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Applicability Failures of Urban Air Quality Models in Coastal Cities and the Role of Sea–Land Breeze and Boundary Layer Dynamics

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Abstract

Urban air quality models are widely applied in environmental assessment and policy making, yet their applicability in coastal cities remains limited. This paper examines why commonly used urban air quality models often fail to represent pollution dynamics in coastal environments. Focusing on conceptual rather than technical issues, the analysis highlights mismatches between model assumptions and key coastal atmospheric processes, including land–sea thermal contrast, sea–land breeze circulation, boundary layer stratification, and strong temporal variability. These processes challenge assumptions of spatial homogeneity, predictable mixing, and monotonic dispersion that underpin many urban models. The paper argues that temporal averaging further obscures critical transition periods that govern pollutant accumulation and exposure. By framing these limitations as applicability failures rather than model errors, the study emphasizes the need for context-sensitive interpretation and development of urban air quality models in coastal urban settings.

Keywords: urban air quality modeling, coastal cities, atmospheric boundary layer dynamics, temporal averaging

1. Introduction

Urban air quality modeling has become a foundational tool in contemporary environmental governance, shaping how cities understand pollution patterns, design mitigation strategies, and evaluate public health risks. These models translate complex atmospheric processes into formalized representations that link emission sources with ambient concentration outcomes. Through numerical simulation, they provide a structured way to interpret how pollutants move, accumulate, react, and dissipate within urban space. Their influence extends beyond scientific analysis into regulatory standards, urban planning decisions, and long term sustainability strategies.

The intellectual foundations of most urban air quality models were established in contexts where atmospheric behavior could be reasonably approximated as horizontally continuous and vertically well mixed over large spatial extents. In such settings, synoptic scale meteorological forcing is treated as the dominant driver of wind patterns, thermal structure, and mixing processes. Local circulations are often framed as secondary

effects that introduce limited perturbations to an otherwise coherent atmospheric system. This conceptual framing has shaped model architecture, parameterization schemes, and evaluation practices for decades.

Coastal cities challenge this foundation at a structural level. Their atmospheric environment is not a marginal variation of inland conditions but a qualitatively different system shaped by persistent interaction between land and sea surfaces. The presence of a coastline introduces abrupt contrasts in thermal inertia, surface roughness, moisture availability, and energy exchange. These contrasts generate mesoscale circulations that are not occasional disturbances but recurring organizing forces of the local atmosphere. As a result, the physical logic underpinning many urban air quality models becomes misaligned with the environment in which they are applied.

In coastal urban areas, atmospheric processes unfold across overlapping spatial and temporal scales that resist simplification. Large scale weather systems interact continuously with locally generated circulations, producing flow fields that shift direction, depth, and intensity within short periods. Vertical structure becomes especially important, as air masses of different origin coexist within shallow layers and exchange is often restricted. Pollutant transport is therefore shaped not only by emission strength and background wind but also by the timing of thermal transitions and the vertical positioning of flow regimes.

When models developed under inland assumptions are applied to such environments, discrepancies emerge that are often interpreted as performance deficiencies or data limitations. In reality, many of these discrepancies reflect deeper issues of applicability. The models may reproduce average conditions while failing to capture accumulation, recirculation, or delayed exposure patterns that are central to coastal pollution dynamics. This produces outputs that appear internally consistent but lack correspondence with the actual pathways through which pollutants persist in coastal cities.

The concept of applicability failure is therefore more appropriate than simple model error in this context. Applicability failure points to a situation in which a model operates as designed but within a setting that violates its underlying conceptual premises. The issue is not the absence of sophisticated algorithms or high resolution inputs but the persistence of assumptions about atmospheric continuity, monotonic dispersion, and scale separation that do not hold in coastal environments.

Sea–land breeze circulation and boundary layer dynamics occupy a central position in this mismatch. These processes are not peripheral features but structural elements of coastal atmospheric organization. They govern the timing, direction, and confinement of pollutant transport while shaping vertical mixing conditions that determine near surface exposure. Their influence is inherently time dependent and often nonlinear, making them difficult to reconcile with modeling frameworks optimized for stability and averaging.

This paper situates the underperformance of urban air quality models in coastal cities within this broader conceptual landscape. Rather than treating coastal complexity as an obstacle to be minimized, it frames it as a lens through which the limits of prevailing modeling paradigms become visible. By examining how standard assumptions interact with coastal atmospheric characteristics, the discussion aims to clarify why certain modeling failures recur and why incremental adjustments are often insufficient.

Through a focus on circulation patterns, boundary layer structure, and temporal representation, the analysis seeks to contribute to a more reflective approach to model application. Understanding the conditions under which urban air quality models lose explanatory power is essential not only for improving technical performance but also for ensuring that model based decisions remain grounded in atmospheric reality.

2. Common Assumptions in Urban Air Quality Models

Urban air quality models are built upon a set of assumptions that function as cognitive shortcuts, allowing complex atmospheric processes to be translated into manageable mathematical representations. These assumptions are rarely neutral. They reflect the historical contexts in which models were developed, the types of cities that originally motivated their use, and the dominant meteorological paradigms that guided early atmospheric science. Over time, these assumptions have become embedded in model architecture, shaping how urban air pollution is

conceptualized, simulated, and interpreted.

2.1 Assumptions of Spatial Homogeneity and Meteorological Continuity

One of the most fundamental assumptions in urban air quality modeling is the relative spatial homogeneity of meteorological forcing within the urban domain. Wind speed, wind direction, temperature fields, and atmospheric stability are commonly assumed to vary gradually across space. This assumption allows models to interpolate meteorological inputs over grid cells and to treat the urban area as a continuous surface rather than a patchwork of competing microclimates.

This spatial continuity assumption is closely tied to the dominance attributed to synoptic scale meteorology. Large scale weather systems are presumed to set the background conditions under which urban dispersion occurs. Local influences such as surface heterogeneity, land use contrast, and small scale circulations are typically framed as secondary modifiers rather than primary drivers. In practice, this means that model performance is evaluated against its ability to respond to changes in regional wind patterns or frontal passages, while internally generated circulations receive limited structural emphasis.

The assumption of homogeneity also simplifies the treatment of urban form. Buildings, roads, vegetation, and open spaces are often aggregated into average roughness lengths and surface parameters. This abstraction reduces computational complexity but simultaneously obscures localized flow disturbances that can shape pollutant pathways. While such simplifications may produce acceptable results in cities where atmospheric forcing is relatively uniform, they become increasingly fragile in environments where sharp gradients dominate airflow behavior.

2.2 Simplified Representation of Urban Boundary Layer Structure

Another core assumption concerns the structure and evolution of the urban atmospheric boundary layer. Most urban air quality models rely on an idealized diurnal cycle in which daytime heating produces a deep, well mixed convective boundary layer, followed by nocturnal cooling that generates a shallow stable layer near the surface. This conceptual model assumes that vertical mixing follows predictable patterns governed primarily by surface heat flux and solar radiation.

Within this framework, turbulence is parameterized using schemes that presume statistical uniformity and steady state conditions over each time step. Vertical exchange is treated as a function of surface energy balance and mechanical shear, while horizontal variability is often minimized. The result is a boundary layer that behaves as a coherent mixing volume rather than a stratified or layered system.

This assumption allows pollutants emitted at the surface to be rapidly distributed through the lower atmosphere during the day and weakly mixed at night. Concentration patterns therefore respond smoothly to changes in emissions and meteorology. Such behavior aligns well with inland settings where surface characteristics and thermal forcing are relatively consistent across the urban area.

The difficulty arises when this assumed boundary layer structure does not materialize. In environments where external air masses intrude, where thermal contrasts persist, or where vertical stability is maintained during daytime, the logic of a predictable mixing cycle breaks down. Models that rely on generic boundary layer evolution then misrepresent both the depth of pollutant confinement and the timing of dispersion.

2.3 Treatment of Local Circulations as Secondary Phenomena

Urban air quality models typically conceptualize local circulations as deviations from a dominant background flow. These circulations are often parameterized implicitly rather than explicitly resolved. Their effects are absorbed into turbulence coefficients or averaged wind fields rather than represented as distinct dynamic systems.

This approach reflects a hierarchical view of atmospheric motion, where synoptic scale processes govern regional transport and mesoscale or microscale circulations play a corrective role. The model logic assumes that local circulations do not fundamentally alter transport pathways but only modulate dispersion efficiency.

Such an assumption influences how models handle complex flow regimes. When wind direction shifts rapidly or reverses, models may interpret this as noise rather than as an organizing mechanism. Pollutant accumulation

caused by circulation loops is therefore underrepresented, and dispersion is implicitly treated as directional and progressive rather than cyclical.

In many inland contexts, this hierarchy is defensible. Local circulations are often weak, transient, or spatially limited. In coastal cities, however, this assumption becomes increasingly problematic because local circulations are persistent, structured, and tightly coupled with surface forcing. Treating them as secondary leads to systematic underestimation of their role in shaping pollution outcomes.

2.4 Assumptions Embedded in Temporal Averaging

Temporal representation constitutes another major assumption in urban air quality modeling. Most models operate on fixed time steps that reflect practical constraints rather than atmospheric process scales. Hourly or daily averages are commonly used for emissions, meteorological inputs, and chemical reactions. This practice rests on the belief that short term variability does not substantially affect longer term concentration patterns.

Temporal averaging simplifies computation and aligns model outputs with regulatory metrics, which are often defined over similar time windows. It also reflects a conceptual preference for stable trends over transient events. Peaks, reversals, and rapid transitions are treated as fluctuations that do not alter the overall pollution narrative.

This assumption carries significant implications. It implies that exposure is best understood as an accumulated quantity rather than as a sequence of discrete events. It also assumes linearity in atmospheric processes, where averaging inputs yields averaged outcomes.

In environments characterized by rapid transitions, this logic breaks down. Short lived circulation shifts can trap pollutants, relocate plumes, or expose populations to elevated concentrations within narrow time windows. When such processes are smoothed through averaging, the model output may appear accurate in a statistical sense while failing to reflect lived exposure conditions.

2.5 Linearization of Transport and Dispersion Processes

Urban air quality models often rely on linear or quasi linear representations of transport and dispersion. Wind fields are treated as steady within each time step, and pollutant movement is simulated as a response to these fields. Dispersion is conceptualized as dilution driven by turbulence and mixing.

This approach assumes that transport pathways are predictable and that pollutant fate is largely determined by mean flow characteristics. Feedback mechanisms between pollutants and atmospheric structure are typically minimized or ignored. Pollutants are passive tracers whose behavior does not alter the system in which they move.

While this assumption is acceptable for many primary pollutants over short timescales, it becomes limiting in environments where transport pathways loop, overlap, or intersect vertically. Linear dispersion logic struggles to represent scenarios in which pollutants return to their source region or remain confined within narrow layers for extended periods.

The linearization of transport also affects how models interpret emission timing. Emissions released at different times of day are often assumed to disperse independently. In reality, atmospheric memory effects can cause emissions from previous periods to influence current concentration patterns through delayed transport or recirculation.

2.6 Assumptions About Chemical Processing and Mixing

Chemical transformation processes in urban air quality models are often linked to assumptions about mixing and residence time. Reaction rates are calculated based on average concentrations and averaged meteorological conditions. This implies that chemical processing occurs within a well mixed volume where reactants are uniformly distributed.

Such an assumption simplifies chemical modeling but obscures the role of stratification and segregation. In layered atmospheres, pollutants may be confined within specific thermal or moisture regimes that alter reaction pathways. Limited mixing can prolong the lifetime of certain species or enhance localized chemical production.

By assuming efficient mixing, models may underestimate the persistence of reactive pollutants or misrepresent the spatial distribution of secondary products. This limitation is particularly pronounced in environments where vertical exchange is

restricted or intermittent.

These assumptions form a coherent modeling philosophy rooted in stability, continuity, and scale separation. They allow urban air quality models to function effectively in settings that align with their conceptual design. The issue arises when these models are transferred to environments that violate the conditions under which the assumptions were formulated.

Coastal cities expose the context dependence of these assumptions. Spatial homogeneity is disrupted by land sea contrasts. Boundary layer structure departs from the idealized diurnal cycle. Local circulations operate as primary drivers rather than secondary modifiers. Temporal variability becomes a defining feature rather than background noise.

The resulting discrepancies are not random errors but systematic outcomes of applying a model outside its conceptual domain. Recognizing this helps shift the discussion from technical calibration toward deeper questions about model scope, validity, and interpretation.

3. Atmospheric Characteristics of Coastal Cities

Coastal cities are situated within atmospheric environments that differ fundamentally from those of inland urban areas. Their defining feature is not simply proximity to the sea, but continuous exposure to interacting surface systems that operate according to distinct physical principles. The atmosphere above a coastal city is shaped by the juxtaposition of land and water surfaces, each imposing its own thermal, mechanical, and moisture related constraints on air movement. This interaction generates atmospheric behavior that is intrinsically dynamic, vertically structured, and temporally sensitive.

3.1 Land–Sea Thermal Contrast as a Structuring Force

At the core of coastal atmospheric behavior lies the contrast in thermal properties between land and sea surfaces. Land responds rapidly to incoming solar radiation, heating quickly during the day and cooling efficiently at night. Water bodies, by contrast, possess high heat capacity and strong thermal inertia, resulting in slower temperature changes over diurnal cycles. This persistent imbalance produces horizontal temperature gradients that are spatially fixed by geography and temporally modulated by solar forcing.

These gradients are not incidental. They function as organizing forces that shape pressure distributions in the lower atmosphere. Air moves in response to these gradients, generating circulations that are predictable in form yet variable in strength and extent. The atmosphere above a coastal city is therefore rarely in equilibrium. Instead, it is continuously adjusting to surface driven thermal contrasts that do not disappear even under stable synoptic conditions.

This thermal asymmetry also affects atmospheric stability. Warm air rising over land interacts with cooler marine air masses, producing stratified layers that resist vertical mixing. The result is an atmosphere that often departs from the idealized vertically uniform structure assumed in many urban frameworks. Pollutants emitted at the surface may encounter thermal barriers that limit upward transport, altering dispersion patterns from those expected under inland conditions.

3.2 Variability and Directionality of Wind Fields

Wind behavior in coastal cities is characterized by pronounced variability in both direction and magnitude. Unlike inland settings where prevailing winds often maintain a consistent orientation over extended periods, coastal wind fields are strongly influenced by diurnal thermal forcing and shoreline geometry. Wind direction can shift by large angles within short time intervals as surface heating patterns evolve.

This variability is not random. It follows a structured rhythm linked to the heating and cooling cycle of land and sea. During certain periods, onshore flow dominates near the surface while offshore flow may persist aloft. At other times, these patterns reverse or weaken, allowing synoptic winds to exert greater influence. The coexistence of competing wind regimes creates a layered flow structure in which air masses move in different directions at different heights.

Such complexity challenges the notion of a single representative wind field for the urban domain. Near surface winds may transport pollutants inland, while upper level flows carry air masses seaward. The net effect is often partial displacement rather than full removal of pollutants. This layered directionality also increases the likelihood of plume distortion and recirculation, as emissions are stretched and folded within the coastal flow system.

3.3 Vertical Stratification and Layered Atmospheric Structure

Vertical structure is a defining feature of coastal atmospheres. The interaction between marine air and continental air frequently produces stratified layers that differ in temperature, moisture content, and turbulence intensity. These layers may persist for hours or days depending on synoptic conditions and surface forcing.

Marine air intrusions often form shallow layers near the surface that are cooler and more stable than overlying air. This configuration suppresses vertical mixing and traps pollutants within a confined volume. Above this layer, warmer and drier air may flow in a different direction, effectively decoupled from surface processes. Such stratification creates a multi layered boundary region that cannot be adequately described by a single mixing height.

The presence of layered structures alters the residence time of pollutants. Emissions may remain confined within a narrow layer, experiencing limited dilution despite moderate wind speeds. Chemical reactions within this layer may proceed differently than expected under well mixed conditions, as reactant concentrations and radiation exposure vary with height.

This vertical complexity also affects the interpretation of surface measurements. Concentrations recorded at ground level reflect not only emission strength but also the degree of isolation between layers. Without accounting for stratification, it is difficult to infer transport efficiency or dispersion capacity from surface data alone.

3.4 Boundary Layer Depth and Stability Regimes

The atmospheric boundary layer over coastal cities exhibits marked variability in depth and stability. Unlike inland cities where daytime heating often produces a deep convective layer, coastal environments may experience suppressed boundary layer growth due to the influence of cooler marine air. This effect can persist even under strong solar radiation.

Shallow boundary layers reduce the volume available for pollutant dilution. Emissions released at the surface are confined to a smaller mixing space, leading to higher concentrations than would occur under deeper boundary layer conditions. This confinement is particularly pronounced during morning transitions when land heating has begun but marine influence remains strong.

Stability regimes in coastal boundary layers are also more diverse. Stable conditions may occur during periods traditionally associated with convective mixing, while weakly unstable conditions may persist into the evening. This irregularity disrupts the assumed correspondence between time of day and mixing behavior that underlies many urban dispersion models.

The frequent occurrence of temperature inversions near the coast further complicates dispersion. These inversions may form through advection rather than radiative cooling, making them resistant to daytime erosion. Pollutants trapped beneath such inversions can accumulate over multiple cycles, increasing the potential for prolonged exposure events.

3.5 Moisture, Cloud Formation, and Radiative Effects

Coastal atmospheres are typically more humid than inland counterparts due to proximity to large water bodies. Moisture content influences several atmospheric processes relevant to air quality. Higher humidity affects thermal stratification by modifying heat exchange and cloud formation. It also influences radiative balance by altering the absorption and scattering of solar radiation.

Cloud development in coastal regions is often linked to marine air intrusion and boundary layer processes. Low level clouds can reduce surface heating, weakening convective mixing and prolonging stable conditions. This feedback reinforces pollutant confinement near the surface.

Moisture also plays a role in chemical transformation. Reaction rates for certain pollutants are sensitive to humidity and liquid water content. The presence of fog or low clouds can facilitate heterogeneous reactions that are not adequately represented in models calibrated for drier inland environments.

These moisture related processes introduce additional layers of complexity to coastal atmospheric behavior, affecting both physical transport and chemical evolution of pollutants.

3.6 Interaction with Urban Morphology and Topography

The atmospheric characteristics of coastal cities

are further shaped by the interaction between coastal processes and urban form. Buildings modify airflow by increasing surface roughness and generating turbulence, while coastal topography such as cliffs, bays, and peninsulas channels wind and alters circulation patterns.

Urban heat island effects interact with coastal thermal gradients in non linear ways. In some cases, urban warming enhances onshore flow by intensifying land sea temperature contrasts. In other situations, marine cooling offsets urban heating, producing complex spatial patterns of stability and mixing.

Topographic features can anchor circulation patterns, causing convergence zones or stagnation regions that persist under specific wind regimes. Pollutants may accumulate in these zones despite favorable regional conditions for dispersion.

The combined influence of urban morphology and coastal geography reinforces atmospheric heterogeneity. Air quality outcomes become highly sensitive to location within the city, challenging assumptions of spatial uniformity.

These characteristics define coastal cities as heterogeneous atmospheric systems rather than modified versions of inland urban environments. Their behavior is governed by interacting surface contrasts, layered flows, variable stability regimes, and persistent local circulations. These processes operate across multiple scales and resist simplification through averaging or uniform parameterization. Local dynamics in coastal cities are not marginal effects that can be treated as noise. They are central to how air moves, mixes, and retains pollutants. Any attempt to model air quality in such settings must confront this complexity at a conceptual level.

4. Sea–Land Breeze Circulation and Applicability Failures of Urban Air Quality Models

Sea–land breeze circulation represents one of the most persistent and structurally influential atmospheric processes in coastal cities. Unlike episodic weather events, this circulation arises from the daily rhythm of differential heating between land and sea and is therefore embedded in the normal functioning of the coastal atmosphere. Its regularity gives it predictive form, yet its interaction with urban surfaces, background winds, and boundary layer structure produces outcomes that are highly sensitive to timing, location, and vertical position.

Urban air quality models often treat wind as a background transport mechanism that responds smoothly to surface forcing and large scale pressure gradients. Within this framework, changes in wind direction associated with sea–land breezes are commonly represented as simple reversals or shifts occurring over prescribed time intervals. This abstraction overlooks the fact that sea–land breeze circulation is not a uniform horizontal flow but a three dimensional system composed of opposing near surface and return flows, convergence zones, and evolving vertical coupling.

The applicability failure begins at the conceptual level. Many models assume that once wind direction changes, the previous transport regime has ended. In coastal environments, transport regimes overlap. Air masses influenced by the previous phase of the circulation often remain present aloft or within residual layers, interacting with newly established flows. Pollutants are therefore not transported away and replaced by cleaner air in a linear sequence. They are redistributed within a closed or semi closed circulation system.

The diurnal development of sea breezes illustrates this problem clearly. During daytime, cooler marine air advances inland at low levels, displacing warmer continental air upward and landward. This process creates a frontal structure characterized by sharp gradients in temperature, humidity, and turbulence. Urban air quality models that rely on averaged wind fields tend to smooth this structure into a gradual transition, eliminating the localized convergence that can trap pollutants near the surface.

Within the sea breeze front, vertical motion plays a critical role. Air is forced upward as marine air undercuts warmer land air. Pollutants emitted near the surface may be lifted into elevated layers where they are transported differently from surface emissions. Models that do not explicitly resolve this vertical motion often misattribute observed concentration patterns to horizontal advection or emission variability. The failure lies not in numerical precision but in the absence of the circulation logic that governs pollutant redistribution.

At night, the reversal to land breeze conditions

introduces a second layer of complexity. Cooling of the land surface generates offshore flow near the ground, while residual marine air and return flows may persist above. Pollutants accumulated during the day may be advected seaward at low levels, yet remain within reach of the urban atmosphere due to weak vertical mixing and limited horizontal displacement. These pollutants can form offshore reservoirs that are reintroduced during the next sea breeze cycle.

This recirculation mechanism directly contradicts the implicit assumption of unidirectional dispersion embedded in many urban air quality models. Dispersion is often conceptualized as a process through which pollutants are progressively diluted and removed from the urban domain. Sea–land breeze circulation replaces this logic with one of retention and return. Pollutants may exit the immediate urban area only to reenter within hours, often in altered vertical positions that change exposure patterns.

Models that do not account for this circulation loop may predict declining concentrations following emission reductions or favorable winds, while actual conditions show persistence or delayed peaks. This discrepancy is frequently interpreted as a problem of emission inventory accuracy or meteorological input quality. In reality, it reflects a deeper incompatibility between model assumptions and coastal transport dynamics.

Another dimension of applicability failure arises from the interaction between sea–land breezes and urban heat island effects. Urban surfaces tend to remain warmer than surrounding rural areas due to heat storage and reduced evapotranspiration. In coastal cities, this thermal anomaly interacts with the land–sea temperature contrast in ways that alter the strength, timing, and inland penetration of sea breezes.

Urban heat can intensify onshore flow by amplifying the temperature gradient between land and sea. It can also delay the onset of nocturnal land breezes by maintaining higher land temperatures after sunset. These effects introduce asymmetry into the diurnal cycle that standard models rarely capture. Many modeling frameworks assume fixed transition times based on solar forcing alone, neglecting the modifying role of urban thermal inertia.

As a result, models may misplace the spatial boundary between marine and continental air masses. Pollutants may be simulated as dispersed inland when they are actually confined near the coast, or simulated as flushed offshore when urban heating sustains onshore flow. This misrepresentation affects not only average concentration levels but also the spatial distribution of exposure across the city.

Sea–land breeze circulation also introduces sensitivity to coastal geometry. The shape of the shoreline, the presence of bays or peninsulas, and the orientation of the coast relative to prevailing synoptic winds all influence circulation patterns. Sea breezes may converge in certain areas and diverge in others, creating localized stagnation zones or accelerated flow corridors.

Urban air quality models that employ regular grids and generalized coastlines often fail to capture these geometric effects. The circulation is effectively flattened into a uniform onshore or offshore wind field. Pollutant hotspots driven by convergence or channeling are therefore underestimated or misplaced. This failure becomes particularly evident when model outputs are compared against localized observations that reflect fine scale circulation features.

Vertical coupling within the sea–land breeze system presents another challenge. Return flows aloft transport air masses back toward the sea during daytime and toward land at night. Pollutants entrained into these flows can be stored above the surface layer, shielded from deposition and chemical loss. When vertical mixing increases, these stored pollutants may descend and influence surface concentrations long after their emission.

Standard urban air quality models often lack the resolution or parameterization needed to represent this storage mechanism. Vertical exchange is simplified into diffusion processes that assume continuous mixing rather than discrete layering. The result is an underestimation of pollutant persistence and an overestimation of dispersion efficiency.

Temporal representation further amplifies applicability failures. Sea–land breeze transitions do not occur instantaneously at fixed times. They develop gradually, with spatially varying onset and decay. When models impose abrupt changes in wind direction based on hourly inputs, they erase the transitional periods

during which pollutant trapping and redistribution are most pronounced.

These transitional periods are often when the highest concentrations occur, particularly in near coastal urban zones. Averaged temporal inputs smooth these peaks, producing outputs that appear stable but fail to represent exposure dynamics accurately. The mismatch is not simply a matter of resolution but of conceptual alignment between model structure and atmospheric process.

The cumulative effect of these issues is a systematic bias in how urban air quality models interpret coastal pollution dynamics. Sea–land breeze circulation transforms the urban atmosphere from an open system into a semi closed one, where removal is conditional and temporary. Models designed around the assumption of progressive dilution struggle to accommodate this logic.

Applicability failure in this context should not be understood as an inability to simulate wind direction changes. It reflects a deeper limitation in representing circulation as an organizing framework for pollutant behavior. When circulation is treated as background variability rather than as a structuring mechanism, model outputs lose explanatory power in coastal settings.

Recognizing this limitation reframes the challenge of coastal air quality modeling. The issue is not the absence of computational sophistication but the persistence of inland oriented conceptual assumptions. Sea–land breeze circulation exposes the boundaries of these assumptions by revealing transport patterns that are cyclical, layered, and sensitive to timing.

5. Boundary Layer Dynamics and Implications for Pollutant Dispersion

The atmospheric boundary layer plays a decisive role in shaping air quality outcomes because it defines the vertical space within which pollutants are diluted, transported, transformed, and retained. In urban air quality modeling, the boundary layer is often treated as a controllable parameter whose depth and stability can be inferred from surface heat flux, wind speed, and time of day. This approach rests on the assumption that boundary layer behavior follows a relatively stable and repeatable diurnal cycle. Coastal cities challenge this assumption at a fundamental level. Boundary layer dynamics in coastal environments are shaped by competing surface influences, layered air mass interactions, and advective processes that operate independently of local surface heating. As a result, pollutant dispersion in coastal cities is governed by a set of boundary layer behaviors that diverge significantly from those anticipated by standard urban modeling logic.

One of the most consequential features of coastal boundary layers is their tendency toward suppressed vertical growth. In inland cities, daytime solar heating typically produces a convective boundary layer that deepens steadily as surface temperatures rise. This growth increases the effective mixing volume available for pollutants, allowing surface emissions to be diluted over hundreds or even thousands of meters. In coastal cities, the presence of cooler marine air limits this process. Onshore flow introduces air masses that are thermally stable relative to the heated land surface. This stability resists vertical motion and constrains turbulent mixing even under strong insolation.

The result is a boundary layer that remains shallow during periods when inland models would predict vigorous mixing. Pollutants emitted at the surface are confined within a reduced vertical space, leading to elevated concentrations near the ground. This confinement persists despite the presence of wind, because horizontal advection does not compensate for limited vertical dilution. Urban air quality models that assume a direct relationship between daytime heating and boundary layer depth therefore systematically underestimate near surface pollutant accumulation in coastal cities.

Boundary layer suppression in coastal environments is not uniform in space or time. Its intensity depends on the strength of marine air intrusion, the thermal contrast between land and sea, and the timing of synoptic influences. In some cases, shallow stable layers persist only in near coastal zones, while inland areas experience deeper mixing. In other cases, marine influence extends far inland, flattening the vertical structure of the boundary layer across the urban region. This spatial variability challenges the common modeling practice of applying a single mixing height across an entire urban domain.

Thermal inversions constitute another defining

element of coastal boundary layer dynamics. Inversions in inland environments often form at night due to radiative cooling of the surface. These inversions are typically shallow and eroded after sunrise as surface heating resumes. In coastal cities, inversions frequently arise through advection rather than radiation. Cool marine air moving beneath warmer continental air creates a temperature profile that increases with height, producing a stable layer that can persist through much of the day.

Advective inversions differ from radiative inversions in both strength and persistence. They are often deeper, less sensitive to surface heating, and spatially extensive. Pollutants trapped beneath such inversions may accumulate over extended periods, particularly when emissions continue and horizontal ventilation is limited. Urban air quality models that rely on simplified stability classes or nocturnal inversion logic often fail to represent these conditions accurately. The duration and vertical extent of advective inversions are underestimated, leading to optimistic predictions of dispersion.

The presence of inversions alters not only pollutant concentration levels but also their vertical distribution. Emissions released at the surface remain confined to a narrow layer, while pollutants injected above the inversion through stacks or buoyant plumes may be transported differently. This vertical separation produces concentration gradients that cannot be captured by models assuming uniform mixing within the boundary layer. Exposure risk becomes height dependent, affecting populations differently based on building elevation and urban form.

Beyond simple inversion structures, coastal boundary layers frequently exhibit internal layering. Distinct air masses with different thermal histories and moisture content coexist within the lower atmosphere. A cool, moist marine layer may occupy the lowest tens or hundreds of meters, overlain by warmer, drier continental air. Turbulent exchange between these layers is often weak, especially when wind shear is modest. Pollutants emitted within one layer may remain isolated from others for long periods.

This layered structure has profound implications for pollutant fate. Chemical reactions proceed under conditions specific to each layer, influenced by temperature, humidity, and radiation. Pollutants confined within the marine layer may experience reduced photochemical activity due to cloud cover or limited sunlight penetration. At the same time, their removal through vertical dilution is restricted. Models that average chemical processes across the entire boundary layer implicitly assume efficient mixing, masking these layer specific dynamics.

Vertical layering also introduces memory effects into the coastal atmosphere. Pollutants stored within residual layers above the surface may descend when boundary layer structure changes, contributing to delayed concentration peaks that are not directly linked to current emissions. Standard modeling approaches often treat each time step independently, assuming that previous boundary layer states have limited influence on current conditions. This assumption breaks down in layered coastal systems where atmospheric history plays a significant role.

The interaction between boundary layer dynamics and wind shear further complicates dispersion. In coastal environments, wind speed and direction often vary sharply with height. Near surface winds may be weak and directed onshore, while stronger offshore or alongshore flows exist aloft. This shear can suppress vertical mixing by stabilizing the atmosphere, while simultaneously transporting pollutants horizontally within specific layers.

Urban air quality models frequently simplify wind profiles, applying logarithmic or power law relationships derived from inland observations. These representations struggle to capture the complex shear structures present in coastal boundary layers. Pollutants may be advected rapidly within elevated layers while surface concentrations remain high due to limited mixing. Such decoupling produces discrepancies between modeled transport pathways and observed concentration patterns.

Boundary layer transitions represent another critical source of applicability failure. In coastal cities, transitions between stable and unstable regimes are often gradual, spatially heterogeneous, and influenced by advection. The collapse of the boundary layer in the evening may occur earlier near the coast than inland. The growth of the daytime boundary layer may be delayed or incomplete. These transitions are periods of heightened sensitivity,

during which small changes in forcing produce large changes in mixing and concentration.

Urban air quality models commonly impose transitions based on time of day or surface flux thresholds. This approach assumes a predictable sequence of boundary layer states. In coastal environments, the timing and nature of transitions vary across the urban domain. Models that do not resolve this variability smooth over critical windows when pollutant trapping or release occurs.

The implications for pollutant dispersion are substantial. Dispersion efficiency becomes decoupled from simple indicators such as wind speed or solar radiation. High wind speeds do not guarantee dilution if vertical mixing remains suppressed. Strong sunlight does not ensure boundary layer growth if marine air maintains stability. The intuitive relationships that guide model interpretation in inland cities lose validity in coastal contexts.

These dynamics undermine a core principle embedded in many urban air quality models, namely that increased atmospheric energy leads to enhanced dispersion. In coastal cities, energy input may be redistributed horizontally or absorbed by the marine layer rather than converted into vertical mixing. Pollutants remain concentrated near the surface despite conditions that would promote dilution inland.

The cumulative effect of these boundary layer behaviors is a shift from an open dispersion system to a constrained retention system. Pollutants are not simply transported away from their source. They are stored, redistributed, and reintroduced within a shallow and stratified atmosphere. This shift challenges the fundamental dispersion logic upon which many models are built.

Applicability failure arises because models interpret boundary layer depth and stability as controllable parameters rather than emergent properties of interacting surface systems. When boundary layer dynamics are driven by advection, layering, and persistent stability, parameter adjustments alone cannot correct the mismatch. The model continues to operate within an inland oriented conceptual framework. Understanding boundary layer dynamics in coastal cities therefore requires a different interpretive stance. Dispersion must be understood as conditional and episodic rather than continuous. Mixing must be viewed as spatially uneven and temporally delayed. Pollutant fate must be linked to atmospheric structure as much as to emission strength.

These insights have implications beyond technical modeling. They affect how air quality risks are assessed, how mitigation strategies are evaluated, and how regulatory thresholds are interpreted. In coastal cities, improvements in emissions may not translate immediately into improved air quality due to boundary layer constraints. Models that fail to represent this reality risk overstating the effectiveness of interventions.

Boundary layer dynamics thus stand at the center of applicability failures in coastal urban air quality modeling. They reveal the limits of assumptions about mixing, dilution, and temporal response that underpin standard modeling approaches. Recognizing these limits is essential for interpreting model outputs responsibly and for developing modeling frameworks that align more closely with the atmospheric realities of coastal cities.

6. Temporal Scale and Averaging Effects in Coastal Air Quality Modeling

Temporal scale is not a neutral modeling choice. It is a theoretical decision that shapes how atmospheric processes are perceived, filtered, and ultimately represented. In urban air quality modeling, time is commonly treated as a container within which emissions, meteorology, and chemistry unfold in a continuous and smooth manner. This treatment reflects a preference for stability, regularity, and comparability across modeling applications. In coastal cities, this preference collides with an atmospheric reality characterized by rapid transitions, intermittent processes, and strong time dependence. The resulting mismatch constitutes one of the most persistent sources of applicability failure in coastal air quality modeling.

Most urban air quality models operate on hourly or longer temporal resolutions. Emission inventories are often compiled as hourly averages derived from activity patterns. Meteorological inputs are typically provided at fixed time intervals that smooth short term variability. Chemical mechanisms are solved using time steps that assume relatively stable boundary conditions across each interval. These choices are justified by computational efficiency and by alignment with regulatory metrics,

which frequently rely on hourly, daily, or annual averages.

This temporal structure embeds a specific view of atmospheric behavior. It assumes that processes operating at shorter timescales do not fundamentally alter longer term concentration patterns. Variability is treated as noise that averages out, while persistent trends are treated as signal. In inland environments with relatively stable wind regimes and predictable boundary layer evolution, this assumption often holds to a reasonable degree. In coastal cities, it does not.

Coastal atmospheric processes are intrinsically time sensitive. Sea–land breeze circulation develops gradually, intensifies, weakens, and reverses within the span of a single day. Boundary layer depth can change rapidly in response to marine air intrusion or cloud formation. Wind direction may shift by large angles over short periods without any change in synoptic forcing. These changes are not anomalies. They are structural features of the coastal atmosphere.

When such processes are represented using hourly or daily averages, their internal dynamics are suppressed. The model captures a simplified narrative in which wind changes occur discretely at fixed times and boundary layer properties evolve smoothly. The transitional phases that dominate pollutant trapping and release are effectively erased. This erasure produces outputs that appear coherent and stable but lack correspondence with actual dispersion behavior.

Temporal averaging introduces what can be described as structural bias rather than random error. The bias arises because the averaging process systematically removes the very fluctuations that drive pollutant accumulation in coastal settings. Concentration peaks associated with stagnation periods are flattened. Short term exposure events are diluted into background levels. Recirculation effects are spread across multiple time steps and interpreted as weak transport rather than retention.

This bias is particularly evident during transition periods between sea breeze and land breeze phases. These periods are often characterized by weak winds, shifting flow directions, and collapsing boundary layers. Pollutants emitted during these windows experience minimal dispersion and can accumulate rapidly near the surface. When meteorological inputs are averaged across the hour, the calm conditions are merged with adjacent periods of stronger flow. The resulting wind field suggests moderate dispersion potential, masking the stagnation that actually occurred.

The same logic applies to boundary layer transitions. In coastal cities, boundary layer collapse in the evening can begin earlier near the coast than inland and may occur in stages rather than as a uniform event. Morning boundary layer growth may be delayed or fragmented by marine influence. Models that impose fixed diurnal cycles smooth these transitions into idealized patterns. Pollutant trapping during early evening or late morning periods is underestimated because the model assumes either full mixing or stable conditions across the entire time step.

Temporal averaging also alters the perceived relationship between emissions and concentrations. In models, emissions released during an hour are often assumed to disperse according to averaged meteorological conditions for that hour. In reality, emissions released during the first minutes of an hour may experience entirely different dispersion regimes than those released later. In coastal environments, the difference between these regimes can be decisive. Averaging erases this distinction and produces an artificial alignment between emission timing and dispersion capacity.

This misalignment undermines the interpretive value of model outputs. Modeled concentrations appear to respond smoothly to emission changes, reinforcing the idea that emission control leads directly to air quality improvement. In coastal cities, the relationship is mediated by timing. Emission reductions may coincide with periods of poor dispersion, producing limited immediate benefit. Conversely, favorable dispersion during low emission periods may lead to misleadingly low concentrations. Temporal averaging obscures this mediation.

Chemical processes introduce an additional layer of temporal sensitivity. Many atmospheric reactions are nonlinear and highly dependent on sunlight intensity, temperature, humidity, and mixing depth. In coastal environments, these controlling variables fluctuate rapidly due to cloud formation, marine air intrusion, and

boundary layer stratification. Short periods of strong sunlight may drive rapid photochemical production, followed by periods of suppression due to cloud cover or stable stratification.

When chemical processes are solved using averaged inputs, nonlinear behavior is distorted. Reaction rates calculated from averaged sunlight and averaged concentrations do not equal the average of reaction rates calculated from instantaneous conditions. This mathematical property leads to systematic errors in secondary pollutant formation. In coastal cities, where rapid alternation between favorable and unfavorable chemical environments is common, this distortion becomes pronounced.

Temporal averaging also affects the representation of moisture dependent chemistry. Coastal atmospheres often experience rapid changes in humidity due to marine air penetration or fog formation. These changes influence heterogeneous reactions and gas particle partitioning. Averaged humidity values fail to capture the episodic conditions under which certain reactions become dominant. The model output reflects a diluted version of chemical reality that underestimates episodic production or persistence.

Exposure assessment represents another domain where temporal scale choices carry significant implications. Human exposure is not determined solely by average concentration levels. It is shaped by short term peaks, timing of exposure relative to activity patterns, and duration of elevated concentrations. Coastal cities often experience sharp concentration spikes during early morning or evening transition periods when people are commuting or engaging in outdoor activities.

Models that rely on hourly or daily averages distribute these spikes across longer intervals. The resulting exposure estimates suggest moderate risk spread evenly over time rather than acute risk concentrated in specific windows. This representation aligns with regulatory metrics but diverges from lived experience. Applicability failure arises because the model output satisfies formal requirements while failing to capture meaningful exposure dynamics.

The issue is not simply insufficient temporal resolution. It is the underlying assumption that atmospheric processes can be meaningfully represented through averaged states. In coastal environments, process sequencing matters. The order in which dispersion regimes occur shapes pollutant fate. A period of stagnation followed by ventilation produces different outcomes than ventilation followed by stagnation, even if averaged conditions are identical. Temporal averaging erases this order dependence.

This loss of sequencing has implications for understanding pollutant accumulation and release. Coastal atmospheres often store pollutants during stable periods and release them during subsequent mixing events. Models that average across these periods represent storage and release as simultaneous processes, flattening the dynamic into a steady state approximation. The resulting concentration fields lack temporal coherence with actual atmospheric behavior.

Temporal mismatch also affects how models respond to synoptic changes. In coastal cities, large scale weather systems interact with local circulations in time dependent ways. A synoptic wind shift may coincide with a sea breeze phase, reinforcing or weakening it depending on timing. Hourly averaged inputs may capture the synoptic shift but miss its interaction with the local cycle. The model output reflects an averaged compromise rather than the actual sequence of dominance and suppression.

This problem extends to model evaluation. Observational data in coastal cities often show high temporal variability, with sharp transitions and episodic peaks. When models are evaluated against averaged observations, apparent agreement may conceal systematic timing errors. The model reproduces mean values while misplacing peaks and troughs. From a regulatory perspective, the model may appear acceptable. From an atmospheric perspective, it has failed to represent the process structure.

The reliance on temporal averaging also shapes how uncertainty is interpreted. Discrepancies between modeled and observed concentrations are often attributed to emission uncertainties or measurement error. The role of temporal smoothing as a source of structural distortion is less frequently acknowledged. This leads to repeated attempts to refine inputs without questioning the appropriateness of the temporal framework itself.

In coastal air quality modeling, temporal scale choice functions as a filter that privileges certain processes while suppressing others. Processes

that operate slowly and consistently are amplified. Processes that operate rapidly and intermittently are attenuated. This filtering aligns with inland atmospheric behavior but conflicts with coastal dynamics, where rapid transitions drive accumulation and exposure.

Recognizing this conflict reframes the notion of model applicability. The issue is not whether models can be run at finer temporal resolution, but whether their conceptual structure allows time dependent processes to shape outcomes meaningfully. Simply reducing time step length without revisiting assumptions about averaging, sequencing, and process interaction may improve numerical detail without resolving conceptual mismatch.

Temporal scale also influences how policy relevance is constructed. Regulatory frameworks often rely on averaged concentration thresholds. Models designed to support these frameworks naturally emphasize averaged outputs. In coastal cities, this emphasis can obscure chronic exposure patterns driven by daily cycles rather than annual means. Applicability failure thus extends beyond scientific accuracy into governance relevance.

A coastal perspective highlights the need to treat time not as a neutral axis but as an active dimension of atmospheric organization. Dispersion capacity, chemical transformation, and exposure risk are all functions of temporal alignment between emissions and atmospheric state. Models that suppress this alignment through averaging produce outputs that are stable but incomplete.

Temporal scale and averaging effects therefore represent a central mechanism through which urban air quality models lose explanatory power in coastal environments. They do not merely reduce precision. They reshape the modeled reality in ways that systematically underrepresent accumulation, delay, and episodic exposure. Understanding this mechanism is essential for interpreting model outputs responsibly and for recognizing the limits of applying inland oriented temporal frameworks to coastal cities.

In coastal air quality modeling, time must be understood as a structuring force rather than a convenience. Until this shift is acknowledged, temporal averaging will continue to act as a silent source of applicability failure, producing models that are formally correct yet atmospherically misaligned.

7. Conceptual Implications for Model Application and Development in Coastal Contexts

The limitations observed in the application of urban air quality models to coastal cities point toward a need for conceptual recalibration rather than incremental technical correction. These models do not simply underperform because of insufficient resolution, imperfect parameterization, or incomplete input data. Their difficulties arise from deeper assumptions about how urban atmospheres function, how dispersion unfolds, and how time and space are organized within the modeling framework. Coastal cities expose these assumptions by presenting atmospheric conditions that follow different organizing principles from those embedded in most urban models.

A central implication is the recognition of coastal cities as distinct atmospheric systems rather than as variations of inland urban environments. In many modeling practices, proximity to the sea is treated as an external modifier that can be accounted for through boundary conditions or adjusted surface parameters. This framing underestimates the degree to which land sea interaction restructures atmospheric behavior. Coastal cities are governed by circulations, stratification patterns, and temporal rhythms that are not peripheral influences but dominant drivers. Treating these drivers as secondary effects produces models that are internally coherent yet externally misaligned with atmospheric reality.

This recognition requires a shift in how model scope is defined. Urban air quality models are often presented as general tools applicable across diverse urban contexts with minor adjustments. Coastal environments challenge this universality. Applicability must be understood as conditional, dependent on whether the conceptual premises of the model align with the dominant processes of the setting. This does not imply that existing models are invalid, but that their domain of meaningful interpretation is narrower than often assumed.

Model development in coastal contexts therefore demands flexibility at the level of conceptual structure. Many current modeling frameworks are optimized around stable hierarchies of scale, where synoptic forcing dominates, mesoscale processes modify, and microscale effects refine.

In coastal cities, this hierarchy collapses. Mesoscale circulations such as sea–land breezes exert control over transport and mixing that rivals or exceeds synoptic influences. Boundary layer structure becomes an emergent outcome of interacting air masses rather than a predictable response to surface heating alone.

Integrating this reality into model design requires rethinking how circulations are represented. Rather than embedding them as parameterized corrections within a background flow, they must be treated as organizing systems that shape pollutant fate. This implies a move away from models that assume monotonic transport and toward frameworks that can accommodate retention, return, and layered redistribution. Such a shift is conceptual before it is numerical. It concerns how dispersion is imagined rather than how finely it is calculated.

Another implication concerns the role of interpretation in model application. In practice, urban air quality models are often deployed as decision tools whose outputs are taken at face value. Concentration maps, exposure estimates, and scenario comparisons are treated as direct representations of environmental conditions. In coastal cities, this practice is particularly risky. Model outputs are sensitive to unresolved temporal transitions, layered boundary structures, and circulation timing that are not fully captured within standard frameworks.

Applying models in coastal contexts therefore requires interpretive restraint. Results should be read as conditional projections rather than definitive forecasts. Patterns of agreement between modeled and observed averages should not be conflated with accurate representation of processes. Discrepancies should prompt reflection on conceptual fit rather than immediate adjustment of inputs. This interpretive stance recognizes that models are structured narratives of atmospheric behavior, shaped by assumptions that may or may not hold in a given context.

This has implications for how uncertainty is understood. In many modeling exercises, uncertainty is framed as a statistical property arising from imperfect data or stochastic variability. In coastal cities, a significant portion of uncertainty is structural. It arises from the mismatch between model assumptions and atmospheric organization. Addressing this form of uncertainty requires acknowledging the limits of what the model is designed to represent, rather than attempting to eliminate discrepancy through calibration alone.

A further conceptual implication involves the meaning of dispersion itself. Traditional urban air quality modeling often treats dispersion as a process of dilution, where pollutants are spread over larger volumes and transported away from sources. This logic underpins expectations about the effectiveness of emission controls and the interpretation of meteorological favorability. In coastal cities, dispersion often takes the form of redistribution within a constrained system. Pollutants are shifted between layers, relocated offshore and back onshore, or stored temporarily before reappearing under changed conditions.

This reframing alters how model outputs should be used in planning and policy contexts. Improvements in modeled dispersion do not necessarily correspond to reductions in exposure or risk. Favorable wind conditions may redistribute pollutants rather than remove them. Short term concentration reductions may precede delayed accumulation. Policies evaluated solely on the basis of averaged model outputs risk overlooking these dynamics.

From a development perspective, this calls for models that can express conditional outcomes rather than single trajectories. Instead of predicting one concentration field for a given scenario, models should help identify ranges of behavior tied to circulation timing, boundary layer structure, and emission alignment. This does not require abandoning deterministic modeling, but it does require embracing multiplicity in interpretation.

There is also a broader epistemological implication. Urban air quality models are often positioned as objective mirrors of atmospheric reality. Coastal environments reveal that these models are better understood as interpretive instruments shaped by theoretical commitments. Their strength lies in clarifying relationships under assumed conditions, not in reproducing all atmospheric behaviors. Recognizing this helps prevent overconfidence in model outputs and encourages more reflective use.

This perspective also affects how model success is evaluated. Performance metrics based on averaged concentration agreement may be insufficient indicators of conceptual adequacy in coastal contexts. A model that reproduces mean

values while misrepresenting timing, layering, and recirculation may appear successful while offering limited explanatory insight. Evaluation criteria should therefore be aligned with process representation rather than numerical fit alone.

The conceptual implications extend to interdisciplinary communication. Coastal air quality issues sit at the intersection of atmospheric science, urban planning, public health, and environmental governance. Models serve as boundary objects linking these domains. If their limitations in coastal contexts are not explicitly recognized, they risk conveying false certainty across disciplines. Clear articulation of applicability conditions enhances transparency and supports more informed decision making.

The challenges posed by coastal cities call for a reorientation in how urban air quality models are applied and developed. The emphasis shifts from technical refinement to conceptual alignment, from universal applicability to contextual validity, and from deterministic prediction to conditional interpretation. Coastal environments do not merely complicate modeling practice. They reveal the assumptions upon which that practice rests and invite a more reflective engagement with what models can and cannot represent.

8. Conclusion

Urban air quality models occupy a central position in contemporary environmental science and governance. They structure how pollution is understood, how risks are evaluated, and how policy responses are justified. Their authority rests not only on numerical sophistication but on the assumption that they provide a faithful representation of atmospheric behavior across urban contexts. Coastal cities challenge this assumption in a systematic and revealing way. The difficulties encountered when applying urban air quality models to coastal environments are not isolated anomalies. They expose foundational tensions between model logic and atmospheric reality.

This study has shown that the atmospheric environment of coastal cities operates according to organizing principles that diverge from those embedded in most urban air quality models. Land sea thermal contrast, sea–land breeze circulation, layered boundary structures, and strong temporal variability are not marginal influences but dominant forces shaping pollutant behavior. These forces disrupt assumptions of spatial continuity, predictable mixing, monotonic dispersion, and temporal smoothness that underpin conventional modeling frameworks. When these assumptions are violated, models may continue to function computationally while losing explanatory and interpretive power.

Sea–land breeze circulation exemplifies this misalignment. Rather than facilitating progressive dilution, it often creates recirculation pathways that retain pollutants within a coastal system. Boundary layer dynamics reinforce this retention by limiting vertical mixing and sustaining stratification even under conditions traditionally associated with dispersion. Temporal averaging further suppresses the visibility of these processes by smoothing transitions that are central to accumulation and exposure. Together, these mechanisms transform the coastal urban atmosphere into a constrained and memory dependent system that resists representation through inland oriented modeling logic.

The resulting applicability failures should not be interpreted as evidence that urban air quality models are inherently flawed. Instead, they demonstrate that models are structured interpretations grounded in specific conceptual premises. When these premises align with environmental conditions, models offer valuable insight. When they do not, model outputs risk becoming internally consistent yet environmentally misleading. Coastal cities bring this conditionality into sharp focus.

Recognizing applicability failure as a conceptual issue rather than a technical defect has important implications. It shifts attention away from endless parameter adjustment and toward critical reflection on model scope. It encourages model users to interpret outputs as conditional representations rather than definitive truths. It also highlights the need to communicate model limitations transparently, especially when outputs inform regulatory decisions or public health assessments.

This perspective has practical significance. In coastal cities, apparent improvements in modeled air quality may not correspond to reductions in exposure. Emission controls may yield delayed or uneven benefits due to atmospheric retention and recirculation. Short term pollution episodes may dominate health

risk even when long term averages appear acceptable. Models that emphasize averaged outcomes without capturing timing and structure risk underestimating these dynamics.

At a broader level, the analysis underscores the importance of contextual sensitivity in environmental modeling. Urban atmospheres are not interchangeable. They are shaped by geography, climate, and surface interaction in ways that demand tailored conceptual approaches. Coastal cities represent one of the clearest cases where universal modeling assumptions encounter their limits.

The implications extend beyond air quality modeling itself. They speak to how scientific tools mediate the relationship between knowledge and governance. Models gain authority through apparent objectivity and generality. Coastal environments remind us that this authority is contingent on alignment between model structure and environmental process. Preserving the credibility and usefulness of models therefore requires acknowledging where that alignment weakens.

The applicability failures of urban air quality models in coastal cities are not obstacles to be eliminated but signals to be interpreted. They reveal the boundaries of prevailing modeling paradigms and invite a more reflective engagement with atmospheric complexity. By recognizing coastal cities as distinct atmospheric systems and by treating model outputs as context dependent interpretations, researchers and policymakers can use urban air quality models more responsibly and more effectively. This shift does not diminish the value of modeling. It clarifies its role within the broader effort to understand and manage air quality in diverse urban environments.

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