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Urban–coastal atmospheric interactions and their influence on fog formation and dissipation: A review of boundary layer processes

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ABSTRACT

Coastal fog is a significant meteorological phenomenon affecting visibility, transportation safety, aviation operations, and maritime activities in urbanized coastal regions. Its development and persistence are influenced by the interaction of marine atmospheric conditions, land-surface characteristics, urban thermal properties, and local circulation systems. Urban expansion introduces substantial changes in surface energy exchange, roughness, moisture availability, and atmospheric turbulence, thereby modifying the occurrence and evolution of fog. This review examines the principal atmospheric and surface processes responsible for fog variability across coastal urban environments, with particular attention to marine air intrusion, urban heat island effects, internal boundary layer formation, and sea-breeze and land-breeze circulation. The study synthesizes findings from observational networks, remote sensing applications, and numerical modeling approaches to assess the mechanisms influencing radiation fog and advection fog. Particular emphasis is placed on the contrasting effects of urbanization, including the reduction of radiative fog under enhanced nocturnal heat retention and the potential alteration of marine stratus and advection fog through changes in boundary layer structure and turbulent mixing. The review further discusses the application of coupled atmospheric and urban modeling systems, satellite-based fog monitoring, and surface visibility observations in understanding coastal fog behavior. Major limitations associated with model resolution, urban surface parameterization, marine layer representation, and aerosol–fog interactions are identified. The synthesis highlights the need for improved integration of urban meteorology, coastal atmospheric observations, and high-resolution numerical prediction to strengthen fog forecasting capabilities. The findings provide a scientific basis for understanding coastal fog variability and supporting future research on weather-related hazards in rapidly developing coastal regions.

Keywords: Coastal Fog, Urban Meteorology, Atmospheric Boundary Layer, Urban Heat Island, Marine Stratus, Sea Breeze, Fog Prediction, Coastal Environment

I. Introduction

Coastal cities host a disproportionate share of the world's population and economic activity, and many of the most fog-prone regions on Earth, including the California coast, the Bohai and Yellow Sea coasts of China, and the Arabian Gulf littoral, are simultaneously heavily urbanized (Fovell *et al.*, 2020) [1]. Fog at these locations imposes substantial operational costs through reduced airport visibility, maritime navigation hazards, and highway accidents, with coastal fog-related flight delays and diversions representing a persistent challenge for aviation forecasting despite decades of numerical weather prediction (NWP) improvement (Gultepe *et al.*, 2007) [2]. Unlike inland fog, which is governed primarily by nocturnal radiative cooling and local moisture availability, coastal fog formation and evolution is controlled by the interaction of marine boundary layer stratus, land-sea thermal contrast, and, in urbanized coastal zones, the additional modification imposed by the urban heat island (UHI) and increased surface roughness (Bretherton *et al.*, 2004) [3]. The atmospheric boundary layer (ABL) at a coastal-urban interface is characterized by pronounced spatial heterogeneity over very short distances. As marine air advects onshore, it encounters an abrupt discontinuity in both surface roughness and thermal properties at the coastline, generating an internal boundary layer (IBL) that grows with downwind distance from the coast, within which turbulence characteristics, temperature, and humidity profiles differ systematically from both the offshore marine boundary layer and the inland continental boundary layer (Arya, 2001) [4]. Where this coastal transition zone is heavily urbanized, the IBL further interacts with the urban boundary layer, which is typically deeper, warmer, and mechanically more turbulent than either the marine or rural continental boundary layer, due to enhanced sensible heat flux and building-induced roughness (Oke, 1987) [5].

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This complex layering has direct implications for coastal fog. Radiation fog, which forms through nocturnal longwave radiative cooling of the surface and overlying air under clear skies and light winds, is systematically suppressed in urban areas because the urban heat island reduces the magnitude of nocturnal cooling and anthropogenic heat flux maintains near-surface temperatures above the dew point that would otherwise be reached in the surrounding rural terrain, a well-documented urban fog-suppression effect observed across multiple mid-latitude and subtropical cities (Sarkar *et al.*, 2020) [6]. In contrast, advection fog, formed when relatively warm, moist marine air is advected over a cooler surface or subsides into a shallow, stable marine layer, behaves differently at urban coastal interfaces: observations along the California coast have shown that the marine stratus deck advecting onshore is frequently trapped beneath a lowered inversion as it encounters the deeper, more turbulent urban boundary layer, in some cases lowering cloud base to the surface and producing fog, while in other cases urban-enhanced turbulent mixing erodes the stratus deck entirely, producing a bifurcated outcome that depends sensitively on the relative depth and stability of the incoming marine layer relative to the urban boundary layer it encounters (Faloona *et al.*, 2020) [7].

The sea-breeze/land-breeze circulation exerts an additional first-order control on this system. During daytime, differential heating between the warmer land surface and cooler ocean generates an onshore sea-breeze circulation that advects moist marine air inland, while at night the land cools more rapidly than the ocean, reversing the circulation into a weaker offshore land breeze (Pielke, 2013) [8]. Over urbanized coastlines, the urban heat island can significantly modify both the timing and strength of this circulation, in some cases advancing sea-breeze onset and enhancing its inland penetration depth due to intensified land-sea thermal contrast, and in other cases suppressing the nocturnal land-breeze phase because urban surfaces retain heat longer than natural rural terrain, altering the diurnal timing of fog-favorable onshore versus offshore flow conditions (Sarkar *et al.*, 2020) [9].

Remote sensing and in-situ observational networks have substantially advanced understanding of these processes. Ceilometer and Doppler lidar-derived boundary layer height retrievals along the California coast have documented systematic differences in nocturnal and morning boundary layer depth between coastal, urban, and inland stations separated by only tens of kilometers, directly linking these differences to observed fog frequency and persistence patterns (Dorman *et al.*, 2017) [10]. Geostationary satellite fog-detection algorithms using infrared brightness temperature differences between the 3.9 μm and 10.7 μm channels have enabled spatially continuous mapping of coastal fog extent and diurnal evolution, revealing that urban areas frequently exhibit later fog dissipation times than adjacent rural coastal terrain due to the combined effects of urban heat retention and aerosol-modified microphysics (Miller *et al.*, 2005) [11].

Coupled mesoscale modeling using the Weather Research and Forecasting (WRF) model with an embedded Urban Canopy Model (UCM) and high-resolution land-surface schemes has been used to reproduce and attribute these observed coastal-urban boundary layer differences, though such studies consistently report that model skill in reproducing fog onset timing and spatial extent remains limited by uncertainty in urban canopy parameterization, the representation of the land-sea thermal discontinuity at model grid resolution, and the microphysical schemes governing fog droplet formation and dissipation (Chen *et al.*, 2011) [12]. This paper synthesizes observational and modeling evidence on diurnal boundary layer dynamics at coastal-urban interfaces, with specific focus on the implications of this dynamical coupling for operational fog prediction.

Research objectives

1. To examine the physical mechanisms governing diurnal boundary layer evolution at coastal-urban interfaces.
2. To review observational evidence of urban modification of radiation and advection fog processes.

3. To evaluate the role of sea-breeze/land-breeze circulation and internal boundary layer development in coastal-urban fog variability.
4. To compare reported boundary layer and fog characteristics across major coastal-urban case studies.
5. To identify modeling limitations and uncertainties constraining operational coastal fog prediction.

II. Literature review

2.1 Marine boundary layer and coastal stratus characteristics

The marine boundary layer along many subtropical and mid-latitude eastern ocean boundaries, including the California coast, is characterized by a persistent, shallow, well-mixed layer capped by a strong subsidence inversion, within which stratus and stratocumulus cloud frequently forms due to longwave radiative cooling at cloud top (Bretherton *et al.*, 2004) [3]. This marine stratus deck is a primary source of advection fog when it is advected onshore and its base lowers to the surface, a process strongly modulated by the depth and strength of the capping inversion relative to coastal terrain elevation and the thermal properties of the surface the air mass encounters upon landfall (Faloona *et al.*, 2020) [7].

2.2 Internal boundary layer development at the coastline

As marine air crosses the coastline, it encounters an abrupt change in surface roughness and thermal forcing, generating an internal boundary layer (IBL) whose depth grows approximately with the square root of downwind distance from the coast under neutral stability, though this growth rate is substantially modified under the stable stratification typical of nocturnal and early-morning conditions common during fog events (Arya, 2001) [4]. Within the IBL, turbulence intensity, temperature, and humidity profiles differ systematically from the undisturbed marine air aloft, and the depth and turbulent structure of this layer directly influences whether advected marine stratus is maintained, lowered to the surface as fog, or eroded through enhanced turbulent mixing with warmer, drier air from above (Arya, 2001) [4], (Faloona *et al.*, 2020) [7].

2.3 Urban heat island effects on nocturnal boundary layer structure

Urban heat island research has consistently shown that urban surfaces exhibit reduced nocturnal radiative cooling relative to rural terrain due to anthropogenic heat flux, reduced sky-view factor within street canyons, and the higher thermal admittance of construction materials, all of which act to elevate nocturnal near-surface temperatures and suppress the surface-based temperature inversions that favor radiation fog formation (Oke, 1987) [5], (Sarkar *et al.*, 2020) [6]. Observational studies comparing paired urban and rural sites have documented that radiation fog frequency is measurably reduced within urban cores relative to surrounding rural or peri-urban terrain, an effect sometimes termed urban fog suppression, attributable primarily to the urban heat island's reduction of the diurnal temperature range required to reach the dew point under radiative cooling conditions (Sarkar *et al.*, 2020) [6].

2.4 Urban modification of advection fog

In contrast to its suppressive effect on radiation fog, urban boundary layer characteristics interact with advected marine stratus in a more complex, sometimes fog-enhancing manner. Observational studies along the central California coast have shown that as marine stratus advects over increasingly urbanized terrain, the deeper and more mechanically turbulent urban boundary layer can either erode the stratus deck through enhanced entrainment of warm, dry air from above the inversion, or, under conditions where the marine layer is sufficiently deep and moist, promote surface fog formation by lowering the effective cloud base as the marine layer is compressed against the urban internal boundary layer (Faloona *et al.*, 2020) [7]. This bifurcated outcome has been linked to the relative depth of the incoming marine

layer compared to the urban boundary layer depth, with shallow marine layers more susceptible to urban-induced erosion and deep marine layers more susceptible to urban-induced fog persistence (Faloona *et al.*, 2020) [7], (Dorman *et al.*, 2017) [10].

2.5 Sea-breeze/land-breeze modulation by urbanization

The sea-breeze circulation, driven by differential land-ocean heating, is a first-order control on the diurnal timing of onshore moisture advection relevant to fog formation (Pielke, 2013) [8]. Urbanization has been shown to modify both sea-breeze onset timing and inland penetration depth, with several studies reporting that enhanced urban heating intensifies the daytime land-sea thermal gradient, advancing sea-breeze onset and increasing its inland extent, while simultaneously delaying or weakening the nocturnal land-breeze reversal due to prolonged urban heat retention through the evening transition (Sarkar *et al.*, 2020) [9]. This asymmetric modification of the diurnal sea-breeze/land-breeze cycle directly alters the timing window during which fog-favorable onshore flow conditions occur at coastal-urban interfaces relative to adjacent non-urbanized coastal terrain.

2.6 Observational and remote sensing evidence

Ceilmeter and Doppler lidar boundary-layer height retrievals deployed across coastal, urban, and inland transects have provided direct evidence of the spatial heterogeneity in nocturnal and pre-dawn boundary layer depth associated with these combined mechanisms, with urban stations typically exhibiting a deeper, more persistent residual boundary layer overnight relative to both coastal and rural inland stations (Dorman *et al.*, 2017) [10]. Geostationary satellite fog-detection techniques using the dual-channel infrared brightness temperature difference method have enabled continuous spatial mapping of fog extent and dissipation timing, revealing systematically delayed fog dissipation over urban areas relative to surrounding rural coastal terrain in multiple case studies, attributed to the combined effects of urban heat retention delaying daytime warming-driven fog burn-off and urban aerosol loading altering fog droplet size distribution and optical thickness (Miller *et al.*, 2005) [11].

2.7 Coupled modeling studies

WRF-UCM coupled simulations incorporating detailed urban canopy and land-surface parameterizations have been used to reproduce the observed coastal-urban boundary layer contrasts and to test sensitivity of simulated fog onset and dissipation timing to urban canopy representation, anthropogenic heat flux magnitude, and model horizontal resolution (Chen *et al.*, 2011) [12]. These studies consistently find that model skill in reproducing fog spatial extent and diurnal timing is highly sensitive to the resolution at which the land-sea thermal discontinuity and urban canopy structure are represented, with coarser-resolution simulations tending to smear the sharp coastal-urban boundary layer gradients that observations show to be critical for accurate fog prediction (Chen *et al.*, 2011) [12], (Zhong *et al.*, 2015) [13].

2.8 Research gap

While urban heat island suppression of radiation fog and marine boundary layer control of advection fog are each individually well studied, relatively few investigations have examined their combined interaction within a single coastal-urban framework that explicitly accounts for the internal boundary layer generated at the coastline (Arya, 2001) [4], (Faloona *et al.*, 2020) [7]. Furthermore, most coupled modeling studies focus on a single case-study city, limiting generalizability of findings regarding the sensitivity of coastal-urban fog to urban canopy parameterization choices across differing coastal geometries and climate regimes (Chen *et al.*, 2011) [12]. This study addresses these gaps by synthesizing evidence across radiation fog suppression, advection fog modification, and sea-breeze circulation pathways within an integrated comparative framework spanning multiple coastal-urban case studies.

III. Methodology

3.1 Research design

This study adopts a qualitative, descriptive, and comparative research design based on synthesis of observational, remote-sensing, and coupled mesoscale/LES modeling literature addressing diurnal boundary layer dynamics and fog processes at coastal-urban interfaces. The approach consolidates reported findings across differing methodological traditions to characterize consistent physical patterns and quantify the range of reported urban modification effects on fog formation and dissipation.

3.2 Conceptual framework

The framework applied in this review models coastal-urban fog outcome as jointly determined by three interacting boundary-layer processes: (1) the depth and stability of the incoming marine boundary layer and its associated stratus deck, (2) the internal boundary layer generated at the coastal roughness/thermal discontinuity, and (3) the urban boundary layer modification imposed by heat island intensity, anthropogenic heat flux, and building-induced turbulence. The interaction of these three layers, modulated by the diurnal sea-breeze/land-breeze cycle, determines whether radiation fog is suppressed inland, whether advected marine stratus is eroded or lowered to the surface as fog, and the timing of fog onset and dissipation relative to non-urbanized coastal terrain.

3.3 Data sources

The literature synthesized in this review draws on coastal micrometeorological tower networks providing paired urban-rural temperature, humidity, and turbulence measurements; ceilometer and Doppler lidar boundary-layer height retrievals from coastal observational networks including sites along the California coast; geostationary satellite fog-detection products using dual-channel (3.9 μm /10.7 μm) infrared brightness temperature difference techniques; in-situ visibility sensors and fog liquid water content measurements; and coupled Weather Research and Forecasting model with Urban Canopy Model (WRF-UCM) and Large-Eddy Simulation (LES) experiments for process-level attribution.

3.4 Analytical framework

Reviewed studies were organized according to the three-layer interaction framework described in Section 3.2. Evidence was classified by fog type (radiation vs. advection), by observational method (in-situ tower, remote sensing, or coupled model), and by coastal-urban case study, enabling systematic comparison of reported urban modification effects across differing coastal geometries, climate regimes, and urban morphologies.

3.5 Evaluation criteria

Comparative evaluation in this review uses metrics standard in the coastal boundary-layer and fog literature: **boundary layer height anomaly** (urban-rural or urban-coastal difference in nocturnal/pre-dawn boundary layer depth), **fog frequency anomaly** (percentage difference in fog occurrence between urban and adjacent rural coastal sites), **fog dissipation time anomaly** (difference in daytime fog burn-off timing between urban and rural sites), and **sea-breeze onset/penetration anomaly** (urban-induced change in sea-breeze timing and inland extent), used to assess the consistency and magnitude of reported coastal-urban boundary layer and fog modification effects.

IV. Results and discussion

4.1 Comparative boundary layer and fog characteristics across coastal-urban case studies

Table I summarizes representative findings on boundary layer and fog modification across the major coastal-urban case studies reviewed in Section II.

Table I. Reported coastal-urban boundary layer and fog characteristics by case study

Location	Urban BL depth anomaly (vs. rural coastal)	Radiation fog effect	Advection fog effect	Dominant mechanism	Source
California Central Coast (urban corridor)	Deeper, more persistent nocturnal residual layer	Suppressed inland	Bifurcated: eroded (shallow marine layer) or enhanced (deep marine layer)	Marine layer depth relative to urban BL	[7], [10]
San Francisco Bay Area	Elevated nocturnal minimum temperature	Suppressed	Delayed dissipation over urban core	UHI + aerosol optical effects	[6], [11]
Los Angeles Basin	Enhanced daytime sea-breeze penetration	Suppressed	Modified stratus persistence inland	Sea-breeze intensification	[8], [9]
Hong Kong coastal-urban zone	Increased turbulent mixing depth	Suppressed	Localized fog trapping in street canyons	Building-induced roughness + IBL	[5], [12]
Generic WRF-UCM sensitivity domain	Model-dependent, sensitive to resolution	Reduced fog frequency with UCM active	Fog extent highly resolution-dependent	Land-sea discontinuity representation	[12], [13]

4.2 Diurnal cycle contrast between fog types

Table II compares the diurnal timing characteristics of radiation and advection fog at coastal-urban interfaces, based on the reviewed observational and modeling literature.

4.3 Internal boundary layer growth and fog outcome

Table III summarizes reported internal boundary layer growth characteristics and their association with fog persistence versus erosion outcomes across the reviewed case studies.

4.4 Reconciling suppression and enhancement outcomes

The comparative results in Tables I–III indicate that the apparently contradictory findings of urban fog suppression and urban fog enhancement are not methodologically inconsistent but reflect the operation of two distinct physical pathways acting on two distinct fog types: urban heat island warming robustly suppresses radiation fog by raising nocturnal near-surface temperatures above the dew point threshold required for saturation (Oke, 1987) [5], (Sarkar *et al.*, 2020) [6], while its effect on advection fog is bifurcated and depends on the relative depth of the incoming marine layer compared to the urban-modified internal boundary layer, sometimes eroding the stratus deck and sometimes trapping it at the surface (Faloona *et al.*, 2020) [7], (Dorman *et al.*, 2017) [10]. This distinction, largely absent from earlier urban fog literature that treated "fog" as a single undifferentiated category, is essential for accurate operational forecasting at coastal-urban interfaces.

Table II. Diurnal timing characteristics of radiation vs. advection fog at coastal-urban interfaces

Characteristic	Radiation fog	Advection fog	Reference basis
Primary formation driver	Nocturnal long-wave radiative cooling	Onshore advection of marine stratus	[3], [6]
Typical onset time	Late night to pre-dawn	Variable; often evening onset with onshore flow	[7], [8]
Urban modification direction	Suppression (reduced frequency/intensity)	Bifurcated (suppression or enhancement)	[6], [7]
Sensitivity to UHI intensity	High (directly reduces cooling needed for saturation)	Moderate (affects IBL depth and mixing)	[5], [6]
Sensitivity to sea-breeze timing	Low	High (governs onshore moisture advection timing)	[8], [9]
Typical dissipation mechanism	Daytime surface heating	Daytime heating + turbulent entrainment of dry air aloft	[7], [11]
Urban effect on dissipation timing	Earlier dissipation (less fog to begin with)	Delayed dissipation over urban core	[11]

4.5 Discussion

Collectively, the evidence reviewed demonstrates that diurnal boundary layer dynamics at coastal-urban interfaces are governed by the interaction of three distinct physical layers, marine, internal, and urban, whose relative depth and stability determine fog outcome in a manner that differs fundamentally between radiation and advection fog types (Bretherton *et al.*, 2004) [3], (Faloona *et al.*, 2020) [7]. The consistent finding of urban radiation fog suppression across multiple independent case studies (California, San Francisco, Los Angeles, Hong Kong) provides strong confidence in this mechanism as a general feature of urbanized coastal terrain (Sarkar *et al.*, 2020) [6], (Sarkar *et al.*, 2020) [9], (Chen *et al.*, 2011) [12]. In contrast, the bifurcated urban effect on advection fog, sometimes enhancing and sometimes suppressing marine stratus-derived fog, indicates that no single universal urban fog-modification factor can be applied across coastal-urban sites; the outcome depends sensitively on the relative depth of the incoming marine layer, the strength of urban heating, and the timing of the sea-breeze/land-breeze cycle at each specific location (Faloona *et al.*, 2020) [7], (Pielke, 2013) [8], (Dorman *et al.*, 2017) [10]. The strong sensitivity of coupled model skill to horizontal resolution and urban canopy parameterization further indicates that operational fog forecasts at coastal-urban interfaces are particularly vulnerable to model resolution limitations, since the physical processes governing fog outcome operate over spatial scales, the internal boundary layer transition zone, that are frequently under-resolved in operational-resolution NWP systems (Chen *et al.*, 2011) [12], (Zhong *et al.*, 2015) [13].

V. Challenges in coastal-urban boundary layer and fog prediction

Several challenges constrain further progress in this field. **Sub-grid-scale representation** of the land-sea thermal discontinuity and internal boundary layer growth remains a persistent limitation in operational-resolution NWP models, since the sharp gradients governing fog outcome typically occur over horizontal scales of a few kilometers that are poorly resolved at standard operational grid spacing (Arya, 2001) [4], (Chen *et al.*, 2011) [12]. **Urban canopy parameterization uncertainty**, including anthropogenic heat flux specification and building-height-dependent roughness representation, introduces substantial spread in simulated boundary layer depth and fog timing across model configurations (Chen *et al.*, 2011) [12], (Zhong *et al.*, 2015) [13]. **Marine layer depth observation gaps** limit the ability to forecast the bifurcated advection-fog outcome, since accurate prediction requires real-time knowledge of incoming marine layer depth relative to the urban-modified internal boundary layer, information not routinely available at the spatial density required for operational use (Faloona *et al.*, 2020) [7], (Dorman *et al.*, 2017) [10]. **Aerosol-fog microphysical interaction** remains incompletely characterized at coastal-urban interfaces, where elevated urban aerosol loading may alter fog droplet size distribution and optical thickness in ways that affect both satellite-based fog detection and visibility forecasting, but that are not yet systematically quantified across diverse coastal-urban settings (Miller *et al.*, 2005) [11]. Finally, **cross-site generalization** remains limited, as most detailed process-level studies focus on a small number of well-instrumented coastal megacities, leaving open the question of how findings transfer to less-studied coastal-urban regions with differing coastline geometry and urban morphology (Oke, 1987) [5], (Chen *et al.*, 2011) [12].

Table III. Internal boundary layer characteristics and associated fog outcomes

IBL growth regime	Stability condition	Marine layer depth relative to IBL	Reported fog outcome	Source
Rapid IBL growth (unstable/neutral)	Daytime, well-mixed	Shallow marine layer	Stratus erosion, fog dissipation	[4], [7]
Suppressed IBL growth (stable)	Nocturnal/pre-dawn	Deep marine layer	Stratus lowering, fog persistence/enhancement	[4], [7]
Urban-enhanced turbulent IBL	Mechanically forced (building roughness)	Variable	Localized fog trapping or clearing (site-dependent)	[5], [12]

VI. Conclusion

This study has reviewed the physical mechanisms governing diurnal boundary layer dynamics at coastal-urban interfaces and their implications for fog prediction. The evidence demonstrates that urban heat island warming robustly and consistently suppresses radiation fog by elevating nocturnal near-surface temperatures above the saturation threshold, an effect documented across multiple independent coastal-urban case studies (Oke, 1987) [5], (Sarkar *et al.*, 2020) [6], (Sarkar *et al.*, 2020) [9]. In contrast, urban modification of advection fog produced by advected marine stratus is bifurcated, sometimes eroding the stratus deck through enhanced turbulent mixing and sometimes trapping it at the surface as fog, with the outcome governed by the relative depth of the incoming marine boundary layer compared to the urban-modified internal boundary layer (Arya, 2001) [4], (Faloona *et al.*, 2020) [7], (Dorman *et al.*, 2017) [10]. The sea-breeze/land-breeze circulation provides an additional, urbanization-sensitive control on the diurnal timing of fog-favorable onshore flow, with several studies documenting urban intensification of daytime sea-breeze penetration alongside delayed nocturnal land-breeze onset (Pielke, 2013) [8], (Sarkar *et al.*, 2020) [9]. Coupled WRF-UCM modeling studies confirm the qualitative direction of these mechanisms but reveal substantial sensitivity of quantitative fog-timing skill to urban canopy parameterization and model resolution, indicating that improved operational coastal-urban fog prediction will require both finer-resolution model configurations and improved observational constraint of marine layer depth and urban boundary layer structure (Chen *et al.*, 2011) [12], (Zhong *et al.*, 2015) [13].

VII. Future work

Future research should prioritize high-resolution, convection-permitting coupled mesoscale/LES simulations explicitly designed to resolve the internal boundary layer transition zone at the coastal-urban interface, since this scale is currently under-resolved in most operational forecast systems. Further work is needed to expand ceilometer and Doppler lidar observational networks across a broader and more climatically diverse sample of coastal-urban sites, enabling improved characterization of marine layer depth relative to urban boundary layer depth as a predictive variable for advection fog outcome. Continued refinement of urban canopy parameterizations, particularly regarding anthropogenic heat flux variability and building-height-dependent turbulence representation, should be pursued to reduce model uncertainty in simulated fog timing. Research should also examine aerosol-fog microphysical interactions specific to coastal-urban environments, given the potential for urban aerosol loading to alter both satellite-based fog detection accuracy and surface visibility forecasts. Finally, studies should assess how projected future urban expansion along fog-prone coastlines may further modify the coupled radiation-advection fog balance, providing forward-looking guidance for aviation and maritime forecasting infrastructure in rapidly urbanizing coastal regions.

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