s time step and treat this dependence as a structural uncertainty of the idealized field.

Table S12. Root-mean-square differences of the horizontal wind vector (m s^{-1}) over the 9348 meteorological (GRAMM) grid cells with centers inside the GRAL domain, equally weighted.

Height (m AGL)	Same-clock model day 2–3 mean RMSE	Ordinary hourly change, median	Ordinary hourly change, maximum	Repeated 23→00 change	Natural 23→24 change	Repeated-versus-natural 00 difference
10	0.269	0.471	0.928	0.123	0.115	0.029
36	0.361	0.602	1.287	0.327	0.307	0.085
300	0.350	0.574	1.467	0.626	0.541	0.156

Heights are above local terrain; wind components were linearly interpolated to them in each model column. The model day 2–3 entry is the mean of 24 same-clock spatial RMSE values; ordinary changes are the 23 nonwrapping transitions in the actual forcing; the repeated-versus-natural 00 difference isolates the replacement of the next field. Forcing wind components are quantized in 0.01 m s^{-1} increments (maximum rounding difference: about 0.005 m s^{-1}).

The repeated transition is smaller than the largest ordinary hourly change at each height, although at 300 m it exceeds the median. Across this transition, stability class changes in 15.42% of the cells, compared with 11.26% in the natural continuation; both fields classify all cells as class 6 or 7. Replacing the natural next field changes class in 8.00% of cells.

Over GRAMM land cells within the GRAL domain, the mean same-clock warming from model day 2 to day 3 was 0.300 K in the lowest air layer, 0.335 K at the surface and 0.792 K in the deepest prognostic soil layer.

S8. Seed Repeatability and Supplementary Diagnostics

The baseline and MA24 were repeated with particle seed 2 at the original particle rate. Figure S3 shows the original stability fields. Table S13 compares seed 2 against seed 1 within each input, and Figure S4 sets these differences against averaging effects over baseline thresholds P90–P99.9. The two seed pairs characterize repeatability under the tested settings; they do not provide a particle-count convergence sequence or a sampling confidence interval. Table S14 lists the compact scenario comparison cited in Section 3.5 of the main text.

Table S13. Seed-2 changes relative to seed 1 over the final 72 h, and seed-pair J at common baseline thresholds.

Input	Mean change (%)	Maximum change (%)	NMAE (%)	J (P90)	J (P95)	J (P99)	J (P99.9)
Baseline	−0.015	+0.138	2.260	0.965	0.962	0.951	0.927
MA24	−0.017	+2.187	2.361	0.966	0.964	0.939	0.949

For MA24, the thresholds in this table are the baseline seed-1 thresholds. Using the MA24 seed-1 percentiles instead gives seed-pair J = 0.943 at P99 and 0.913 at P99.9. Both simulations retain the same 96 h normalization factor.

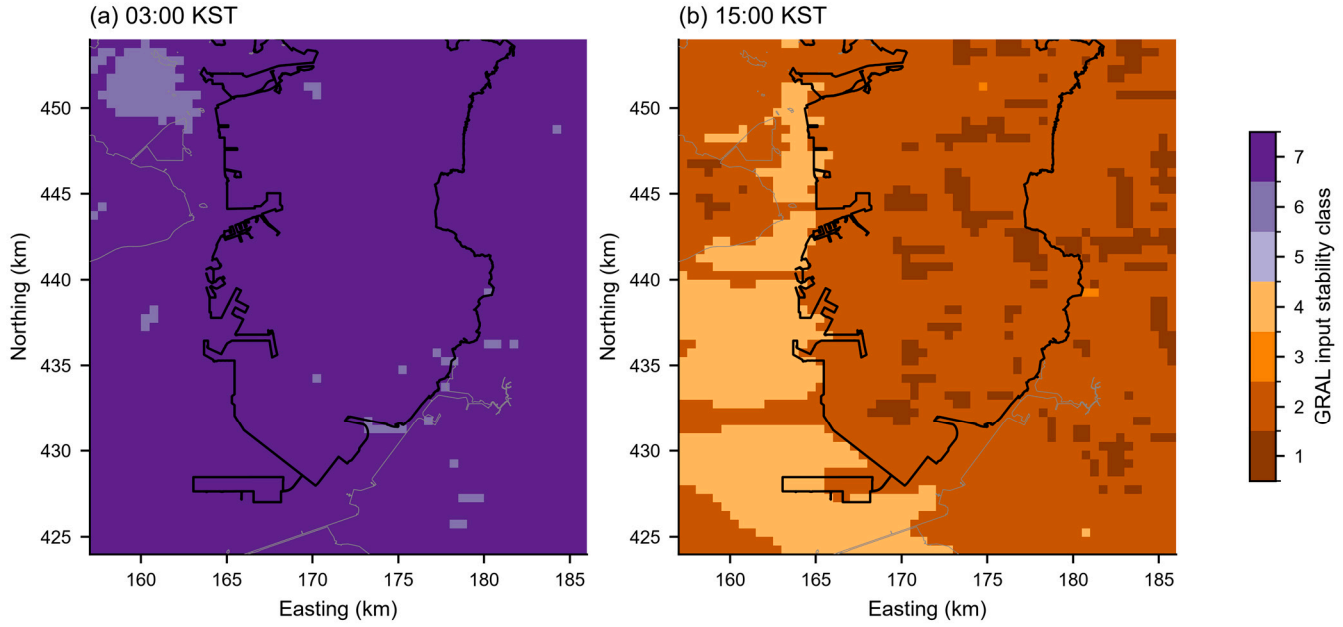

Figure S3. Spatial stability classes supplied to GRAL over the eastern GRAL domain on the representative day. Panel times are nominal clock hours (Section S15.1). The classes (1, very unstable; 4, neutral; 7, very stable) are the start-of-hour GRAMM diagnostics for the original treatment. Section S9 describes the neutral treatment that sets nighttime water classes to 4. The bold outline marks the Incheon mainland.

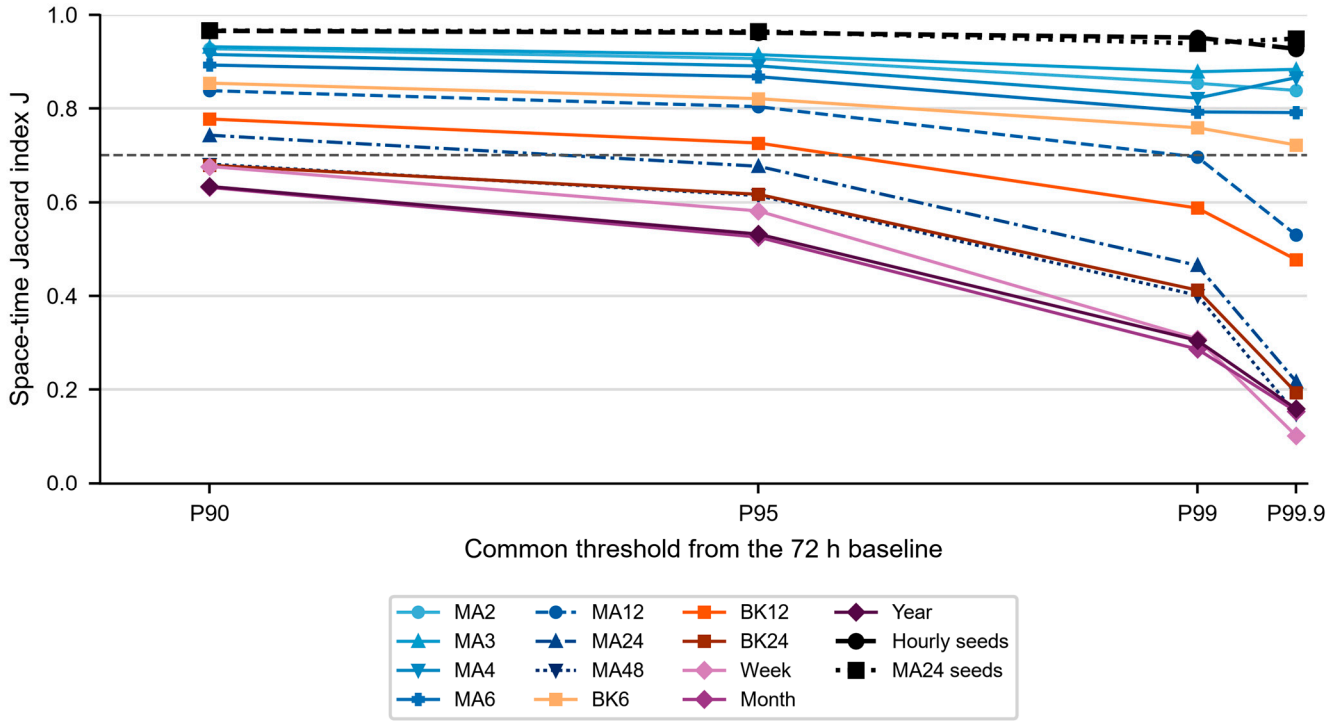

Figure S4. Jaccard overlap at common baseline thresholds. Averaging scenarios use the seed-1 baseline. Seed pairs compare seeds 1 and 2 of the same input. The horizontal line marks the descriptive $J = 0.70$ level.

Table S14. Compact comparison of final-72 h mean change, concentration NMAE and hotspot overlap.

Scenario	Mean change (%)	NMAE (%)	J (P99)	J (P99.9)
MA2	−0.9	4.9	0.854	0.838
MA3	+0.3	4.5	0.878	0.883
MA4	−0.5	6.0	0.822	0.866
MA6	−0.1	7.6	0.793	0.791
MA12	+1.6	11.7	0.696	0.530
MA24	+8.7	20.7	0.465	0.217
MA48	+8.7	25.8	0.401	0.148
BK6	+1.4	10.1	0.759	0.722
BK12	+8.3	17.1	0.587	0.477
BK24	+9.1	25.7	0.412	0.194
Week	+9.5	27.6	0.308	0.101
Month	+11.9	31.3	0.286	0.153
Year	+13.7	31.9	0.305	0.159

Table S15 describes the actual GRAMM terrain-following layer centers over the GRAL domain. Nominal GRAMM thickness begins at 10 m and increases by a factor of 1.2; terrain modifies local layer positions. GRAL uses a 2 m lowest flow-field cell and a vertical growth factor of 1.01. Its concentration sampling layers are 4 m thick and centered at 2, 6, 10, 15, 20, 30, 50, 75 and 100 m AGL. These sampling heights differ from the flow-field grid geometry.

Table S15. GRAMM vertical grid: nominal thickness and layer-center height, and actual layer-center AGL heights over the GRAL domain.

Layer	Nominal thickness (m)	Nominal center (m)	Actual median (m)	Actual min (m)	Actual max (m)
1	10.00	5.00	4.98	4.84	4.98
2	12.00	16.00	15.95	15.49	15.95
3	14.40	29.20	29.10	28.26	29.10
4	17.28	45.04	44.89	43.59	44.89
5	20.74	64.05	63.83	61.99	63.84
6	24.88	86.86	86.56	84.07	86.57
7	29.86	114.23	113.84	110.56	113.85
8	35.83	147.07	146.57	142.35	146.59
9	43.00	186.49	185.85	180.50	185.88
10	51.60	233.79	232.99	226.28	233.02
11	61.92	290.55	289.55	281.22	289.59
12	74.30	358.65	357.43	347.14	357.47
13	89.16	440.39	438.88	426.25	438.93
14	106.99	538.46	536.62	521.18	536.69
15	128.39	656.16	653.91	635.09	653.99
16	154.07	797.39	794.66	771.79	794.76
17	184.88	966.86	963.56	935.82	963.68
18	221.86	1170.24	1166.24	1132.67	1166.38
19	266.23	1414.28	1409.45	1368.88	1409.62
20	319.48	1707.14	1701.31	1652.33	1701.51
21	383.38	2058.57	2051.53	1992.48	2051.78
22	460.05	2480.28	2471.80	2400.66	2472.11
23	552.06	2986.34	2976.13	2890.47	2976.50
24	662.47	3593.61	3581.32	3478.24	3581.76
25	794.97	4322.33	4307.55	4183.56	4308.08
26	953.96	5196.79	5179.03	5029.96	5179.66
27	1144.75	6246.15	6224.80	6045.63	6225.56
28	1373.71	7505.38	7479.73	7264.43	7480.64

The alternative normalization in Table S16 multiplies each complete stored concentration field by the baseline-to-scenario emission-mass ratio over the final 72 h. This separate post-processing comparison rescales contributions released both before and during

the evaluation window, whereas the primary comparison retains the 96 h episode-mass control. Table 5 of the main text extends the comparison to exceedance area-time and J for all 13 scenarios and for the matched BK96 inputs.

Table S16. Alternative final-72 h emission-mass normalization of the stored fields.

Scenario	Final-72 h mass difference, 96 h control (%)	Primary mean change (%)	Alternative mean change (%)	Alternative maximum change (%)
MA2	−0.096	−0.94	−0.85	−2.71
MA3	+0.195	+0.27	+0.07	+0.34
MA4	+0.041	−0.52	−0.56	−2.55
MA6	+0.028	−0.08	−0.11	−0.93
MA12	−0.237	+1.60	+1.85	−7.69
MA24	−0.494	+8.69	+9.23	−21.02
MA48	−1.456	+8.67	+10.28	−24.82
BK6	+0.000	+1.44	+1.44	−2.61
BK12	+0.000	+8.33	+8.33	+4.03
BK24	+0.000	+9.11	+9.11	−25.18
Week	−4.277	+9.50	+14.39	−25.55
Month	−4.277	+11.86	+16.86	−21.91
Year	−4.277	+13.74	+18.82	−18.81

Both controls use the same stored GRAL fields and match the hourly baseline's emission mass over 96 h (primary) or the final 72 h (alternative). The alternative factors raise the Week, Month and Year rates to 7.464 kg h^{-1}, the rate at which the direct BK96 runs exceeded the rescaled fields by 0.11–0.18% (Section S14); these three rows were not run directly and may carry a departure of that size. At P99.9, not tabulated here, the area-time change reversed sign only for MA2 among the 13 scenarios: from −0.08% to +2.00%, under 1 km^2 h of the 22.46 km^2 h above the baseline P99.9.

S9. Nighttime Water-Stability Sensitivity

The stability sensitivity set comprised ten simulations, using seeds 1 and 2 for the hourly baseline, MA24 and Week under neutral nighttime water stability, and for BK96 under original and neutral treatments (Table S17). The neutral treatment assigned class 4 to all 13,596 meteorological cells with FW > 0.99 from 20:00 to 07:59. It retained the wind fields, land-cell classes and the water classes from 08:00 to 19:59. The neutral treatment includes 07:00, when parts of the water cells were already unstable under the original classes; it therefore tests the defined nighttime block rather than replacing stable classes alone.

The hourly baseline, MA24 and Week neutral runs share the wind realization of the main sea-breeze field. Their emission geometry, hourly activation series, grid and numerical settings match the corresponding original inputs. BK96 uses the episode-mean emissions at every source element and a second, separately generated wind realization. Its original and neutral runs share that realization. For BK96, the 96 h mass is already equal to the baseline; MA24 and Week retain post-processing factors of 1.003361 and 1.037448, respectively, applied once to the stored fields.

Each additional run supplies 108 hourly concentration outputs, including 12 h of spin-up. The final-72 h analysis uses the same fractional mainland mask of 1339 positive-area cells covering 314.5125 km^2. Release-group accounting found zero spin-up contribution in that window; Day 1 contributions remain included.

Table S18 compares MA24 and Week with the hourly baseline under the same stability treatment and particle seed. Each treatment's baseline percentiles are recomputed over the final 72 h, so these comparisons concern averaging within each treatment rather than exceedance of one fixed absolute concentration across treatments. For neutral seeds 1 and 2, P99 is 1.295609 and 1.296398 μg m^{-3}, and P99.9 is 2.226853 and 2.241264 μg m^{-3}. Classification uses unrounded values. The original Week configuration has one seed; its neutral configuration has two.

The night/day unit-mass response ratios in Table S19 use the same Days 2–3 release groups and final-72 h receiving window as Figure 6b. Each group is weighted by its emitted mass and has at least 24 h of follow-up. Table S20 compares the second seed with the first within each additional configuration, using that configuration's seed-1 percentiles. This differs from the common hourly-baseline thresholds used for the original MA24 seed pair in Table S13. The seed pairs describe repeatability under the tested settings.

Table S21 reports the paired stability effect within BK96 under the second realization. Common-threshold J compares neutral and original-stability BK96 fields using the same-seed original-stability BK96 percentile, while own-percentile J is computed with each field thresholded separately. The matched hourly–BK24–BK96 averaging comparison uses the wind realization of the main sea-breeze field and is reported separately in Section S10.

Table S17. Additional simulations and 96 h emission-mass control.

Input	Stability	Wind realization	Seeds	Input mass (kg)	Mass factor
Hourly	neutral	Main	1, 2	685.915	1.000000
MA24	neutral	Main	1, 2	683.617	1.003361
Week	neutral	Main	1, 2	661.156	1.037448
BK96	original	Second	1, 2	685.915	1.000000
BK96	neutral	Second	1, 2	685.915	1.000000

Main denotes the wind realization of the main sea-breeze field; Second denotes the separately generated realization used by both BK96 treatments. Each row represents two runs, giving ten additional simulations. Mass factor is the original hourly baseline mass divided by the input mass, applied once to the stored concentrations. Original retains the GRAMM stability classes; neutral sets the specified nighttime water cells to class 4.

Table S18. Averaging effects over the final 72 h under the original and neutral nighttime water-stability treatments.

Input / seed	Stability	Mean change (%)	Max. change (%)	P99 area-time change (%)	J (P99)	J (P99.9)
MA24 / 1	original	+8.69	−21.41	+41.69	0.465	0.217
MA24 / 2	original	+8.69	−19.80	+42.58	0.460	0.216
Week / 1	original	+9.50	−28.74	+27.89	0.308	0.101
MA24 / 1	neutral	+6.35	−28.41	+9.84	0.578	0.488
MA24 / 2	neutral	+6.35	−28.74	+8.74	0.578	0.494
Week / 1	neutral	+8.38	−35.89	+1.51	0.361	0.279
Week / 2	neutral	+8.40	−36.00	+1.31	0.361	0.270

Each row compares an averaged input with the hourly baseline under the same wind realization, stability treatment and seed. All fields retain equal 96 h episode emission mass. Thresholds are the corresponding hourly baseline percentiles. The original Week configuration has only seed 1.

Table S19. Night/day unit-mass response ratios for Days 2–3 releases and retained Day 1 contributions to the final-72 h land mean.

Input / stability	Seed	Night/day ratio; day 08–19	Night/day ratio; day 05–19	Day 1 contribution (%)
Hourly / original	1	8.154	6.525	6.73
Hourly / original	2	8.156	6.527	6.73
Hourly / neutral	1	7.626	5.749	5.19
Hourly / neutral	2	7.625	5.750	5.19
MA24 / original	1	7.506	5.822	5.40
MA24 / original	2	7.508	5.823	5.41
MA24 / neutral	1	6.576	4.868	4.26
MA24 / neutral	2	6.576	4.867	4.27
Week / original	1	7.205	5.526	5.72
Week / neutral	1	6.422	4.733	4.27
Week / neutral	2	6.422	4.734	4.28
BK96 / original	1	7.517	5.723	5.93
BK96 / original	2	7.516	5.724	5.94
BK96 / neutral	1	6.610	4.830	4.38
BK96 / neutral	2	6.607	4.828	4.38

Day 08–19 denotes 08:00–19:59; day 05–19 denotes 05:00–19:59. Night is the complement of the stated daytime interval. Ratios use emission-mass-weighted responses integrated over the final 72 h. Every included release has at least 24 h of follow-up. Day 1 contributions remain in the concentration metrics; spin-up contributions are zero. BK96 values belong to the second realization.

Table S20. Repeatability of the five additional configurations: seed 2 relative to seed 1 over the final 72 h.

Input / stability	Mean change (%)	Max. change (%)	J (P95)	J (P99)	J (P99.9)
BK96 / original	−0.016	+0.338	0.961	0.933	0.914
BK96 / neutral	−0.001	+0.229	0.958	0.946	0.893
Hourly / neutral	−0.030	+0.037	0.962	0.959	0.957
MA24 / neutral	−0.032	−0.419	0.956	0.935	0.963
Week / neutral	−0.013	−0.125	0.952	0.923	0.947

Thresholds are the seed-1 percentiles of the corresponding input and stability configuration. Table S13 instead uses the original hourly baseline thresholds for its MA24 seed pair.

Table S21. Paired BK96 stability response under the second realization.

Metric	Seed 1	Seed 2
Original mean (μg m^{-3})	0.219288	0.219253
Neutral mean (μg m^{-3})	0.189994	0.189992
Mean change (%)	−13.36	−13.35
Original maximum (μg m^{-3})	3.046	3.056
Neutral maximum (μg m^{-3})	3.327	3.335
Maximum change (%)	+9.25	+9.13
Original P99 (μg m^{-3})	1.520363	1.517313
Neutral area-time above original P99 (km^2 h)	84.928	87.582
P99 area-time change (%)	−62.49	−61.29
J at common original P99	0.164	0.168
J at each field's own P99	0.248	0.250

Both treatments use the same constant episode-mean source map, total emission mass and wind realization. Changes compare neutral with original stability. Common-threshold quantities use the corresponding original-stability BK96 percentile; own-percentile J is computed with each field thresholded at its own percentile. The hourly and BK24 controls in the original comparison use a different wind realization. Section S10 provides the matched comparison under the wind realization of the main sea-breeze field.

S10. Matched Hourly, Daily-Mean and Episode-Mean Comparisons

The matched design combines three inputs (hourly, BK24 and BK96), two nighttime water-stability treatments (original and neutral) and two particle seeds, giving 12 combinations. All combinations share the wind fields of the main sea-breeze field, source geometry, particle release rate of 8000 particles s^{-1}, 108 h duration, fractional mainland mask and final-72 h evaluation. The neutral treatment is defined in Section S9.

Table S22 gives the emission-mass controls. All three inputs emit 685.914848 kg over the 96 h episode. The hourly and BK24 inputs emit 537.423844 kg during the final 72 h, whereas BK96 emits 514.436136 kg, 4.2774% less. The primary comparison uses a mass factor of one. All earlier-release contributions that reach the final 72 h remain in the concentration fields. Spin-up contributions are zero, and Day 1 contributes 3.93–6.73% of the final-72 h land mean across these combinations.

Each averaging comparison in Table S23 uses the hourly baseline with the same stability treatment and particle seed. The corresponding baseline percentiles are recomputed for each comparison and applied to both fields. Changes in exceedance area-time therefore measure averaging effects within a treatment. Thresholding each field at its own P99 gives a BK24 J of 0.436–0.441 under original stability and 0.506–0.507 under neutral stability; the corresponding BK96 values are 0.327–0.331 and 0.413–0.416. Overlap thus remains low even when exceedance area-times are approximately equal.

Table S24 compares seed 2 with seed 1 within each input and stability configuration, using that configuration's seed-1 percentiles. These pairs describe particle-seed repeatability. Table S25 instead compares neutral with original stability within the same input and seed, using the original-treatment percentile for common-threshold metrics. Its own-percentile J is computed with each field thresholded separately. These stability comparisons have a different reference from the averaging comparisons in Table S23.

For the alternative mass control in Table S26, BK96 emission rates are multiplied by 1.044685 throughout the input to match the hourly input's final-72 h emission mass, and the values come from direct simulations (Section S14). This scaling also raises releases before the evaluation window. Under neutral stability and the alternative control, the BK96 P99 area-time is approximately equal to that of the hourly baseline (+0.89% to +1.16%, about 2.0–2.6 km² h), compared with −16.03% to −15.27% under the primary control. Its P99 J is 0.412–0.421 under the alternative, and its maximum remains 39.68–40.10% below the hourly baseline. The negative primary P99 area-time response therefore depends on the mass-control window, whereas the neutral P99.9 response stays negative under both controls. Low overlap and reduced maxima also persist. Under original stability, the BK96 P99.9 area-time responses of +1.22% and −6.28% (seeds 1 and 2) under the primary control become +26.58% and +25.30% under the alternative, in a reference set of 101 cell-hours. BK24 needs no additional scaling.

Table S27 lists these Day 1 contributions and uses Days 2–3 releases for the night/day unit-mass response ratios; each release has at least 24 h of follow-up within the evaluation window. Table S28 applies the symmetric timing–map decomposition of Equation (4) to every release group contributing within that window. Its one-sided alternatives use each input's response or mass in turn. The terms account exactly for the simulated land-mean difference, including the allocation of emission mass across the evaluation-window boundary.

Table S22. Matched comparison design and emitted mass.

Input	Stability	Seeds	96 h mass (kg)	72 h mass (kg)	96 h factor
Hourly	original	1, 2	685.915	537.424	1.000000
Hourly	neutral	1, 2	685.915	537.424	1.000000
BK24	original	1, 2	685.915	537.424	1.000000
BK24	neutral	1, 2	685.915	537.424	1.000000
BK96	original	1, 2	685.915	514.436	1.000000
BK96	neutral	1, 2	685.915	514.436	1.000000

All 12 combinations use the wind realization of the main sea-breeze field. Original retains the GRAMM stability classes; neutral applies class 4 over water during 20:00–07:59. The 96 h factor is the baseline-to-input episode-mass ratio.

Table S23. Matched averaging effects over the final 72 h.

Input / seed	Stability	Mean change (%)	Max. change (%)	NMAE (%)	P99 area-time change (%)	J (P99)	J (P99.9)
BK24 / 1	original	+9.11	−25.18	25.72	+43.67	0.412	0.194
BK24 / 2	original	+9.13	−24.44	25.71	+44.05	0.412	0.181
BK24 / 1	neutral	+6.73	−33.19	24.33	+8.37	0.500	0.421
BK24 / 2	neutral	+6.74	−33.15	24.30	+7.78	0.498	0.419
BK96 / 1	original	+6.10	−28.70	26.08	+18.47	0.330	0.081
BK96 / 2	original	+6.12	−27.88	26.08	+16.98	0.330	0.077
BK96 / 1	neutral	+3.89	−42.28	24.67	−16.03	0.391	0.276
BK96 / 2	neutral	+3.91	−42.71	24.64	−15.27	0.400	0.264

BK24 and BK96 use the hourly baseline with matching winds, stability treatment and seed. NMAE is the concentration normalized mean absolute error. P99 and P99.9 are the baseline area-time-weighted percentiles. All fields retain equal 96 h episode mass.

Table S24. Particle-seed repeatability in the six matched configurations.

Input / stability	Mean change (%)	Max. change (%)	NMAE (%)	J (P99)	J (P99.9)
Hourly / original	−0.015	+0.138	2.260	0.951	0.927
Hourly / neutral	−0.030	+0.037	2.418	0.959	0.957
BK24 / original	+0.001	+1.121	2.384	0.936	0.921
BK24 / neutral	−0.022	+0.103	2.581	0.948	0.960
BK96 / original	+0.005	+1.292	2.381	0.942	0.952
BK96 / neutral	−0.009	−0.705	2.576	0.943	0.920

Seed 2 changes are relative to seed 1 for the same input and stability treatment. J uses the seed-1 percentiles.

Table S25. Paired stability response under the same main sea-breeze winds.

Input / seed	Mean change (%)	Max. change (%)	P99 area-time change (%)	Common P99 J	Own P99 J
Hourly / 1	−11.13	+29.77	−33.69	0.357	0.381
Hourly / 2	−11.14	+29.64	−34.21	0.354	0.375
BK24 / 1	−13.06	+15.87	−55.97	0.199	0.278
BK24 / 2	−13.08	+14.70	−55.95	0.199	0.279
BK96 / 1	−12.98	+5.06	−61.33	0.172	0.250
BK96 / 2	−12.99	+2.99	−60.50	0.175	0.251

Changes compare neutral with original stability at the same input and seed. Common-threshold metrics use the original P99. Own P99 J uses each field's P99. Table S23 compares averaging effects.

Table S26. Sensitivity to the emission-mass control window.

Input / seed	Stability	Mean: primary (%)	Mean: alternative (%)	P99 area-time: primary (%)	P99 area-time: alternative (%)	P99.9 area-time: primary (%)	P99.9 area-time: alternative (%)	Alternative P99 J
BK24 / 1	original	+9.11	+9.11	+43.67	+43.67	+62.34	+62.34	0.412
BK24 / 2	original	+9.13	+9.13	+44.05	+44.05	+58.65	+58.65	0.412
BK24 / 1	neutral	+6.73	+6.73	+8.37	+8.37	−26.87	−26.87	0.500
BK24 / 2	neutral	+6.74	+6.74	+7.78	+7.78	−24.21	−24.21	0.498
BK96 / 1	original	+6.10	+10.97	+18.47	+34.96	+1.22	+26.58	0.332
BK96 / 2	original	+6.12	+10.99	+16.98	+33.18	−6.28	+25.30	0.330
BK96 / 1	neutral	+3.89	+8.72	−16.03	+1.16	−59.59	−48.98	0.421
BK96 / 2	neutral	+3.91	+8.75	−15.27	+0.89	−60.99	−50.51	0.412

The primary control matches 96 h mass. The alternative matches final-72 h mass by applying a factor of 1.044685 to all BK96 emission rates in direct simulations (Section S14). BK24 keeps a factor of one. Each hourly reference matches stability and seed. Both controls include contributions from earlier releases. The P99.9 reference sets contain 101 (original) and 112 (neutral) cell-hours, so small changes in percentage represent few cell-hours.

Table S27. Night/day unit-mass response ratios and retained Day 1 contributions for the matched inputs.

Input / stability	Seed	Night/day; day 08–19	Night/day; day 05–19	Day 1 contribution (%)
Hourly / original	1	8.154	6.525	6.730
Hourly / original	2	8.156	6.527	6.727
Hourly / neutral	1	7.626	5.749	5.188
Hourly / neutral	2	7.625	5.750	5.193
BK24 / original	1	7.590	5.799	5.095
BK24 / original	2	7.591	5.800	5.106
BK24 / neutral	1	6.656	4.853	3.925
BK24 / neutral	2	6.656	4.852	3.933
BK96 / original	1	7.418	5.683	5.875

Input / stability	Seed	Night/day; day 08–19	Night/day; day 05–19	Day 1 contribution (%)
BK96 / original	2	7.420	5.683	5.881
BK96 / neutral	1	6.551	4.807	4.350
BK96 / neutral	2	6.552	4.807	4.358

Ratios use emission-mass-weighted responses of Days 2–3 releases over the final 72 h. Daytime is 08:00–19:59 or 05:00–19:59, with night as the complement. Each included release has at least 24 h of follow-up. Day 1 contribution is the share of the final 72 h land mean attributable to Day 1 releases. All concentration metrics include those releases. Spin-up contributions are zero.

Table S28. Symmetric timing–map decomposition of matched land-mean differences.

Input / seed	Stability	Timing term (pp)	Map term (pp)	Total (%)	Map one-sided range (pp)
BK24 / 1	original	+15.42	−6.32	+9.11	−7.12 to −5.51
BK24 / 2	original	+15.42	−6.30	+9.13	−7.10 to −5.49
BK24 / 1	neutral	+15.55	−8.82	+6.73	−10.13 to −7.51
BK24 / 2	neutral	+15.55	−8.81	+6.74	−10.12 to −7.50
BK96 / 1	original	+11.61	−5.51	+6.10	−6.15 to −4.87
BK96 / 2	original	+11.61	−5.49	+6.12	−6.12 to −4.85
BK96 / 1	neutral	+11.56	−7.67	+3.89	−8.74 to −6.60
BK96 / 2	neutral	+11.56	−7.65	+3.91	−8.71 to −6.58

Terms are percentage points of the hourly reference land mean for the same stability and seed. The decomposition uses all contributing releases and equal 96 h episode mass. The unrounded terms sum to the total.

S11. Emission Distribution by Operating Mode

Figure S5 separates the final-72 h mean hourly baseline emissions of Figure 1b by operating mode. The 500 m grid covers the whole GRAL domain (9348 cells), but only cells along the AIS-recorded tracks of the inventory vessels carry emissions: 1076 cells (11.5%) in the model input over Days 2–4, of which 75 held half and 406 held 90% of the mass. Cruising emissions (38% of the final-72 h mass) lie along the fairways, maneuvering emissions (10%) along the port approaches, anchoring emissions (13%) in the anchorages and hoteling emissions (38%) at the berths. For this figure, each inventory-cell center was assigned to the 500 m GRAL cell that contains it, and the main-engine, auxiliary-engine and boiler emissions were summed per mode; the model input instead divides each inventory cell among 200 m source elements (Section S1). The center-assigned final-72 h mass was 1.000 times the model-input mass, and the two hourly series had a Pearson correlation of 1.000.

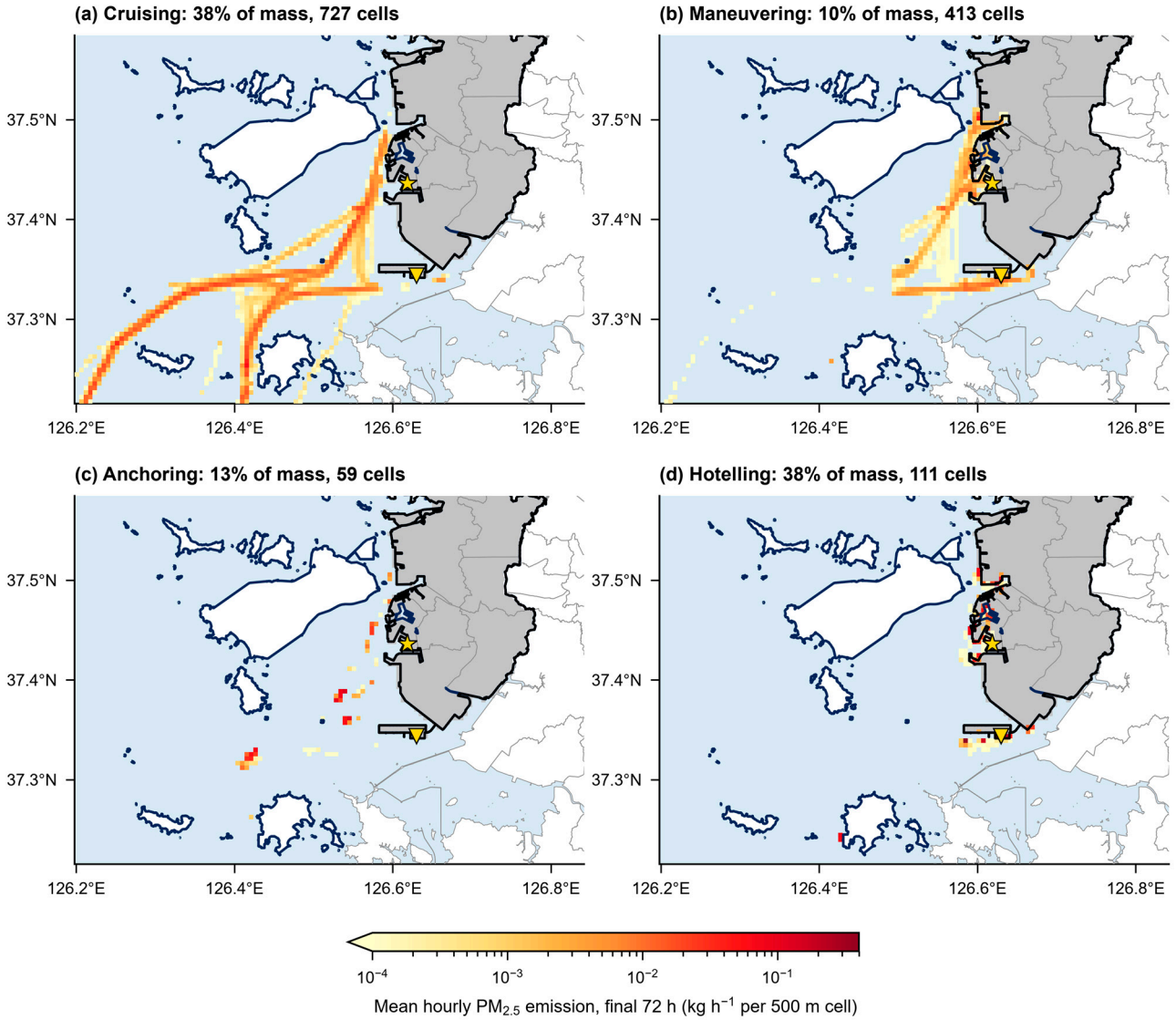

Figure S5. Final-72 h mean hourly baseline $PM_{2.5}$ emissions per 500 m cell by operating mode. The black outline encloses the shaded mainland analysis area. Dark blue lines mark the Incheon city boundary and thin gray lines mark administrative boundaries. The star marks the centroid of the Port of Incheon's port areas and the triangle marks Incheon New Port. Where only the base map is visible, no emissions were assigned to that mode. Maps assign each inventory-cell center to its 500 m cell. Cells can carry more than one mode, so the counts are not additive and differ from the 1076 cells of the model input.

S12. Optimized-Build Sea-Breeze Field and Numerical Sensitivities

The optimized-build sea-breeze field in Section 3.7 used the same model, grid, terrain, land cover, calm background, numerical settings and initial inputs as the main sea-breeze field (Tables S4 and S29). It was integrated for 120 h with a performance-optimized build of the same modified GRAMM, and the third model day (model hours 42–66) supplied the repeated forcing. This field is distinct from the second, separately generated wind realization of Section S9. Its MA24 land-mean change, night/day response ratio, timing and map terms, NMAE and J were similar to those of the main sea-breeze field (Tables 6 and S30), whereas its maximum change (−26.8% versus −21.4%) and P99 area-time change (+46.1% versus +41.7%) differed by 5.4 and 4.4 percentage points. Build, integration length and realization changed together, so the comparison does not isolate the source of these two differences. GRAL settings, emission inputs, particle seed 1, the 108 h

simulation and the final-72 h mainland evaluation are those of the main analysis. Section S16 reports BK96, MA6, FMHT and HMCT on this field. MA24 retains its 96 h emission-mass factor (1.003361). Using the main sea-breeze field's percentiles for both fields, the baselines of the main and optimized-build sea-breeze fields gave J values of 0.864 (P99) and 0.798 (P99.9), with an NMAE of 5.0%. This comparison measures variation in the exceedance set between the two integrations; the optimized-build sea-breeze field has no comparison with a second particle seed.

At night, 100% of the emissions was released under onshore flow at 36 m in the optimized-build sea-breeze field, and stability class 7 applied to 70% of the night emissions (class 6: 9%). Over the Days 2–3 releases, the night and day unit-mass responses were 0.0553 and 0.0068 μg m^{-3} h kg^{-1}. Day-to-day repeatability was measured as the mean over 24 h of the hourly root-mean-square difference of the 10 m wind vector between consecutive 24 h blocks (model hours 48–72 and 72–96, starting at 06:00), over cells outside the lateral relaxation zones. It was 0.14 m s^{-1} over water and 0.35 m s^{-1} over land in the optimized-build sea-breeze field.

Table S30 lists the comparisons for the main and optimized-build sea-breeze fields, using each field's own baseline percentiles. It also gives the effect of repeating the fourth model day instead of the third for the optimized-build sea-breeze field. Rerunning GRAL on the main sea-breeze field reproduced the MA24 row of Table 3. Table S30 also holds three sensitivity pairs on the main sea-breeze field, with the hourly and MA24 inputs, particle seed 1 and the 96 h emission-mass control. The first uses a 250 m flow and concentration grid (228 × 164 cells) with the same source elements. The second assigns class 4 to water cells from 08:00 to 19:59, the complement of the nighttime treatment of Section S9, and retains the wind fields. For these first two pairs, the night/day response ratios were 7.79 and 5.37 (8.15 in the main simulations), their timing/map terms +15.0/−6.0 and +13.5/−5.8 percentage points, and their P99.9 area-time changes +12.9% and +3.9% (+64.6% in Table S7). Relative to the main baseline, the hourly baseline land mean changed by −5.5% and +10.2% and the maximum by +29.2% (−3.1% when the 250 m field is aggregated to 500 m) and +49.4%. At the main P99 and P99.9, the 250 m baseline aggregated to 500 m overlapped the main baseline with J values of 0.704 and 0.682, and the daytime-water baseline with 0.835 and 0.645. With class 4 over daytime water, the night share of baseline P99 area-time fell from 94.0% to 77.7%.

The third pair uses the forcing of the main sea-breeze field and a 500 m grid with the adaptive particle time step constrained to 0.1–4 s. This is a bound on the adaptive step, not a fixed 4 s step or a time-step convergence sequence. The ordinary and clamp-enabled cases used seed 1, 8000 particles s^{-1} and the same 108 h duration, with MA24 multiplied by its 96 h mass factor (1.003361) before the final-72 h metrics were calculated. A comparison of the retained case records found matching hashes for 14 input and configuration files, the same application identifier in all four logs, and matching GRAL configuration fields apart from the step bound. External wind-file hashes and a complete executable-to-source linkage were not re-established in this check.

Recalculation of the retained concentration arrays gave a clamp-enabled hourly baseline land mean of 0.1504 μg m^{-3}, 26.94% below the main baseline of 0.2058 μg m^{-3}. Relative to its own hourly baseline, clamp-enabled MA24 changed the land mean by +9.30%, the maximum by −35.17%, P99 area-time by +19.01% and P99.9 area-time by −19.90%; J was 0.533 at P99 and 0.302 at P99.9 (Table S30). The corresponding main P99.9 area-time change was +64.62%. Thus, the positive mean response persisted while the extreme-tail area-time response changed sign. These results describe the sensitivity to the adaptive-step bound; they do not identify either setting as converged or more accurate. This recalculation used stored arrays without rerunning the model or independently decoding every original concentration file.

Table S29. GRAMM settings and release-height winds of the main and optimized-build sea-breeze fields.

Circulation	Solar date	Water (°C)	Initial state (06:00 KST mean, Incheon station)	Integration	Realizations	Night eastward wind at 36 m (m s^{-1})	Day eastward wind at 36 m (m s^{-1})
Main sea-breeze field	18 June	19.6	18–21 June 2024: air 21.4 °C, RH 83%, surface 20.5 °C, soil 21.4 °C	72 h	1	–	–
Optimized-build sea-breeze field	18 June	19.6	As for the main sea-breeze field	120 h	1	+1.6	+3.8

Mean eastward winds use instantaneous hourly fields of the repeated day, weighted by final-72 h baseline emissions. Night is 20:00–07:59 and day 08:00–19:59. Positive values are onshore. A dash indicates no calculation. Section S4 describes the main field's nighttime release-height wind. RH is relative humidity. Soil refers to 1 m depth. Other settings follow Table S4.

Table S30. MA24 effects relative to the matched hourly baseline under the main and optimized-build sea-breeze fields and in three June sensitivity pairs (final 72 h, seed 1).

Circulation	Repeated model day	Baseline land mean (μg m^{-3})	Baseline P99 / P99.9 (μg m^{-3})	Mean change (%)	Max. change (%)	NMAE (%)	P99 area-time change (%)	J (P99)	J (P99.9)
Main sea-breeze field	3	0.206	1.447 / 2.319	+8.7	−21.4	20.7	+41.7	0.465	0.217
Main sea-breeze field, 250 m grid	3	0.194	1.490 / 2.512	+9.1	−26.4	21.9	+30.2	0.505	0.254
Main sea-breeze field, class 4 over daytime water	3	0.227	1.521 / 2.556	+7.7	−26.1	20.5	+40.7	0.482	0.273
Main sea-breeze field, adaptive step 0.1–4 s	3	0.150	1.143 / 1.954	+9.3	−35.2	22.9	+19.0	0.533	0.302
Optimized-build sea-breeze field	3	0.205	1.444 / 2.354	+8.8	−26.8	20.7	+46.1	0.469	0.218
Optimized-build sea-breeze field	4	0.202	1.402 / 2.178	+9.1	−10.6	21.1	+48.2	0.443	0.175

Unlabeled day-3 rows repeat Table 6 of the main text. Section S12 describes the sensitivity pairs and the day-4 comparison. The 0.1–4 s bound on the adaptive particle time step gives a P99.9 area-time change of −19.90% (+64.62% in the main calculation). Each row uses its own hourly baseline for thresholds and concentration NMAE.

S13. Computational Procedures and GRAL Control Settings

The reported metrics are derived from the stored hourly concentration fields by the steps below; Tables 1, S4, S15 and S31 list the settings of the model runs. Hit rate, false-alarm ratio, footprint and timing diagnostics are defined in Section S6.

(1) Emission input. Inventory cells with centers outside the union of the VTS polygons are excluded. Each remaining hourly inventory cell is divided equally among 200 m × 200 m source elements, elements not entirely inside the GRAL domain are discarded (Section S1), and each averaged scenario is formed with Equation (2) of the main text, the midnight-aligned block means or the long-term means (Section S3). Contributions to the concentration fields are stored separately for each release hour.

(2) Meteorology. The 24 hourly intervals of the GRAMM fields of model hours 42–66 are repeated by clock hour for the 12 h spin-up and the 96 h episode. Each GRAL hour receives the mean of the wind fields at its start and end and the stability class at its start (Sections S4 and S7).

(3) Mass normalization. For scenario s, the factor $k_s = \sum_t E_1(t) / \sum_t E_s(t)$ is formed over the hours of the 96 h episode (primary) or of Days 2–4 (alternative), where $E(t) = \sum_i E(t,i)$ is the in-domain emissions of hour t and subscript 1 denotes the hourly baseline. Except for the direct BK96 runs under the alternative control (Section S14), all 108 stored hourly concentration fields of the scenario are multiplied by k_s (Table S3).

(4) Land weights. The mainland analysis area is derived from province and municipal administrative boundary layers. Cells of Incheon with at least 20% administrative land are reduced to the connected mainland, which excludes the islands, and each retained 500 m cell, i, receives the area, A_i, of its part inside the Incheon boundary, computed on a 50 m sub-grid (1339 cells with $A_i > 0$, 314.5 km² in total). The land mean is $\sum_t \sum_i A_i C(t,i) / (T \sum_i A_i)$ over the $T = 72$ evaluation hours, and the maximum is the largest $C(t,i)$ with $A_i > 0$.

(5) Thresholds. All cell-hours with $A_i > 0$ in the baseline field are sorted by concentration; the P95, P99 or P99.9 threshold is the lowest concentration at which the cumulative area-time reaches 95%, 99% or 99.9% of the total (Section S6). Exceedance is strict.

(6) Overlap and errors. Exceedance area-time is $\sum_t \sum_i A_i I[C(t,i) > q]$; J follows Equation (3) of the main text, with the baseline threshold applied to both fields, or with each field cut at its own percentile for the own-percentile variant. The concentration NMAE follows Equation (S1).

(7) Release-hour accounting. For each release hour, h, the land-mean contribution of its stored field is summed over the 72 evaluation hours and divided by its emitted mass to give d_h. The night/day response ratio divides the mass-weighted mean, d_h, of night releases on Days 2–3 by that of daytime releases. Equation (4) of the main text and its two one-sided splits use all release hours, with each release-hour mass including the normalization factor of step (3), so the timing and map terms sum to the change in the normalized land mean.

(8) Emission diagnostics. $M(t)$ follows Equation (1) of the main text on the 500 m grid; the emission NMAE sums the absolute difference between scenario and baseline over source elements and hours and divides it by the baseline mass (Section 2.3 of the main text). Table S32 gives the hourly in-domain baseline emissions that enter steps (3) and (7).

Table S31. GRAL control settings of the main simulations.

Setting	Value
Particles released	8000 per second (28.8 million per hour)
Dispersion time per hour	3600 s
Mode	Transient; end-of-hour three-dimensional concentration field carried to the next hour
Transient concentration threshold	0.001 μg m^{-3}
Meteorological input	GRAMM wind and stability fields; 24 situations mapped to the 108 simulated hours
Latitude of the domain center	37.40° N
Wind meandering	On
Buildings	None (no building or prognostic sub-domain calculation)
Roughness length	Per cell from the GRAMM land-use file; adaptive roughness off
Flow-field grid	500 m × 500 m; lowest cell: 2 m, vertical stretching factor: 1.01
Concentration grid	114 × 82 cells of 500 m; nine 4 m slices centered at 2, 6, 10, 15, 20, 30, 50, 75 and 100 m
Domain (EPSG:5181)	129,000–186,000 m east, 413,000–454,000 m north
Pollutant	$PM_{2.5}$; no dry or wet deposition, no decay
Particle seeds	Reproducible-results option on; seed 1 for all scenarios, seed 2 for the repeat runs
Output	Hourly concentration fields of every slice; contributions stored by release hour

Settings come from in.dat, GRAL.geb, Pollutant.txt and the transient threshold file. Other runs varied only emission input or seed, water-cell stability (Sections S9 and S12), the GRAMM field (Sections S9, S12 and S16), or the emission week (Section S16). The first and third sensitivity pairs in Section S12 also tested grid spacing and the adaptive particle time-step bound, respectively.

Table S32. Hourly in-domain $PM_{2.5}$ emissions in the baseline (kg h^{-1}).

Hour (KST)	Day 1 (18 June)	Day 2 (19 June)	Day 3 (20 June)	Day 4 (21 June)
00:00	4.669	5.851	5.767	6.217
01:00	4.770	6.094	5.305	5.934
02:00	3.545	6.621	5.383	6.630
03:00	2.681	5.164	6.664	5.827

Hour (KST)	Day 1 (18 June)	Day 2 (19 June)	Day 3 (20 June)	Day 4 (21 June)
04:00	3.966	6.760	6.062	5.425
05:00	5.473	6.198	4.725	6.110
06:00	6.655	5.904	5.749	7.029
07:00	7.342	6.159	5.866	6.202
08:00	7.758	8.261	5.663	8.244
09:00	9.893	6.061	6.625	5.909
10:00	8.352	9.034	11.014	7.631
11:00	5.414	14.261	7.653	8.902
12:00	8.373	7.871	7.326	10.468
13:00	7.033	9.617	8.157	7.991
14:00	5.216	8.425	10.582	10.293
15:00	6.487	8.806	15.133	7.843
16:00	7.192	8.775	13.173	5.665
17:00	5.540	6.592	9.146	6.009
18:00	7.187	6.556	9.393	7.628
19:00	6.527	8.271	13.312	8.748
20:00	4.262	7.137	7.850	6.770
21:00	5.036	6.097	7.684	5.841
22:00	5.926	5.172	6.465	6.315
23:00	9.190	5.857	5.362	8.189
Total (kg per day)	148.49	175.54	190.06	171.82

For the vessels in the inventory, in-domain emissions total 685.9 kg over 96 h, including 537.4 kg on Days 2–4. The 12 h spin-up (17 June, 12:00–23:00) emitted 77.3 kg.

S14. Direct Mass-Scaling Tests

S14.1. Design and Run Integrity

The cases, tolerances and reporting rules of the direct tests were specified before their results were examined. The tests comprised two unscaled repeat runs, four BK96 integrations at factor 1.0446852500896402 (original and neutral stability, seeds 1 and 2) and one Year integration at factor 1.2597859531546884 (original stability, seed 1), all under the wind realization of the main sea-breeze field (Section S9). The factors were applied to the emission inputs throughout the simulation, and each direct field was compared with the same-seed field multiplied after calculation. All seven runs completed their 108 hourly fields, and re-analysis of the 756 stored fields reproduced the results reported for each run. The comparison addresses the scaling implementation; it neither selects a mass-control window nor estimates independent particle uncertainty.

S14.2. Observed Departures

The BK96 land-mean differences (Table S33) were +0.1136 to +0.1766%, exceeding the 0.1% tolerance and the +0.003 to +0.04% expected before the runs, so the BK96 alternative-control rows in Tables 5 and S26 use the direct results. The Year difference was +0.02425%, within the tolerance, so the Year row of Table 3 uses the rescaled fields. Table S34 lists the direct and rescaled effects. Two unscaled repeat runs reproduced their references. Because the mean departures exceeded the difference between seeds 1 and 2 in the same effect, particle-seed repeatability does not bound the numerical uncertainty of these comparisons.

Table S33. Differences between direct and rescaled fields and tolerance outcomes.

Case	Factor	Mean bias (%)	NMAE (%)	Max. error (%)	ΔP99 effect (pp)	Outcome
Unscaled repeat, original, seed 1	1.000000	+0.000000	0.000000	0.000000	+0.0000	Reproduced
Unscaled repeat, neutral, seed 1	1.000000	+0.000002	0.000069	0.000000	+0.0000	Reproduced
BK96, original, seed 1	1.044685	+0.113699	0.123475	0.022142	+0.2208	Above tolerance
BK96, original, seed 2	1.044685	+0.113618	0.123516	0.006286	−0.1104	Above tolerance
BK96, neutral, seed 1	1.044685	+0.176614	0.187492	0.030621	+0.2210	Above tolerance
BK96, neutral, seed 2	1.044685	+0.176413	0.187168	0.076552	+0.1867	Above tolerance
Year, original, seed 1	1.259786	+0.024248	0.037802	0.048685	−0.0729	Within tolerance

Bias is direct minus rescaled, divided by the rescaled mean. The land-mean bias tolerance was 0.1%. NMAE also uses the rescaled mean. Maximum error uses the rescaled maximum. ΔP99 is the difference in direct and rescaled area-time effects against the matched hourly reference.

Table S34. Direct and rescaled effects relative to the matched hourly reference.

Case	Mean, direct (%)	Mean, rescaled (%)	Maximum, direct (%)	P99 area-time, direct (%)	P99 area-time, rescaled (%)	J (P99), direct	J (P99), rescaled	J (P99.9), direct
BK96, original, seed 1	+10.967	+10.841	−25.497	+34.956	+34.74	0.3321	0.3325	0.0920
BK96, original, seed 2	+10.990	+10.864	−24.650	+33.185	+33.30	0.3295	0.3293	0.0959
BK96, neutral, seed 1	+8.722	+8.530	−39.681	+1.159	+0.94	0.4213	0.4208	0.3057
BK96, neutral, seed 2	+8.745	+8.554	−40.101	+0.890	+0.70	0.4116	0.4121	0.3114
Year, original, seed 1	+13.770	+13.742	−22.321	+49.961	+50.03	0.3045	0.3048	0.1589

Rescaling multiplies the stored field after calculation. BK96 uses the final-72 h mass factor and Year the 96 h factor. Direct tests omitted the Year 72 h factor and the Week and Month factors in Table S16. Uniform rescaling preserves own-percentile J, which can change in a new integration. Near a percentile, small area-time changes reflect discrete cell-hour changes, so their sign alone can be misleading.

S14.3. Source of the Departures

Source-group budgets show where the difference arises. Each source group is one release hour. Material in its release hour matched the factor to within 3×10^{-9} in the domain sum, and the emission inputs matched it to within 1×10^{-12}, so the emitted mass was delivered as specified. All of the mean departure came from re-released material. For groups released at 18:00–06:00, the difference between the direct and rescaled domain sums over the layers up to 100 m grew from +0.05–0.10% at age 1 h to about +12% at 13 h under BK96, and from +0.03 to +1.1% under Year. These groups supplied 92–94% of the BK96 bias and 72% of the Year bias. The departure was steady across Days 2–4 and was largest at low concentrations: 07:00–13:00 held 26–27% of the land mean and 73–78% of the BK96 bias, and BK96 cell-hours above the P99 threshold differed by 0.02–0.08%.

The threshold test acts per source group and per cell on particles of nearly equal mass: 99.8% of freshly released particles lie within 0.5% of the mean. Re-released material is split so that every particle stays below 10 times the mean mass of the particles being released in the same hour, which equals the group's own mean for constant-rate inputs, and particles re-released for the first time average about 9.8 times that mean (an upper-bound estimate). In the transient layers above 256 m, which are 20 m and 30 m thick, two and three such particles, respectively, reach 0.001 μg m^{-3} only when the mean mass exceeds about 250–255 μg. At 8000 particles s^{-1} over 1 h, this mean mass corresponds to an emission rate of at least 7.20 kg h^{-1}, about 7.35 kg h^{-1} for the observed re-released particle masses. The mean particle mass of BK96 moves from 248.1 to 259.2 μg across this value. That of Year moves from 196.9 to 248.1 μg and stays below this step, although it crosses smaller particle-count steps in the lowest layers, whose contribution was not separated. In the paired same-seed runs, survival of 32 night-released groups from 10:00 to 12:00 was 13.7% higher at 7.464 than at 7.145 kg h^{-1} (30 of 32 positive) and unchanged between 5.672

and 7.145 kg h⁻¹ (ratio: 1.000, s.d.: 0.2%). The other scenario runs show a rise of the same sign: survival of night-released groups from 10:00 to 12:00 was 17–19% higher between 7.35 and 8.4 kg h⁻¹ than below 7.17 kg h⁻¹, with no rise of comparable size at lower rates. The expectation stated before the runs treated the threshold as a continuous cut, whereas particle counts in each cell make the response stepped. The stepped response accounts for the ordering of BK96 and Year. It does not predict the size of either bias, and the contributions of the threshold and of domain export to the loss of old groups were not separated. The direct values include this discretization, so they measure the response of GRAL to scaling and do not provide a more exact tracer field. The same discretization enters differences between the hourly and averaged inputs; its size there was not quantified. Material released in the same hour supplied 2.5–11.0% of the baseline 2 m land mean in each clock hour from 00:00 to 07:59 and 7.3% over the night (20:00–07:59), so most of the night concentration passed through the re-release step.

Week and Month were not run directly, and their primary rows may carry an error of the same sign. Their 96 h factors raise the rate from 6.887 and 5.886 kg h⁻¹ to 7.145 kg h⁻¹, which stays below the step, so we expect departures of the order of the Year departure or smaller, based on one Year case (original stability, seed 1). The BK96 neutral departure was 1.55 times its original-stability value, so a neutral rerun could be larger. The 72 h factors in Tables 5 and S16 raise Week, Month and Year to 7.464 kg h⁻¹, across the step, so those rescaled values may carry a departure of BK96 size.

S15. Observational Context and Limits of Validation

S15.1. Meteorological Data and Comparison Method

The comparison covers the period from 12:00 on 17 June 2024 to 23:00 KST on 21 June, and its metrics use the final 72 h, 19–21 June. It uses winds at ten ASOS and AWS stations; Section S15.2 adds an air-temperature comparison at the same stations. All lie within the GRAMM domain, and six lie within the smaller GRAL concentration domain (Table S35). For each site, the archived station history gave the coordinates, elevation and anemometer height for the study period. Nine anemometers were at 10 m above ground and AWS 509 at 7 m.

Observed winds are the archived on-the-hour ASOS and AWS records. The KMA December 2022 observation guideline, Section 2.4.5 [50], defines the reported wind at a whole hour from the preceding ten one-minute values: for example, 13:00 represents 12:51–13:00. Wind speed is the arithmetic mean and wind direction a vector average. Components were derived as $u = -V\sin\theta$ and $v = -V\cos\theta$ from the archived speed and the direction from which the wind blows, measured clockwise from north. Section S15.4 reports the 60 min mean vector over h:00–h:59 as a sensitivity test. Missing data remain missing. Provider flags 0, 1 and 9 denote normal, erroneous and missing values, but the archived files omit those flags, so numeric screening cannot establish that each record passed quality control.

Model winds are the 24 time-centered hourly fields of the main sea-breeze field. At each station, u and v were interpolated bilinearly in the horizontal and linearly in height above model ground at each surrounding grid corner, and stations were not relocated to nearby land cells. Pairing keeps the nominal model-hour correspondence with the KST emission schedule: observation hour h is paired with model situation $h + 1$. The idealized forcing uses solar time, so this correspondence is not a physical conversion to KST. Periodic linear interpolation of u and v tested model-phase shifts of −1 h, +1 h and approximately −34 min; no phase was selected to optimize agreement.

Speed bias is model minus observation. Speed and component RMSE use the available paired hours, and vector RMSE is the square root of the mean sum of squared eastward

and northward component errors. Direction MAE uses the shortest angular difference and includes only pairs with both speeds of at least 0.5 m s^{-1}. Daytime is 08:00–19:59 and nighttime 20:00–07:59. Matching anemometer height above ground does not remove terrain or coastal exposure differences at 500 m resolution.

Table S35. Station locations, exposure and interpolation context.

Station	GRAL	Lat. (° N)	Lon. (° E)	Height above ground (m)	Elev. (m)	Δz (m)	Water (%)
112	In	37.4777	126.6249	10	68.99	−47.1	0.0
631	In	37.3478	126.6154	10	9.74	−4.6	65.5
508	In	37.4665	126.3609	10	140.91	−83.0	0.0
509	Out	37.4528	126.9502	7	141.64	26.7	0.0
230	Out	37.2645	126.1030	10	12.00	15.5	62.7
664	In	37.2247	126.4584	10	17.72	−16.4	0.0
404	In	37.5739	126.8295	10	9.30	0.6	0.0
543	In	37.4990	126.5496	10	25.79	4.3	0.0
376	Out	37.4474	126.8590	10	68.57	−7.0	0.0
571	Out	37.1953	126.8209	10	45.39	6.4	0.0

GRAL, membership in the concentration domain; all stations are in GRAMM. Elev., station elevation; Δz, interpolated model terrain minus station elevation. Water, percentage of horizontal interpolation weight on water cells. Coordinates and exposure refer to the station-history record covering the study period.

S15.2. Meteorological Differences

Across the ten sites, 1077 of 1080 station-hours were usable over 108 h and 717 of 720 over the final 72 h. The three missing hours were AWS 571 on 21 June at 17:00–19:00 KST. At ASOS 112, observed and modeled means were 1.989 and 1.069 m s^{-1}, with a speed bias of −0.920 m s^{-1}, a speed RMSE of 1.150 m s^{-1} and a vector RMSE of 1.443 m s^{-1} (Table S36; Figures S6 and S7). Direction MAE was 29.69° for 44 pairs. Even with matching hourly labels, the ten-minute observation and the hourly model field differ in temporal representation.

At ASOS 112, observed and modeled daytime means were 2.361 and 1.674 m s^{-1} and nighttime means 1.617 and 0.463 m s^{-1}, each from 36 speed pairs; eleven nighttime pairs met the direction criterion. Modeled nighttime means were below those observed at all ten stations. The records do not establish a repeated sea–land-breeze reversal, and the model omits synoptic forcing and daily variability. The interpolated model terrain is 47.1 m below ASOS 112 and 83.0 m below AWS 508, and the Songdo site (AWS 631) has a 65.5% water interpolation weight; their contributions to error were not isolated. For air temperature, the mean diurnal cycle of 18–21 June at the same ten stations (AWS 571: 93 of 96 hours) was compared with the repeated day at the lowest model level (5 m), using the station cell or, where that cell is water (AWS 230 and 631), the nearest land cell; this differs from the wind interpolation of Section S15.1. The diurnal range was 5.4–12.6 K observed (median: 8.4 K) and 8.5–25.6 K modeled (median: 18.4 K); at ASOS 112, it was 7.0 K observed and 25.6 K modeled. Modeled daytime maxima exceeded those observed at eight of the ten stations. At nominal 05:00, the model was colder than observed at all ten stations, by 0.2–6.9 K (6.1 K at ASOS 112). A separate grouping used AWS stations more than 3 km from the sea and below 100 m elevation, classed by artificial land cover in the surrounding 2.5 km square: eight urban sites with at least 60% (405, 410, 433, 434, 437, 438, 510, and 590) and seven non-urban sites with at most 35% (367, 376, 377, 511, 514, 565, and 649). At 05:00, urban sites were 3.6 K warmer than non-urban sites in the observations and 2.8 K colder in the model.

Table S36. Final-72 h meteorological diagnostics under the nominal clock-hour pairing.

Station	n	Obs.	Model	Bias	RMSE	Vector RMSE	Dir. n	Dir. MAE (°)	Night obs.	Night model
112	72	1.989	1.069	−0.920	1.150	1.443	44	29.69	1.617	0.463
631	72	1.701	1.730	0.029	1.053	1.461	44	25.90	0.969	0.707
508	72	2.750	1.161	−1.589	1.969	2.508	57	49.71	2.961	0.763
509	72	1.918	0.948	−0.970	1.218	1.947	54	60.44	2.011	0.853
230	72	1.428	0.873	−0.555	0.789	1.682	38	72.81	1.086	0.398
664	72	2.189	0.798	−1.391	1.725	2.363	39	61.90	1.633	0.238
404	72	1.357	1.070	−0.286	0.752	1.273	35	39.74	0.864	0.241
543	72	1.592	1.180	−0.412	0.809	1.356	43	33.22	0.883	0.464
376	72	1.122	1.309	0.187	0.685	1.189	41	38.93	0.636	0.501
571	69	1.051	1.172	0.121	0.863	1.792	36	63.75	0.578	0.167

Obs. and Model give mean wind speeds. Night means use 36 pairs per station (20:00–07:59). Speed and vector quantities use m s^{-1}. The n column counts available vector pairs. Dir. n requires both speeds to reach 0.5 m s^{-1}. Bias is model minus observation. Direction MAE uses the shortest angular difference (Section S15.1).

S15.3. Ambient $PM_{2.5}$ Availability and Interpretation

The June 2024 AirKorea records contain 4536 unique station-hour keys for 42 Incheon station codes over the 108 h window, with 4267 finite nonnegative $PM_{2.5}$ values in that window and 2904 of 3024 possible values over the final 72 h. Station codes 831481 and 831491 each had 108 duplicated records with matching pollutant values and different network labels; each station-hour was counted once. Missing concentrations were neither interpolated nor replaced with zero.

The 2024 air-monitoring guideline [51] confirms that AirKorea one-hour observations use interval-ending labels, with 02:00:00–02:59:59 reported as 03, and finalized-data hours are numbered 1–24. Under this rule, the hour labels convert to interval starts 00–23 on the same date. The guideline specifies validity flags and transport missing codes, but the archived file has no record-level flags, and its download and finalization history could not be authenticated. We read its time stamps as KST by convention.

All five port-network sites are kept as descriptive observations (Table S37; Figure S8). The guideline requires at least nine valid five-minute values for an hourly value, 18 hours for a daily value and 75% availability over a statistical period; the archived file does not expose the five-minute values needed to audit the first requirement. Gyeongin Port (code 823901) supplies 51 of 72 hours (70.8%), below 75%, so its mean describes those hours only. Total ambient $PM_{2.5}$ includes background, non-ship and secondary contributions absent from the modeled primary ship component, so these series do not validate source-specific concentrations, hotspot overlap or $J = 0.70$.

Table S37. Ambient $PM_{2.5}$ at five port-network stations (final 72 h).

Station code	Available / 72 h	Mean (μg m^{-3})	Minimum (μg m^{-3})	Maximum (μg m^{-3})
823901	51	31.18	17	48
823902	69	18.62	5	41
823903	72	20.51	6	41
823904	72	20.71	7	52
823905	70	20.36	7	42

Statistics use finite, nonnegative total ambient concentrations from available hours. Missing hours were left unfilled. The 51 h series falls below 75% period availability.

The guideline [51] gives the general averaging and interval-ending rules, and the 2024 Annual Report of Air Quality [52] gives December 2024 coordinates for all 42 ambient sites. Quality-control flags for individual 2024 records, calibration and replacement logs, June location continuity of the ambient sites, inlet heights, and instrument identifiers were not available. Evaluation against a specific event would also require observed-event

meteorology and a defensible comparison between the primary ship component and measured total $PM_{2.5}$.

S15.4. Aggregation Sensitivity and Dated Station Metadata

Table S38 compares the archived on-the-hour ASOS statistic, a reconstruction from ten one-minute records ending at that hour, and the 60 min mean vector. All 108 ten-minute windows are complete. This comparison changes both the averaging interval and the speed statistic, because arithmetic mean speed differs from the magnitude of a mean vector. With speed-weighted averaging of u and v, the mean absolute difference between the reconstructed and archived directions is 7.49°, so the reconstruction does not validate the provider algorithm. Table S39 gives the dated coordinates of the port-network stations.

Table S38. ASOS 112 sensitivity to observation aggregation (final 72 h).

Observation	Subset	n	Obs. (m s^{-1})	Bias (m s^{-1})	RMSE (m s^{-1})	Dir. n	Dir. MAE (°)
Archived 10 min	All	72	1.989	−0.920	1.150	44	29.69
Archived 10 min	Day	36	2.361	−0.687	1.021	33	28.43
Archived 10 min	Night	36	1.617	−1.154	1.265	11	33.48
Reconstructed 10 min	All	72	1.981	−0.912	1.140	44	29.02
Reconstructed 10 min	Day	36	2.353	−0.678	1.013	33	28.15
Reconstructed 10 min	Night	36	1.609	−1.146	1.254	11	31.66
60 min vector	All	72	1.724	−0.655	0.942	45	26.87
60 min vector	Day	36	2.121	−0.446	0.872	33	24.69
60 min vector	Night	36	1.327	−0.864	1.008	12	32.87

Day (08:00–19:59) and night (20:00–07:59) each have 36 possible hours. All has 72. The model and nominal pairing are the same across definitions.

Table S39. Port-network station coordinates (December 2024 inventory).

Code	Station	Longitude (° E)	Latitude (° N)	Installed
823901	Gyeongin Port	126.5951	37.5665	August 2020
823902	Incheon Port	126.6269	37.4616	October 2020
823903	Incheon New Port	126.6437	37.3880	November 2022
823904	Incheon North Port	126.6409	37.4991	November 2022
823905	Incheon South Port	126.6009	37.4435	November 2022

Data are from Appendix 13.1 of the 2024 Annual Report of Air Quality [52]. Installation dates and year-end coordinates do not establish continuity of June locations, inlet heights or instruments.

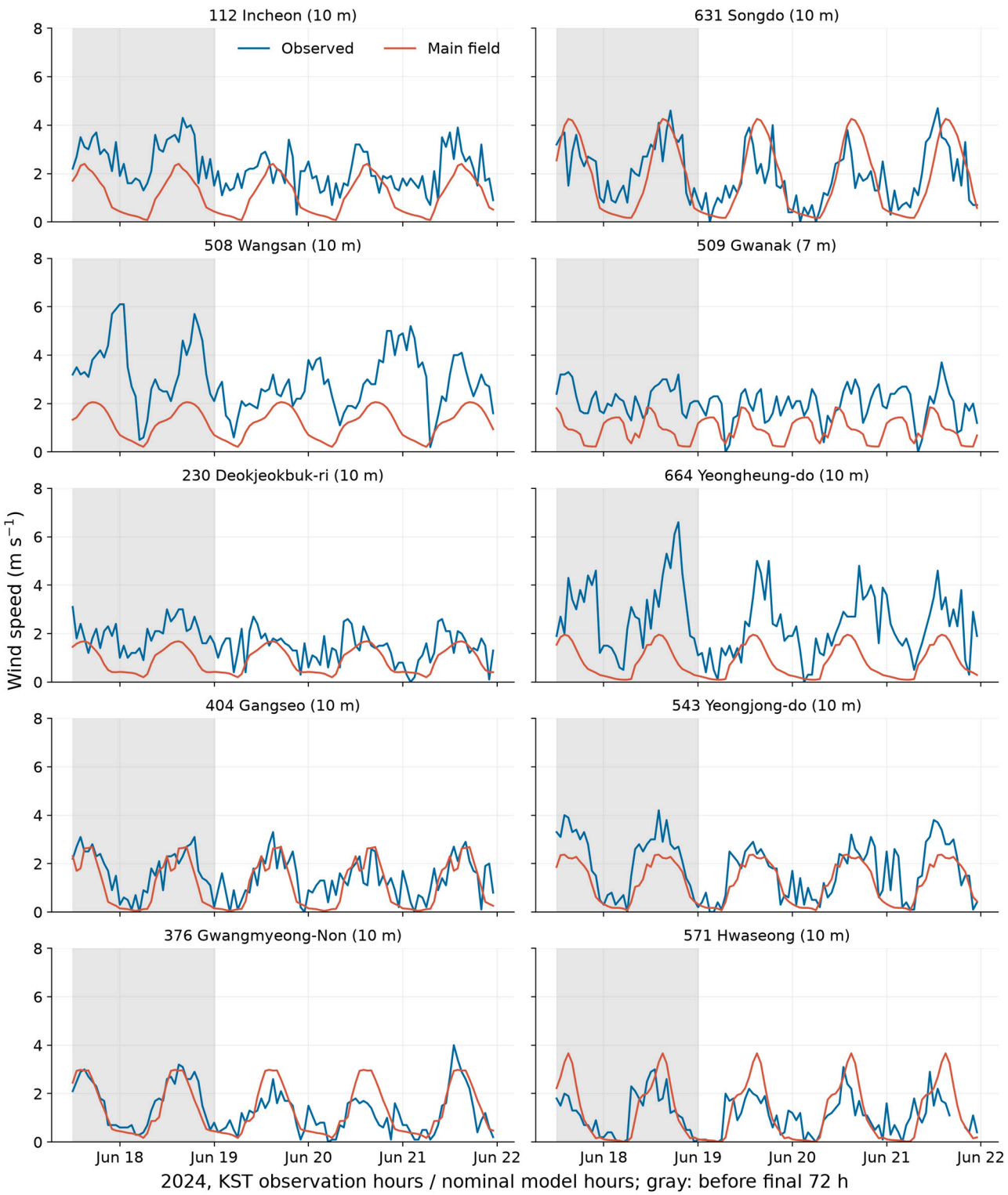

Figure S6. Wind speed from archived observations and from the main sea-breeze field at ten ASOS and AWS stations, 17 June 12:00 to 21 June 23:00 KST. Model components were interpolated to station coordinates and anemometer heights, with nominal clock-hour pairing. Missing observations remain gaps. All stations are in GRAMM; 230, 376, 509 and 571 are outside GRAL.

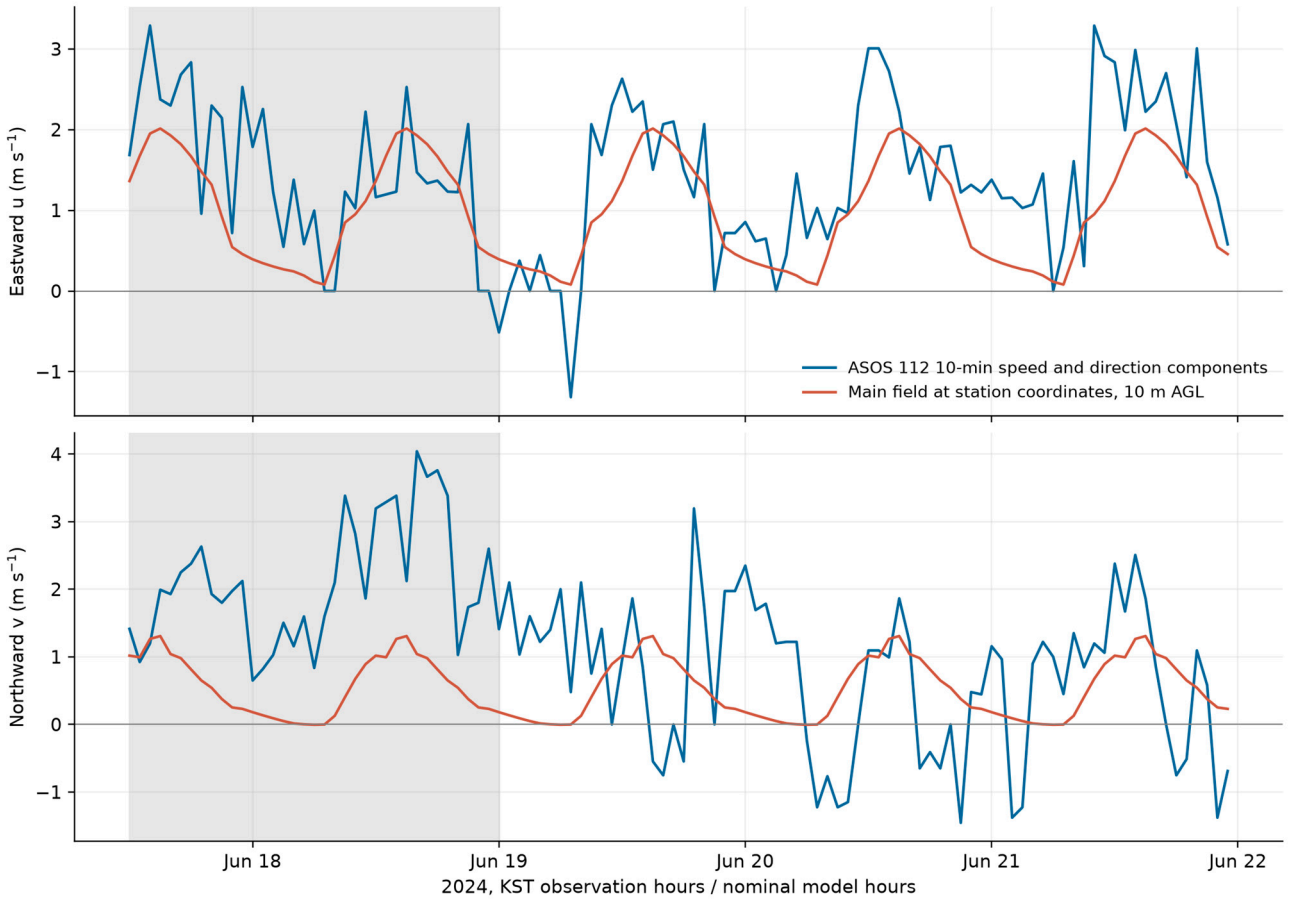

Figure S7. Eastward and northward wind components from the archived ten-minute observations at ASOS 112 and from the main sea-breeze field at the station coordinates and 10 m above ground. The idealized model cycle repeats daily. Shading marks the period before the final 72 h. Model terrain is approximately 47 m below the station elevation, and the clock pairing is nominal.

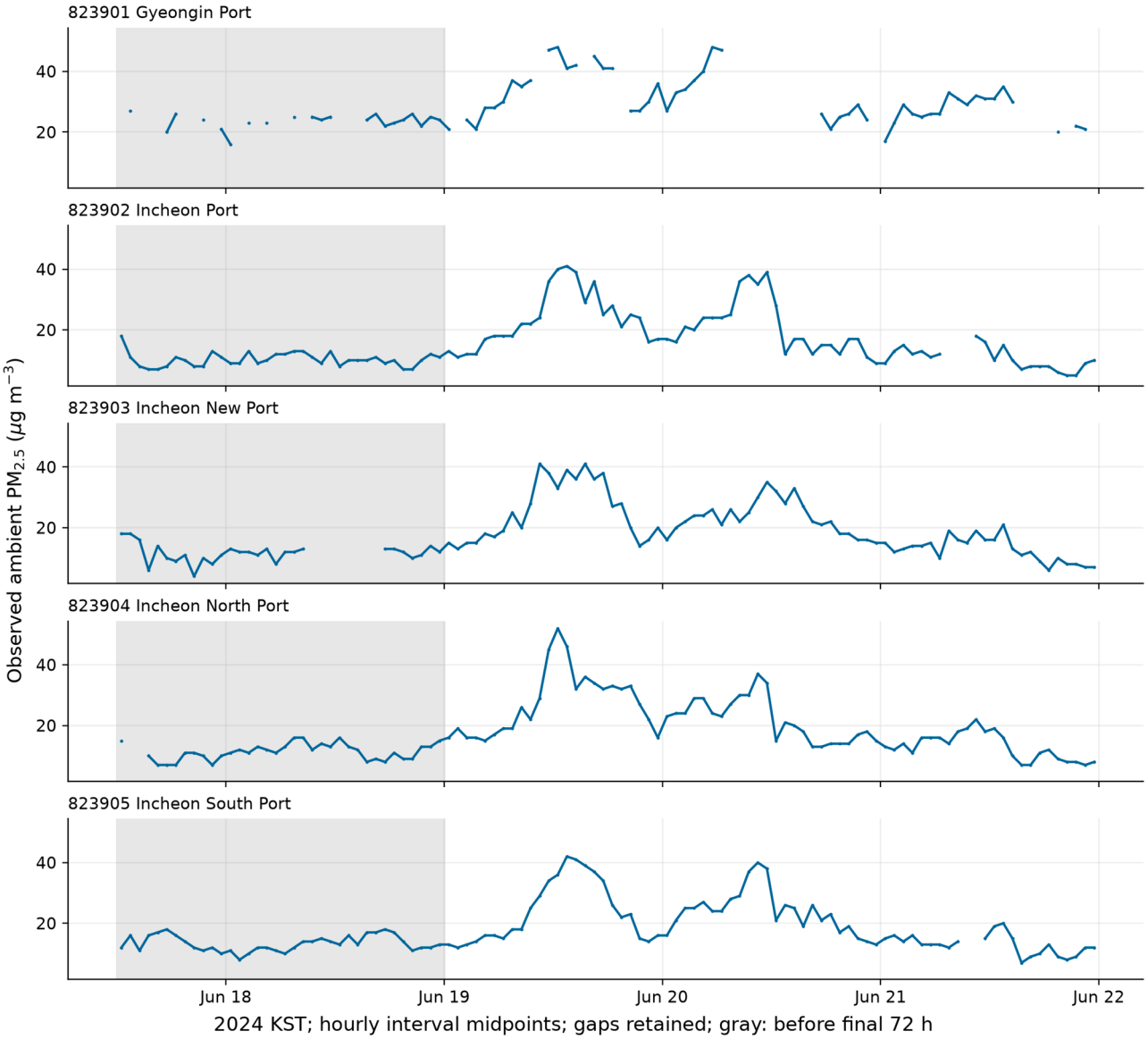

Figure S8. Archived ambient $PM_{2.5}$ at five port-network stations. Points sit at interval midpoints under the 01–24 end-hour convention. Table S37 reports data availability. These total ambient observations are not a validation target for modeled primary ship $PM_{2.5}$.

S16. Idealized Circulation Patterns, Component Inputs and Additional Emission Weeks

Section 3.7 compares MA24 and the component inputs under six idealized GRAMM fields, and Section 3.8 repeats the main averaging comparison for two further emission weeks. This section lists the field settings and classification (Table S40), the results by field (Table S41), the release-hour diagnostics (Table S42), the results for the further weeks (Table S43) and the repeatability checks (Table S44). All comparisons use the final 72 h, the 2 m level and the area-weighted mainland cells of the main analysis, with thresholds taken from the hourly baseline of the same field and week and the 96 h emission-mass control of Section 2.3.

S16.1. Field Settings and Pattern Classification

All fields used the GRAMM domain, terrain and land cover of the main sea-breeze field (Table S4), and each supplied the 24 hourly fields of its third model day, repeated on every emission day as in Section 2.4. The pattern rules were fixed before the MA6, BK96, FMHT and HMCT results of these fields were examined; the baseline and MA24 of the

optimized-build sea-breeze field and the land-breeze-dominated field had already been computed when the rules were fixed. The rules are applied in order, the first match giving the class. The coastal band is the land within five grid cells of water, excluding the lateral boundary zone; the emission cells are the water parts of the ship-emission cells at the 36 m release height; positive eastward wind is onshore; night is 20:00–07:59. (1) D, all-day offshore: coastal 10 m eastward wind below 0.5 m s^{-1} throughout the day. (2) B, full sea–land breeze: coastal eastward wind of at least 0.5 m s^{-1} for at least 6 h with a maximum of at least 1.5 m s^{-1} (the sea-breeze condition), a coastal mean below −0.3 m s^{-1} at 23:00–04:59 and at least 50% offshore flow at the emission cells at night. (3) C, land-breeze dominated: at least 80% offshore flow at the emission cells at night, a coastal nighttime mean (20:00–07:59) of −0.5 m s^{-1} or less, and a weak or short sea breeze (maximum below 1.5 m s^{-1} or shorter than 6 h). (4) B−, coastal land breeze: the sea-breeze condition, at least 6 h of negative coastal eastward wind and less than 50% offshore flow at the emission cells. (5) A, residual class: none of the above; in the three sea-breeze fields (main, optimized-build and 2.5 s; Table S40) this is a sea breeze with weak onshore flow at night. Fields are named after their circulation (Table S40): the three sea-breeze fields fall in class A, the coastal land-breeze field in B− and the land-breeze-dominated field in C. The weak-sea-breeze offshore-night field also falls in A, although most of its night flow at the emission cells was offshore.

The weak-sea-breeze offshore-night field changed only the sea-surface temperature of the June forcing, from 19.6 to 24.5 °C, to strengthen the nocturnal land–sea contrast. It met none of rules 1–4: its coastal maximum of 1.466 m s^{-1} at 15:00 was below the 1.5 m s^{-1} sea-breeze criterion, and its nighttime offshore share of 74.9% at the emission cells was below the 80% criterion of rule 3, so the rules assign it to A. Its nighttime coastal flow was nevertheless offshore (−0.76 m s^{-1} at 23:00–04:59, negative for 14 h), and Section 3.7 describes it by its measured flow diagnostics.

Table S40. Settings and third-day flow diagnostics of the six idealized GRAMM fields.

Field (pattern)	Solar date; sea surface; background wind	GRAMM build; time step; integration	Coastal onshore maximum (m s^{-1}; hour)	Coastal mean 23:00–04:59 (m s^{-1})	Hours of offshore coastal flow	Night offshore flow at emission cells (%)	Night wind speed at emission cells (m s^{-1})	Night class 7 at emission cells (%)	GRAL inputs
Sea breeze, main (A)	18 June; 19.6 °C; calm	Main build; 1.5 s; 72 h	2.40 (16:00)	+0.22	0	0	1.71	70	Main set (Table 3)
Sea breeze, optimized build (A)	18 June; 19.6 °C; calm	Optimized build; 1.5 s; 120 h	2.39 (16:00)	+0.22	0	0	1.72	70	Baseline, MA6, MA24, BK96, FMHT, HMCT
Sea breeze, 2.5 s step (A)	18 June; 19.6 °C; calm	Main build; 2.5 s; 120 h	2.41 (15:00)	+0.21	0	0	1.69	68	Baseline, MA6, MA24, BK96, FMHT, HMCT
Coastal land breeze (B−)	18 June; 19.6 °C; 90°, 1.0 m s^{-1}	Main build; 2.5 s; 120 h	2.79 (16:00)	−0.08	9	25	1.74	3	As the 2.5 s sea-breeze field; baseline seed 2
Land-breeze-dominated (C)	22 September; 25.2 °C; calm	Optimized build; 1.5 s; 120 h	0.57 (14:00)	−1.17	19	93	3.56	4	As the 2.5 s sea-breeze field; baseline and MA24 seed 2
Weak sea breeze, offshore night (A)	18 June; 24.5 °C; calm	Optimized build; 1.5 s; 120 h	1.47 (15:00)	−0.76	14	75	3.71	9	As the 2.5 s sea-breeze field; baseline seed 2

The coastal band is interior land within five cells of water. Emission-cell diagnostics use ship $PM_{2.5}$ emissions to weight the water portions of ship-emission cells at 36 m. Night is 20:00–07:59. Positive eastward wind is onshore. Very stable denotes class 7. Table S29 describes the main and optimized GRAMM builds. Under Section S16.1, the weak-sea-breeze offshore-night field is class A,

although most nighttime flow at its emission cells was offshore. GRAMM output hours mark interval ends, one hour later than the labels in Figure 2b.

S16.2. Component Inputs and Results by Field

FMHT and HMCT were built from the hourly inventory of each week: FMHT multiplies the fixed 96 h mean source map of BK96 by the hourly domain-total emissions of the baseline, and HMCT rescales each hourly baseline map to the constant episode-mean total. In the 12 h spin-up, FMHT carries the baseline hourly totals and HMCT the constant total; this difference does not affect the final-72 h metrics. For the main sea-breeze field, the 2 × 2 uses the baseline and BK96 of the main analysis and FMHT and HMCT simulated separately with the same model version, seed and settings; that BK96 input lists the same source map in a different element order, so the four runs are not common-random-number pairs. The interaction term combines four runs and therefore carries the particle sampling of each; Table S44 gives seed pairs that indicate the size of this sampling variation.

Table S41. MA6, MA24 and component effects by idealized field (main episode, final 72 h, seed 1).

Field	Input	Mean change, % (μg m^{-3})	NMAE (%)	Maximum change (%)	P99 area-time change (%)	P99.9 area-time change (%)	J (P99)	J (P99.9)
Sea breeze, main (A)	MA6	−0.08 (−0.0002)	7.6	−0.9	+0.3	−12.4	0.793	0.791
Sea breeze, main (A)	MA24	+8.69 (+0.0179)	20.7	−21.4	+41.7	+64.6	0.465	0.217
Sea breeze, main (A)	BK96	+6.10 (+0.0126)	26.1	−28.7	+18.5	+1.2	0.330	0.081
Sea breeze, main (A)	FMHT	−4.87 (−0.0100)	23.5	−37.9	−40.8	−81.3	0.296	0.029
Sea breeze, main (A)	HMCT	+12.26 (+0.0252)	17.0	+9.9	+76.5	+174.0	0.566	0.365
Sea breeze, optimized build (A)	MA6	−0.07 (−0.0001)	7.7	+0.2	+0.7	−14.6	0.798	0.718
Sea breeze, optimized build (A)	MA24	+8.76 (+0.0180)	20.7	−26.8	+46.1	+50.6	0.469	0.218
Sea breeze, optimized build (A)	BK96	+6.18 (+0.0127)	26.1	−33.7	+19.1	−9.1	0.331	0.092
Sea breeze, optimized build (A)	FMHT	−4.84 (−0.0099)	23.5	−42.2	−37.6	−81.0	0.311	0.027
Sea breeze, optimized build (A)	HMCT	+12.28 (+0.0252)	16.9	+13.2	+78.8	+158.9	0.555	0.386
Sea breeze, 2.5 s step (A)	MA6	−0.07 (−0.0001)	7.7	+0.0	+0.1	−18.3	0.791	0.707
Sea breeze, 2.5 s step (A)	MA24	+8.75 (+0.0180)	21.0	−26.4	+49.6	+59.5	0.453	0.193
Sea breeze, 2.5 s step (A)	BK96	+6.17 (+0.0127)	26.1	−34.6	+21.0	−6.4	0.336	0.077
Sea breeze, 2.5 s step (A)	FMHT	−4.82 (−0.0099)	23.3	−39.5	−38.4	−75.7	0.290	0.055
Sea breeze, 2.5 s step (A)	HMCT	+12.19 (+0.0250)	17.0	+12.2	+77.8	+183.0	0.562	0.353
Coastal land breeze (B−)	MA6	+0.92 (+0.0011)	8.5	−7.4	−5.6	−7.4	0.844	0.793
Coastal land breeze (B−)	MA24	+9.43 (+0.0108)	18.4	−3.6	+9.3	−12.6	0.695	0.627
Coastal land breeze (B−)	BK96	+6.32 (+0.0072)	21.2	−35.4	+0.0	−44.7	0.589	0.314
Coastal land breeze (B−)	FMHT	−0.93 (−0.0011)	19.3	−41.6	−36.9	−76.2	0.442	0.152
Coastal land breeze (B−)	HMCT	+9.09 (+0.0104)	15.7	+25.7	+35.6	+99.7	0.719	0.481
Land-breeze-dominated (C)	MA6	−3.05 (−0.0010)	10.9	−13.2	−8.3	−14.5	0.821	0.816
Land-breeze-dominated (C)	MA24	−12.26 (−0.0038)	20.5	−16.3	−16.8	−27.1	0.717	0.710
Land-breeze-dominated (C)	BK96	−16.70 (−0.0052)	26.8	−32.0	−28.4	−40.6	0.606	0.594
Land-breeze-dominated (C)	FMHT	−1.07 (−0.0003)	21.5	+5.1	−7.3	−16.4	0.646	0.725
Land-breeze-dominated (C)	HMCT	−12.99 (−0.0041)	19.6	−10.0	−12.8	−13.3	0.737	0.770
Weak sea breeze, offshore night (A)	MA6	−1.40 (−0.0005)	10.7	−1.2	+1.1	−7.0	0.837	0.722
Weak sea breeze, offshore night (A)	MA24	−8.20 (−0.0027)	19.7	−21.6	−1.0	−16.5	0.726	0.419
Weak sea breeze, offshore night (A)	BK96	−12.27 (−0.0040)	25.8	−38.4	−12.1	−50.1	0.585	0.233
Weak sea breeze, offshore night (A)	FMHT	+6.74 (+0.0022)	23.9	−14.3	+23.4	+70.8	0.564	0.391
Weak sea breeze, offshore night (A)	HMCT	−15.34 (−0.0050)	19.8	−16.3	−16.5	−45.4	0.707	0.433

Changes use the hourly baseline and percentiles of the same field. Main sea-breeze rows other than MA6 and MA24 repeat Table 4. For the optimized build, MA6, FMHT and HMCT use a separate baseline with the same inputs. MA24 and BK96 use the Table 6 baseline. All fields use 96 h emission-mass control.

Table S42. MA24 land-mean release-hour diagnostics by field and emission week.

Field; emission week	Night/day response ratio (daytime 08:00–19:59)	Night/day response ratio (daytime 05:00–19:59)	Daytime emission share, Days 2–3 (%)	Day 1 share of the baseline land mean (%)	MA24 mean change (%)	Timing term, pp (one-sided range)	Map term, pp (one-sided range)
Sea breeze, main (A)	8.15	6.53	60.1	6.73	+8.69	+15.15 (+14.2 to +16.1)	−6.47 (−7.4 to −5.5)
Sea breeze, optimized build (A)	8.18	6.52	60.1	6.71	+8.76	+15.19 (+14.3 to +16.1)	−6.42 (−7.3 to −5.5)
Sea breeze, 2.5 s step (A)	8.02	6.52	60.1	6.78	+8.75	+15.12 (+14.2 to +16.0)	−6.36 (−7.2 to −5.5)
Coastal land breeze (B−)	5.05	5.09	60.1	11.20	+9.43	+11.65 (+10.7 to +12.6)	−2.22 (−3.1 to −1.3)
Land-breeze-dominated (C)	0.13	0.15	60.1	0.05	−12.26	−10.64 (−11.9 to −9.4)	−1.61 (−2.9 to −0.4)
Weak sea breeze, offshore night (A)	0.23	0.30	60.1	0.06	−8.20	−13.46 (−15.1 to −11.8)	+5.27 (+3.6 to +6.9)
Sea breeze, main (A); median week I	5.88	5.13	56.9	5.91	+14.41	+19.05 (+17.3 to +20.8)	−4.65 (−6.4 to −2.9)
Sea breeze, main (A); median week II	6.30	5.17	56.7	6.07	+10.79	+13.73 (+12.9 to +14.6)	−2.94 (−3.8 to −2.1)

Rows without a week label use the main episode. Night/day ratios use emission-mass-weighted unit-mass responses to releases on Days 2–3. These ratios, the daytime emission share and the Day 1 share of the land mean use the hourly baseline (Section 2.5). Timing and map terms follow Equation (4), in percentage points of the baseline land mean. Ranges span the two one-sided splits. The main sea-breeze row repeats Figure 6 and Table 6.

S16.3. Additional Emission Weeks

The two further weeks were selected by a rule fixed before they were simulated. Among the 50 complete Tuesday–Friday windows of 2024 (the population of Section 2.1), each window was placed by the percentiles of its in-domain 96 h emission mass and of its daytime (08:00–19:59) emission share, and the two windows closest to the median of both were chosen: 25–28 June (median week II; 569.9 kg; daytime: 55.5%; 52nd and 46th percentiles) and 11–14 June (median week I; 571.1 kg; 56.2%; 56th and 54th percentiles), against 685.9 kg and 58.3% for the main episode. No season filter was applied; both windows fall in June, so they were simulated under the main sea-breeze field with the settings of the main analysis. Month and Year for these weeks reuse the stored Month and Year fields of the main analysis, whose inputs do not depend on the episode, rescaled to each week's 96 h baseline mass; Week averages the Monday–Sunday week that contains each episode (10–16 and 24–30 June).

Table S43. Averaging effects in two additional emission weeks (main sea-breeze field, final 72 h, seed 1).

Emission week	Input	Mean change, % (μg m^{-3})	NMAE (%)	Maximum change (%)	P99 area-time change (%)	P99.9 area-time change (%)	J (P99)	J (P99.9)
Median week I	MA2	−0.12 (−0.0002)	5.7	+2.1	+4.3	+3.0	0.891	0.867
Median week I	MA3	+0.66 (+0.0011)	4.9	+3.7	+2.6	+1.9	0.927	0.892
Median week I	MA4	+0.84 (+0.0014)	7.2	+3.1	+6.9	+5.4	0.861	0.796
Median week I	MA6	+2.01 (+0.0033)	9.4	+2.4	+11.6	+6.0	0.810	0.707
Median week I	MA12	+6.64 (+0.0108)	16.4	+11.2	+36.0	+40.9	0.635	0.483
Median week I	MA24	+14.41 (+0.0234)	24.5	+12.9	+62.8	+98.8	0.497	0.256
Median week I	MA48	+17.45 (+0.0283)	30.2	+3.6	+66.4	+102.9	0.429	0.232
Median week I	BK6	+5.02 (+0.0081)	13.0	+2.1	+17.3	+7.6	0.750	0.709
Median week I	BK12	+14.47 (+0.0235)	24.5	+3.6	+71.5	+122.4	0.494	0.309
Median week I	BK24	+16.48 (+0.0267)	31.5	+30.0	+72.3	+145.9	0.371	0.162
Median week I	Week	+19.34 (+0.0314)	36.9	−1.3	+59.5	+66.4	0.373	0.211
Median week I	Month	+18.17 (+0.0295)	36.4	−16.4	+44.7	+26.9	0.358	0.169

Emission week	Input	Mean change, % (μg m^{-3})	NMAE (%)	Maximum change (%)	P99 area-time change (%)	P99.9 area-time change (%)	J (P99)	J (P99.9)
Median week I	Year	+20.15 (+0.0327)	39.2	−13.1	+53.7	−1.4	0.344	0.206
Median week I	BK96	+16.31 (+0.0265)	34.8	−12.0	+49.1	+76.3	0.356	0.140
Median week I	FMHT	−4.49 (−0.0073)	25.6	+29.5	−38.9	−61.3	0.372	0.143
Median week I	HMCT	+24.20 (+0.0393)	30.3	+84.4	+138.0	+411.5	0.399	0.182
Median week II	MA2	−0.04 (−0.0001)	5.2	−7.5	+5.4	−5.9	0.881	0.767
Median week II	MA3	+0.65 (+0.0012)	4.5	−3.6	+3.2	−11.1	0.890	0.805
Median week II	MA4	+0.77 (+0.0014)	6.5	−4.1	+6.3	−14.5	0.839	0.741
Median week II	MA6	+1.97 (+0.0035)	8.4	−0.3	+8.7	−16.5	0.806	0.734
Median week II	MA12	+6.75 (+0.0119)	14.7	+5.7	+24.4	+6.7	0.682	0.633
Median week II	MA24	+10.79 (+0.0190)	21.2	−0.5	+33.7	−12.7	0.577	0.460
Median week II	MA48	+8.93 (+0.0158)	24.8	−12.1	+14.9	−55.3	0.490	0.257
Median week II	BK6	+5.65 (+0.0100)	13.1	+5.4	+9.6	−7.0	0.747	0.645
Median week II	BK12	+11.17 (+0.0197)	21.4	+3.3	+32.3	−12.6	0.601	0.527
Median week II	BK24	+10.53 (+0.0186)	25.9	−6.9	+28.6	−23.5	0.474	0.277
Median week II	Week	+10.01 (+0.0176)	29.6	−29.4	+16.2	−67.6	0.368	0.089
Median week II	Month	+8.51 (+0.0150)	30.4	−29.9	−4.8	−75.0	0.351	0.063
Median week II	Year	+10.33 (+0.0182)	32.3	−27.1	−7.3	−80.9	0.366	0.055
Median week II	BK96	+9.16 (+0.0162)	28.4	−28.4	+19.3	−73.6	0.404	0.086
Median week II	FMHT	−1.26 (−0.0022)	25.4	−20.7	−32.3	−83.9	0.370	0.061
Median week II	HMCT	+12.06 (+0.0213)	20.3	+25.9	+68.2	+160.1	0.549	0.350

Changes and exceedance thresholds use each week's hourly baseline. Month and Year reuse the stored fields of the main analysis rescaled to the week's 96 h baseline mass.

S16.4. Repeatability and Computing Time

Table S44 lists the particle-seed pairs and the uninterrupted reruns of the circulation-pattern and emission-week runs. With the same particle settings and computers, the GRAL wall time was 138–147 min per case for inputs from the hourly inventory to the weekly mean (two identical computers; timed runs of median weeks I and II). Three runs were interrupted and resumed from the transient GRAL checkpoints written every 24 situations: the FMHT of the coastal land-breeze field after situation 48 of 108 (hour 36 of the 96 h episode); the MA24 of the 2.5 s sea-breeze field after situation 72 (hour 60); and the hourly baseline of the weak-sea-breeze offshore-night field (particle seed 1), also after situation 72. FMHT, MA24 and the weak-sea-breeze offshore-night baseline were repeated without interruption with the same inputs and particle seed. The reruns agreed with the resumed runs to within 0.0004 μg m^{-3} in every mainland cell and hour of the final 72 h at 2 m; land means differed by less than 0.001%, and each P99 or P99.9 hotspot set was identical or differed by one cell-hour ($J \geq 0.989$; Table S44).

Table S44. Particle-seed repeatability and uninterrupted reruns by field and emission week (final 72 h).

Field or week; input	Comparison	Mean change (%)	NMAE (%)	J (P99)	J (P99.9)
Sea breeze, main; baseline	Seed 2 vs seed 1	−0.015	2.26	0.951	0.927
Sea breeze, main; BK96	Seed 2 vs seed 1	+0.005	2.38	0.942	0.952
Coastal land breeze; baseline	Seed 2 vs seed 1	−0.039	2.66	0.959	0.948
Land-breeze-dominated; baseline	Seed 2 vs seed 1	−0.064	2.70	0.968	0.969
Land-breeze-dominated; MA24	Seed 2 vs seed 1	−0.008	2.76	0.961	0.965
Weak sea breeze, offshore night; baseline	Seed 2 vs seed 1	+0.024	2.77	0.962	0.934
Median week I; baseline	Seed 2 vs seed 1	+0.016	2.24	0.958	0.979
Median week I; MA24	Seed 2 vs seed 1	+0.007	2.28	0.958	0.968
Median week I; BK96	Seed 2 vs seed 1	−0.001	2.33	0.942	0.929
Median week II; baseline	Seed 2 vs seed 1	−0.012	2.22	0.952	0.931
Median week II; MA24	Seed 2 vs seed 1	−0.002	2.27	0.970	0.885
Median week II; BK96	Seed 2 vs seed 1	+0.005	2.28	0.945	0.891
Coastal land breeze; FMHT	Rerun vs resumed run	<0.001	<0.01	0.999	1.000
Sea breeze, 2.5 s step; MA24	Rerun vs resumed run	<0.001	<0.01	1.000	0.989
Weak sea breeze, offshore night; baseline	Rerun vs resumed run	<0.001	<0.01	1.000	1.000

Seed pairs differ only in seed. Uninterrupted reruns use the same inputs and seed as the checkpoint-resumed runs. J uses the reference run's P99 and P99.9. The 2.5 s and optimized-build sea-breeze fields have no seed pair.

References

Reference numbers refer to the reference list of the main article.

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