

Quantifying the impacts of cloud seeding on severe winter sea fog dissipation and visibility using a coupled atmosphere–ocean model

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Article

Keywords: Cloud seeding, Sea fog dissipation, Visibility, Modified Morrison scheme, Coupled atmosphere-ocean model

Posted Date: July 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10292968/v1>

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Additional Declarations: No competing interests reported.

Abstract

This study quantitatively assesses the effects of cloud seeding on winter sea fog dissipation and the resulting visibility improvement along the western coast of South Korea, bordering the Yellow Sea, during a severe sea fog event from December 23 to 24, 2017. A coupled atmosphere–ocean modeling system incorporating a modified Morrison microphysics scheme was used to perform calcium chloride (CaCl_2)-seeded (SEED) and unseeded (UNSD) simulations for comparison. In the primary SEED simulation, CaCl_2 particles were released at an altitude of 672 m. Additional sensitivity simulations evaluated seeding at altitudes of 410 and 23 m, representing the middle (200–500 m) and lower (0–200 m) portions of the fog layer, respectively, to examine the influence of release height on seeding effectiveness. By 120 min after the end of seeding, the SEED simulation exhibited greater winter sea fog dissipation and improved near-surface visibility relative to the UNSD simulation, with a mean increase in visibility of 0.2 km and localized improvements of up to 1.6 km around Incheon International Airport. This improvement was likely attributable to enhanced cloud-to-rain conversion and the more efficient removal of fog droplets through collision–coalescence processes, thereby accelerating fog dissipation. The SEED simulation was also characterized by changes in the thermal and moisture structures of the marine boundary layer, including variations in near-surface hydrometeors, relative humidity, and air temperature, collectively contributing to differences in sea fog evolution and the effectiveness of cloud seeding. Sensitivity simulations further showed that seeding at 23 m resulted in significantly greater improvements in near-surface visibility than seeding at 410 and 672 m, indicating that lower-altitude seeding was more effective under the simulated conditions.

1. Introduction

In recent decades, the frequency and intensity of sea fog have increased in several coastal regions worldwide, including the eastern North Pacific, the North Atlantic, and the Yellow Sea^{1,2,3}. Substantial evidence indicates that climate change can intensify sea fog persistence and reduce visibility by increasing sea surface temperatures (SSTs), enhancing air–sea thermal contrasts, and altering atmospheric stability^{3,4,5}. As sea fog forms over the ocean and often extends inland under favorable meteorological conditions, it can substantially affect coastal airports, harbors, and populated areas. Reduced visibility associated with dense sea fog leads to flight delays and cancellations, shipping disruptions, and an increased risk of accidents, thereby imposing considerable socioeconomic costs on coastal regions^{6,7,8}. Therefore, reliable forecasting of sea fog is crucial and requires a better understanding of air–sea interactions, a comprehensive assessment of regional climate variability, and the development of effective early warning and disaster management systems to minimize safety hazards and economic losses^{5,6,9,10}.

Most previous numerical modeling and observational studies of sea fog have investigated its formation, persistence, and dissipation using either high-resolution atmospheric or ocean models, with a particular focus on boundary-layer processes, radiative cooling, and moisture transport^{11,12,13,14}. However, recent

research has increasingly emphasized the incorporation of air–sea coupling into numerical studies of sea fog. Several studies have demonstrated that air–sea coupling improves simulations of sea fog events by producing more realistic SSTs, surface heat and moisture fluxes, and lower-tropospheric stability^{9,15,16,17}. These coupled processes regulate air–sea heat and moisture exchange through variations in SSTs and surface fluxes, which modify near-surface atmospheric stability, thereby controlling turbulent mixing and the vertical distribution of liquid water and ultimately influencing both the formation and dissipation of sea fog^{9,18}. These findings highlight the critical importance of explicitly representing air–sea coupling in sea fog prediction systems, particularly for improving the understanding of the sea fog life cycle and its associated processes.

Various strategies have been proposed for fog dissipation, including heating, mechanical mixing, and chemical approaches, such as cloud seeding with hygroscopic or glaciogenic particles^{13,19}. Among these approaches, cloud seeding has emerged as a promising technique because it enhances collision–coalescence processes and promotes the growth of fog droplets into raindrops, which subsequently fall as precipitation, accelerating fog dissipation in coastal regions^{20,21}. This process modifies fog microphysics through the introduction of seeding agents, such as hygroscopic salts or glaciogenic materials, which enhance droplet growth, promote sedimentation, and ultimately improve visibility^{22,23,24,25}.

Numerical studies have demonstrated the potential of cloud seeding for fog dissipation. For instance, He et al.²³ simulated a cold-fog event over Beijing using a liquid-nitrogen seeding parameterization in a mesoscale meteorological model and showed that a 10-min upwind seeding operation produced noticeable improvements in visibility after approximately 9 min, with the effect peaking at approximately 24 min and persisting for about 25 min. The strongest response occurred at a release rate of 15 g s^{-1} applied 5–6 km upstream. Similarly, He et al.²⁴ showed that 80- μm salt particles improved visibility beginning 18 min after seeding, with the effect peaking at 21 min and lasting for 35 min over the Beijing–Tianjin region of China. They found that an optimal seeding amount of 30 g m^{-2} resulted in a maximum visibility of 380 m. In addition, both field and laboratory experiments have confirmed that cloud seeding can modify fog microphysics and improve visibility. Jin et al.²⁶ reported significant increases in droplet number concentration and liquid water content (LWC) during a warm fog event following the use of hygroscopic flares. Khain et al.¹⁹ showed that sodium chloride (NaCl) seeding rapidly enhanced visibility to approximately 100 m in fog chamber experiments and produced short-term visibility improvements lasting 1.5–2 min in small-scale outdoor tests.

Despite recent advances in fog modeling, significant challenges remain in accurately simulating and assessing the evolution of sea fog in coastal regions. These challenges arise from the inadequate representation of air–sea coupling processes, uncertainties in fog microphysics and cloud-seeding parameterizations, and limited marine observations for model validation. Most previous studies have relied on uncoupled atmospheric or oceanic models, which could not fully capture the coupled air–sea processes governing sea fog evolution. In addition, studies of fog using standalone atmospheric models

with explicit cloud-seeding parameterizations remain limited, whereas research investigating the effects of cloud seeding on sea fog within a coupled atmosphere–ocean modeling framework is virtually nonexistent. These limitations are particularly relevant in the Yellow Sea region, one of the most sea fog-prone marginal seas in East Asia²⁷, where frequent sea fog events impose substantial socioeconomic impacts^{28,29,30,31,32}. To address these gaps, this study employed a coupled atmosphere–ocean modeling framework to investigate the mechanisms governing sea fog dissipation over the Yellow Sea, with a particular emphasis on the western coast of South Korea. By explicitly resolving air–sea interactions, the coupled system provides a more realistic representation of the environmental conditions governing sea fog evolution. Furthermore, a cloud-seeding parameterization was incorporated into the microphysics scheme of the atmospheric model to quantitatively evaluate its effectiveness in enhancing sea fog dissipation and improving coastal visibility.

2. Materials and Methods

2.1. Study area, data and methods

The study area encompassed the western coast of South Korea bordering the Yellow Sea and surrounding regions, including Incheon International Airport (IIA). The Yellow Sea is a semi-enclosed marginal sea bordered by the Korean Peninsula to the east and mainland China to the west, forming an important oceanic region for air–sea interactions. Because of the Yellow Sea’s shallow bathymetry and weak topographic gradients, air–sea interactions play a crucial role in regulating the exchange of heat, moisture, and momentum between the ocean and the atmosphere, thereby influencing regional weather and oceanic conditions^{33,34,35,36,37}. These interactions further influence regional atmospheric conditions by modulating the underlying ocean state and properties of air masses advected over the sea, thereby affecting the thermodynamic structure of the marine boundary layer^{18,38,39,40,41,42}. Consequently, Incheon, located in the western coastal zone of South Korea, frequently experiences sea fog, with approximately 65–105 fog days per year during 2016–2025, according to observations from the Korea Meteorological Administration (KMA; <https://data.kma.go.kr/climate/fog/selectFogChart.do?pgmNo=706>). Such sea fog events occur most frequently under conditions of strong air–sea temperature contrasts, which are favorable for sea fog formation.

In this study, we employed a coupled atmosphere–ocean numerical modeling system to investigate the processes governing sea fog dissipation under coupled air–sea interaction conditions and assess the impact of cloud seeding on sea fog dissipation and associated visibility improvement in coastal regions. The analysis focused on a severe sea fog event that developed along the western coast of South Korea, particularly over the IIA region, during December 23–24, 2017, as identified from satellite-derived fog imagery. During this event, visibility decreased to as low as 50 m, triggering low-visibility warnings and causing > 1,100 flight disruptions between December 23 and 24, 2017⁴³. This event resulted in a record-high impact on airport operations⁴³. The occurrence and spatial evolution of sea fog during the study

period were further examined using observations from the Communication, Ocean, and Meteorological Satellite (COMS) operated by the KMA.

For model validation, 27 monitoring sites were selected to evaluate several meteorological variables (Fig. 1), including air temperature, wind speed (WS), relative humidity (RH), visibility, dew point temperature, atmospheric pressure, solar radiation (RAD), precipitation, and cloud fraction. Hourly meteorological data were obtained from the Automated Synoptic Observing System (ASOS), Aerodrome Meteorological Observation System (AMOS), and Automatic Weather Station (AWS) operated by the KMA. In addition, SST data were collected from six marine observation stations (Fig. 1), including three buoy stations and three tidal stations, operated by the Korea Hydrographic and Oceanographic Agency (<https://www.khoa.go.kr>). Model performance was evaluated using standard statistical metrics, including the index of agreement (IOA), root mean square error (RMSE), and mean bias error (MBE), for all selected meteorological variables and SST.

In numerical models, visibility is commonly estimated by combining a hydrometeor extinction-based approach with an RH-based clear-air formulation^{44,45,46,47}. In this study, visibility was estimated using this combined framework to accurately characterize atmospheric visibility under various moisture conditions. The visibility associated with hydrometeor extinction was calculated using the Koschmieder formula as follows:

$$Vis_{hydro} = \frac{-\ln(C_T)}{\beta}$$

1

where C_T is the contrast threshold, representing the minimum contrast required for an observer to distinguish a target from its background. In this study, C_T was set to 0.05, a commonly used value for visibility estimation and Meteorological Optical Range calculations, following the guidelines of the World Meteorological Organization⁴⁸, which yields $-\ln(0.05) \approx 3.00$. The extinction coefficient, β , was calculated using the implementation in the NOAA/NCEP Unified Post Processor, which is based on the visibility algorithm developed by Stoelinga and Warner.⁴⁵ In this approach, β was calculated as the sum of the extinction contributions from multiple hydrometeor species, as follows:

$$\beta = 144.7C_c^{0.88} + 2.24C_r^{0.75} + 327.8C_i^{1.00} + COEF_{snow}(T)C_s^{1.00} + 4.0C_g^{0.75}$$

2

$$COEF_{snow}(T) = \begin{cases} 10, & T \leq 271.15 \text{ K} \\ 10 - 4(T - 271.15), & 271.15 \text{ K} < T < 272.15 \text{ K} \\ 6, & T \geq 272.15 \text{ K} \end{cases}$$

3

where C_c , C_r , C_i , C_s , and C_g represent the mass concentrations of cloud water, rainwater, cloud ice, snow, and graupel, respectively (g m^{-3}). The temperature-dependent coefficient in the snow extinction term, $\text{COEF}_{\text{snow}}(T)$, represents the linear transition from dry to wet snow as air temperature increases. In addition, clear-air visibility based on RH was computed using the Rapid Update Cycle formula⁴⁴:

$$Vis_{RH} = 60 \times \exp\left[-\frac{2.5(RH - 15)}{80}\right]$$

4

In this study, visibility was diagnosed as the minimum of the hydrometeor-extinction-based and RH-based visibility estimates, representing the greater atmospheric attenuation associated with either hydrometeors or near-saturation RH^{47,49}. This approach accounts for both hydrometeor effects and RH-related processes, including hygroscopic growth and the possible formation of subgrid-scale clouds or ice, thereby providing a more realistic estimate of visibility under varying atmospheric conditions⁴⁹.

2.2. Model descriptions and cloud seeding methodology

We employed version 3.2 of the Coupled Ocean-Atmosphere-Wave Sediment Transport (COAWST) modeling system⁵⁰ to simulate the evolution of sea fog, with particular emphasis on its dissipation phase during the study period. The COAWST system consists of four component models: the Weather Research and Forecasting (WRF) model⁵¹, Regional Ocean Modeling System (ROMS)⁵², Simulating Waves Nearshore⁵³, and Community Sediment Transport Modeling System⁵⁴. The COAWST system supports optional coupling among these component models, allowing users to configure different coupled modeling frameworks depending on the application. In this study, we employed the coupled WRF–ROMS configuration to simulate the coupled atmosphere–ocean processes associated with sea fog evolution. The WRF and ROMS models were coupled using the Model Coupling Toolkit (MCT)^{55,56}, which facilitates the exchange of variables between the atmosphere and ocean components during model integration. The WRF model provides the ROMS model with surface wind, sea-level pressure, RH, air temperature, cloud fraction, precipitation, and net longwave and shortwave radiation fluxes, whereas the ROMS model provides the WRF model with SST. These variables were exchanged between the WRF and ROMS models at 6-min intervals throughout the simulation period. Additional details regarding the exchange processes between the WRF and ROMS models are provided in our previous studies^{57,58,59}.

The computational domain of the COAWST model was centered over Gyeong-gi Bay along the western coast of South Korea in the eastern Yellow Sea. The model employed four nested WRF domains and three nested ROMS domains using a one-way nesting configuration, with horizontal grid spacings of 13.5, 4.5, 1.5, and 0.5 km for the WRF domains and 9, 3, and 1 km for the ROMS domains, respectively. The model domains covered four regions: East Asia (domain 1 [D1]), the Korean Peninsula (D2), the western coastal region of South Korea (D3), and Gyeong-gi Bay (D4; WRF only; Fig. 1). The initial and lateral boundary conditions for the WRF model were derived from the European Centre for Medium-

Range Weather Forecasts ERA5 reanalysis dataset, with a spatial resolution of 0.25° and temporal resolution of 3 h. To improve the representation of surface conditions, high-resolution datasets were incorporated, including 1-arc-second topographic data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (<https://asterweb.jpl.nasa.gov/gdem.p/>) and 1-arc-second land-use data from the Korean Land Use Dataset⁶⁰. In addition, the Noah land surface model was used to represent land–atmosphere interactions and simulate surface heat fluxes^{61,62}. For the ocean component, the initial and boundary conditions for the ROMS model were derived from the Global Hybrid Coordinate Ocean Model analysis (<https://www.hycom.org/>), and the bathymetric data were obtained from the General Bathymetric Chart of the Oceans 2020 dataset (<https://www.gebco.net/>). Tidal forcing was prescribed using the TPX07-atlas global tide model, which is based on TOPEX/Poseidon satellite altimetry⁶³. The coupled simulation was conducted from 00:00 UTC on December 12 to 00:00 UTC on December 31, 2017, including a 10-d spin-up period to minimize the influence of the initial conditions on the model results. The physical options for the WRF and ROMS models are summarized in Table S1.

In the WRF model, the Morrison microphysics scheme is a bulk double-moment parameterization that predicts both the number and mass concentrations of hydrometeors while allowing the prognostic treatment of aerosols, thereby providing a more realistic representation of cloud microphysical processes^{64,65}. To investigate the effects of cloud seeding on sea fog dissipation, we implemented a modified version of the Morrison microphysics scheme that incorporates seeding modules for silver iodide (AgI) and calcium chloride (CaCl₂)^{60,65}. In this study, CaCl₂ was selected as the seeding material because the air temperature at the target release altitude (672 m; 3.2°C) was above the freezing point, representing warm-cloud conditions whereby hygroscopic seeding materials are commonly used⁶⁶. The 672-m release altitude was selected because it corresponds to the model level with the maximum LWC within the fog layer and falls within the release-altitude range (≤ 1 km) used in drone-based cloud-seeding experiments for fog dissipation conducted by the National Institute of Meteorological Sciences⁶⁷. In addition, sensitivity experiments were conducted using release altitudes of 23 and 410 m to examine the sensitivity of sea fog dissipation to seeding altitude. These release altitudes were selected because they correspond to the levels of maximum LWC within the lower (0–200 m) and middle (200–500 m) portions of the fog layer, where hygroscopic seeding particles are expected to interact most effectively with fog droplets. For all experiments, cloud seeding was performed over the study area from 08:00 to 09:00 LST on December 24, 2017, to ensure consistent experimental conditions across all simulations.

Seeding particles were represented using a bimodal size distribution based on the NIMS flight experiments, with the small particle mode treated through activation processes and larger particle mode treated through autoconversion⁶⁰. For CaCl₂, the geometric mean radii were set to 0.14×10^{-6} m for the small mode and 0.50×10^{-6} m for the large mode, with corresponding geometric standard deviations of 1.14 and 2.51, respectively. The seeding modules were incorporated into five WRF source-code files (mp_morr.F, mp_driver.F, solve_em.F, phy_init.F, and start_em.F) following the implementation framework

described in previous studies^{60,68,69}. As shown in Fig. S1, paired numerical experiments were conducted, consisting of an unseeded control experiment (UNSD) and a seeded experiment (SEED), with cloud seeding initiated 1 h before the occurrence of minimum visibility in the UNSD simulation. Based on previous findings reported by Jung et al.⁷⁰, which indicated that hygroscopic seeding can influence cloud evolution for up to 3 h after release, we analyzed changes in visibility, cloud water mixing ratio, and rainwater mixing ratio at 60 and 120 min after seeding (i.e., 10:00 and 11:00 LST) to evaluate the temporal response to cloud seeding.

3. Results and Discussion

3.1. Observational characteristics of a severe winter sea fog event

To examine the meteorological characteristics of the severe sea fog event that occurred along the western coast of South Korea during December 23–24, 2017, synoptic weather charts and COMS fog imagery were analyzed at three representative stages: 09:00 LST on December 23 (PI), 15:00 LST on December 23 (PII), and 09:00 LST on December 24 (PIII; Fig. 2). During PI, a high-pressure system was located north of the Korean Peninsula, resulting in a weak pressure gradient over the western coastal region of South Korea. This synoptic pattern was associated with weak ambient winds and enhanced lower-atmospheric stability, thereby promoting near-saturation conditions within the marine boundary layer^{28,71}. Consistent with this synoptic pattern, the COMS fog imagery revealed widespread sea fog and low-level clouds along the western coast of South Korea. During PII, the spatial extent of sea fog and low-level clouds decreased as the high-pressure system shifted over the Korean Peninsula, including the western coastal region of South Korea. The passage of the anticyclone likely intensified atmospheric subsidence, resulting in drier conditions in the lower atmosphere and suppressing the persistence of sea fog²⁸. In contrast, during PIII, a low-pressure system developed over the Yellow Sea near the western coast of South Korea. The associated cyclonic circulation promoted the transport of moist air from the East China Sea and Yellow Sea toward the western coast of South Korea. COMS imagery indicated a widespread sea fog field over the Yellow Sea and the western coastal region, including the vicinity of IIA, suggesting that sea fog was more extensive and denser during PIII than during the earlier stages. The strong agreement between the satellite-derived sea fog patterns and surface observations further supports the robustness and reliability of the observed sea fog evolution.

To further examine the near-surface meteorological conditions associated with the synoptic changes shown in Fig. 2, time series of visibility, RH, air-dew point temperature difference (ADTD), and RAD were analyzed using observations from IIA and nearby ASOS sites (Seoul [SL], Incheon [ICA], Suwon [SW], and Ganghwa [GH]; Fig. 1) (Fig. 3). Because RAD was not observed at IIA, its analysis was limited to the ASOS sites. During PI, visibility ranged from 50 m at IIA to 3,020 m at SW, indicating widespread fog conditions across the observation sites. The mean RH, ADTD, and RAD across these sites were 91%, 1.4°C, and 0.0 MJ m⁻², respectively. During PII, visibility partially recovered, ranging from 1,730 m at GH

to 3,600 m at ICA, accompanied by a decrease in the mean RH to 67%, an increase in the mean ADTD to 5.9°C, and an increase in the mean RAD to 0.6 MJ m⁻². These changes suggest that enhanced RAD during the daytime increased near-surface air temperature and atmospheric mixing, leading to a higher ADTD, lower RH, and the temporary weakening of sea fog. During PIII, visibility decreased again, with values ranging from 70 m at GH to 1,000 m at IIA, indicating the redevelopment of dense sea fog. Accordingly, the mean RH increased to 95%, whereas the mean ADTD decreased to 0.7°C. Compared with PI, visibility remained consistently low across the observation sites, indicating the redevelopment of dense sea fog under more saturated near-surface atmospheric conditions. Overall, the evolution of the sea fog event was primarily controlled by synoptic-scale pressure changes, which likely modulated near-surface moisture availability and radiative conditions, influencing the formation and dissipation of sea fog^{14,28}.

3.2. Validation and performance of the coupled model

To evaluate the reliability of the model in simulating winter sea fog events, meteorological variables (air temperature, WS, RH, and visibility) and SST from the coupled and uncoupled simulations were compared with observations. Time series from two inland observation sites (IIA and ICA) and two marine buoy stations (Incheon [ICB] and Yeonpyeong [YP]) were analyzed between December 23–29, 2017, which included the severe sea fog event (Fig. 4). The IIA and ICA sites represent the target area of this study, while the ICB and YP stations were selected as the nearest buoy stations to IIA within the sea fog region identified from satellite-derived fog imagery (Fig. 2). Overall, the coupled COAWST model reproduced the temporal variations in the observed meteorological variables and SST more accurately than the uncoupled WRF model. During the sea fog period (December 23–24, 2017), the coupled model exhibited improved performance in simulating air temperature, WS, RH, and visibility at the IIA site. At the ICA site, improvements were evident in the simulation of WS, RH and visibility, whereas air temperature showed comparatively smaller improvements. In addition, the coupled model reproduced the observed temporal variability of SST at the ICB and YP stations more realistically, whereas the uncoupled model exhibited little variability compared with the observations. Consequently, the coupled model more accurately reproduced the observed air–sea temperature difference (ASTD), particularly at the YP site, demonstrating the benefit of atmosphere–ocean coupling for simulating coastal environment conditions (Fig. S2).

The improved representation of the ASTD suggests that the coupled model more realistically simulates air–sea interactions, which are closely linked to air–sea heat-exchange processes^{72,73}. Although the surface moisture flux could not be directly evaluated because of the lack of observational data, the improved ASTD served as an indirect proxy for changes in near-surface thermodynamic conditions and latent heat exchange, thereby likely contributing to the improved simulation of RH and visibility during the study period. Moreover, at both the IIA and ICA sites, the coupled model showed better agreement with the observations for additional meteorological variables, including dew point temperature, RAD, atmospheric pressure, precipitation, and cloud fraction (Fig. S3 and S4). Because RAD and cloud fraction

were not observed at IIA and were therefore analyzed only at the ICA site. These improvements are likely attributable to atmosphere–ocean feedback within the coupled system, wherein atmospheric and oceanic variables were exchanged every 6 min, thereby enabling a more realistic representation of coupled processes than that achieved by the uncoupled model.

Table 1 summarizes the statistical performance of the coupled and uncoupled models based on the IOA, RMSE, and MBE for meteorological and oceanic variables, including air temperature, WS, RH, visibility, dew point temperature, atmospheric pressure, RAD, precipitation, cloud fraction, and SST across all meteorological (27) and marine (6) sites. Consistent with the temporal comparisons presented in Fig. 4, the coupled model generally outperformed the uncoupled model by exhibiting higher IOA values and lower RMSE values for all evaluated variables. The largest improvements were observed for variables that are closely associated with the evolution of sea fog. Specifically, the IOA increased from 0.93 to 0.94 for air temperature, from 0.67 to 0.79 for WS, from 0.87 to 0.96 for RH, from 0.89 to 0.98 for visibility, and from 0.57 to 0.84 for SST. Correspondingly, the RMSE decreased from 2.20 to 1.90°C for air temperature, from 2.74 to 2.14 m s⁻¹ for WS, from 14.4 to 9.4% for RH, from 4.4 to 2.0 km for visibility, and from 2.13 to 1.52°C for SST. The coupled model also showed improved performance in simulating dew point temperature, atmospheric pressure, RAD, precipitation, and cloud fraction, as indicated by higher IOA values and lower RMSE values. In addition, the magnitude of the MBE was reduced for most variables, although RH exhibited a slightly larger positive bias in the coupled simulation. Overall, the statistical evaluation supports the time-series analysis and demonstrates that atmosphere–ocean coupling improves the representation of both meteorological conditions and SST, enhancing the simulation of environmental conditions governing the evolution of sea fog.

Table 1

Statistical evaluation of meteorological variables and SST between observations and simulations from the coupled and uncoupled models. The comparison was conducted using data from 27 meteorological monitoring sites and six marine observation sites (Fig. 1) during the analysis period of December 23–29, 2017.

Variable	Coupled			Uncoupled		
	IOA ^a	RMSE ^b	MBE ^c	IOA	RMSE	MBE
Air temperature (°C)	0.936	1.895	-1.368	0.930	2.189	-1.344
Wind speed (m s ⁻¹)	0.789	2.138	1.291	0.674	2.739	1.565
Relative humidity (%) ^d	0.957	9.370	3.955	0.867	14.382	1.068
Visibility (km) ^e	0.983	1.956	-0.065	0.888	4.397	1.313
Dew point temperature (°C) ^d	0.982	2.056	-0.538	0.945	3.536	-0.664
Atmospheric pressure (hPa) ^f	0.920	3.684	1.504	0.857	5.044	3.099
Solar radiation (MJ m ⁻²) ^g	0.854	0.447	0.303	0.777	0.575	0.424
Precipitation (mm hr ⁻¹)	0.493	1.823	-0.763	0.421	2.833	-2.215
Cloud fraction (octa) ^g	0.962	1.717	-0.097	0.867	3.182	-0.382
Sea surface temperature (°C)	0.836	1.525	-1.151	0.570	2.129	1.214
^a IOA: index of agreement.						
^b RMSE: root mean square error.						
^c MBE: mean bias error.						
^{d,e,f,g} Values were calculated using observed and simulated data from 18, 5, 13, and 3 available sites, respectively, out of a total 27 meteorological sites.						

3.3. Effects of cloud seeding on sea fog dissipation

To investigate the mechanisms underlying cloud-seeding-induced sea fog dissipation, the SEED and UNSD simulations were first compared in terms of their precipitation enhancement characteristics (Fig. 5). The analysis focused on the period from 08 LST (the start of seeding) to 11 LST (120 min after the end of seeding) on December 24, 2017, encompassing PIII, during which the most severe low-visibility conditions occurred around IIA. At 60 min after the end of seeding, the artificial rainfall (AR;

SEED – UNSD) was predominantly negative around IIA, with localized positive values northwest of the airport. This reduction in AR may have been associated with a decrease in the mean raindrop mass near the surface (Fig. S5(c)). Although the rainwater mixing ratio increased (Fig. S5(b)), a proportionally larger increase in rain number concentration resulted in smaller raindrops⁷⁴, thereby reducing sedimentation efficiency and suppressing surface precipitation⁷⁵. At 120 min after the end of seeding, positive AR values became more evident along a southwest–northeast band across the IIA region, whereas the previously positive AR region northwest of the airport became negative. Differences in the mean raindrop mass were relatively small over the region of enhanced AR, suggesting that raindrop size played a less important role in determining surface precipitation. Instead, the increased rainwater mixing ratio was converted more effectively into surface rainfall, resulting in positive AR values (Figs. 5, S5(b), and S5(c)). Consistent with the increase in precipitation, cloud seeding reduced the cloud water mixing ratio and increased the rainwater mixing ratio at the seeding altitudes (Fig. S6 and Table 2), indicating enhanced conversion of cloud water into rainwater through hygroscopic growth. The seeding-affected area west and southwest of IIA expanded along the transport pathway of the CaCl₂ seeding material over time, suggesting enhanced droplet growth and sedimentation, which promoted subsequent sea fog dissipation²⁴. Although AR was predominantly negative around IIA 60 min after seeding, the area-averaged AR over the IIA region was slightly positive (0.03 mm). By 120 min after the end of seeding, the mean AR had increased to 0.35 mm, indicating a measurable enhancement in surface precipitation attributable to cloud seeding (Table 2).

Table 2

Summary of area-averaged cloud-water mixing ratio, rainwater mixing ratio, precipitation, and visibility over the IIA region in the UNSD and SEED simulations at 60 and 120 min after the end of seeding. DIFF denotes the difference between the SEED and UNSD simulations (SEED – UNSD).

	60 min			120 min		
	UNSD	SEED	DIFF	UNSD	SEED	DIFF
Cloud water mixing ratio (g kg ⁻¹)	0.15	0.02	-0.13	0.46	0.32	-0.13
Rain water mixing ratio (g kg ⁻¹)	0.11	0.62	0.50	0.06	0.22	0.16
Precipitation (mm hr ⁻¹)	1.34	1.37	0.03	2.73	3.08	0.35
Visibility (m)	4360	2486	-1874	317	474	157
SEED and UNSD represent simulations with and without the inclusion of cloud seeding (CaCl ₂), respectively.						

To validate the simulated precipitation enhancement resulting from cloud seeding, simulations of the sea fog event on December 10, 2021, corresponding to the NIMS drone-based cloud-seeding experiment, were directly compared with observations (Table S2) because no field experiment was available for the 2017 sea fog case. Although observational data were available from the 2021 field experiment, the fog

dissipation induced by cloud seeding was limited⁶⁷. Therefore, the severe sea fog event of December 23–24, 2017, was selected as the primary case study, whereas the 2021 field experiment was used solely for model evaluation. The AR amounts measured during the drone experiment, defined as the difference between the affected and unaffected regions, were 0.16 and 0.15 mm at 60 and 120 min, respectively (Table S2). The corresponding simulated AR values from the simulations (SEED – UNSD) over the same experimental area were 0.12 mm at 60 min and 0.14 mm at 120 min. Overall, the simulated changes in AR were in good agreement with the drone-based observations. This supported the capability of the model to reproduce the observed precipitation enhancement associated with cloud seeding.

The horizontal distribution of near-surface visibility differences between the SEED and UNSD simulations was further analyzed at 60 and 120 min after the end of seeding (Fig. 6). At 60 min after the end of seeding, visibility generally decreased along a southwest–northeast–oriented band extending toward IIA. The area-averaged visibility over the IIA region decreased from 4,360 m in the UNSD simulation to 2,486 m in the SEED simulation (– 1,874 m), indicating a temporary deterioration in visibility following cloud seeding. This deterioration coincided with the negative AR signal around the IIA region (Fig. 5), suggesting that reduced sedimentation and enhanced evaporation of smaller raindrops contributed to suppressed surface precipitation and increased near-surface moisture content⁷⁵. Consistent with these changes, the water-vapor mixing ratio and relative humidity increased, whereas the near-surface air temperature decreased, indicating enhanced atmospheric moistening and evaporative cooling within the lower atmosphere (Fig. S5). These conditions likely favored the persistence and growth of fog droplets, as evidenced by localized increases in the cloud water mixing ratio (Fig. S5(a)) and liquid-phase extinction coefficient (Fig. S7(a)), indicating stronger light attenuation near the surface⁷⁶. At 120 min after the end of seeding, localized improvements in visibility were simulated around the IIA region, particularly to the west and south. The area-averaged visibility over the IIA region increased from 317 m in the UNSD simulation to 474 m in the SEED simulation, corresponding to a mean increase of 157 m, with local increases of up to 1,609 m (Fig. 6 and Table 2). This improvement coincided with a positive AR signal at the same time (Fig. 5), suggesting that enhanced conversion of cloud water into rainwater contributed to increased surface precipitation and a reduction in the liquid water content of the fog layer²⁴. Consistently, the cloud-water mixing ratio decreased, whereas the rainwater mixing ratio increased, together with negative differences in the liquid-phase extinction coefficient around the IIA region. These changes indicated reduced light attenuation near the surface, thereby improving near-surface visibility⁴⁵.

To further examine the vertical structure of the visibility response, a longitudinal height cross-sectional analysis was conducted along the dashed black line shown in the horizontal distribution (Fig. 7). At 60 min after the end of seeding, visibility decreased primarily within the near-surface layer, particularly below approximately 100 m, with localized reductions extending up to approximately 400 m around IIA (near 126.4°E). In contrast, visibility generally increased in the upper layers of the atmosphere, although localized decreases were also evident below 1 km east of the IIA. At 120 min after the end of seeding,

the vertical structure shifted toward a more pronounced improvement in visibility within the lower atmosphere. Visibility increases were evident primarily below approximately 500 m and were most pronounced from the western to the central portions of the cross-section. Compared with the response at 60 min, the improvement extended more prominently toward the near-surface layer, indicating a progressive enhancement in near-surface visibility following cloud seeding.

To identify the factors responsible for the vertical visibility response, the vertical distributions of the cloud-water and rainwater mixing ratios, the wind field (u - and w - components), and the liquid-phase extinction coefficient were analyzed (Figs. S7(b), S8, and S9). At 60 min after the end of seeding, the cloud-water mixing ratio generally decreased below approximately 600 m, whereas the rainwater mixing ratio increased from the surface to approximately 1 km, indicating enhanced conversion of cloud water into rainwater⁶⁰. However, near-surface visibility decreased primarily below approximately 100 m, including a localized reduction extending up to approximately 400 m around the IIA region (Fig. 7). This reduction was associated with increases in the cloud-water mixing ratio and liquid-phase extinction coefficient within the lowest atmospheric layer (Figs. S7(b), and S8). In addition, the relatively strong upward motion and westward airflow in the SEED simulation within the lower atmosphere, including the seeding altitude, likely contributed to the vertical and horizontal redistribution of hydrometeors, thereby delaying the downward propagation of the visibility response (Fig. S9). At 120 min after the end of seeding, the decrease in the cloud-water mixing ratio extended more broadly below approximately 800 m, whereas the rainwater mixing ratio remained elevated. Together with weakened upward motion and the development of low-level subsidence, these changes likely facilitated the downward propagation of the microphysical response, thereby enhancing the near-surface visibility response⁷⁷. Consistently, reductions in the liquid-phase extinction coefficient became more pronounced within the lower atmospheric layer, broadly coinciding with the downward extension of the visibility improvement⁴⁵. These findings highlight a vertically evolving microphysical response that governs the delayed improvement in visibility following cloud seeding.

To investigate the sensitivity of the visibility response to seeding altitude, the visibility differences between the SEED and UNSD simulations in the primary experiment (seeding an altitude of 672 m) were compared with those in the sensitivity experiments (seeding altitudes of 23 and 410 m). The analysis was conducted at 120 min after the end of seeding using near-surface horizontal distributions and longitude–height cross-sections (Fig. 8). A detailed description of the primary and sensitivity experiments, including their respective seeding altitudes, is provided in Section 2.2. In the 23-m experiment (Fig. 8(a)), visibility improvements were evident mainly to the west and south of IIA, although localized reductions in visibility remained to the southeast and northwest of IIA. Compared with the 672-m experiment, the longitude–height cross-section showed broader improvement in visibility within the lower atmospheric layer, particularly between approximately 100 and 500 m. In the 410-m experiment (Fig. 8(b)), the visibility responses in both the near-surface horizontal distribution and longitude–height cross-section were generally similar to those in the 672-m experiment, although the magnitude of the

visibility improvement was smaller. Overall, lower-altitude seeding, particularly at 23 m, produces a more pronounced improvement in near-surface visibility than seeding at 410 and 672 m.

4. Summary and Conclusions

In this study, we evaluated the effects of hygroscopic cloud seeding on winter sea fog dissipation and visibility along the western coast of South Korea using the coupled COAWST model with a modified Morrison microphysics scheme. The analysis focused on a severe sea fog event around IIA during December 23–24, 2017. The coupled model reproduced the meteorological and oceanic conditions associated with sea fog evolution more realistically than the uncoupled model, particularly for air temperature, visibility, RH, WS, and SST. Cloud seeding with CaCl_2 enhanced the area-averaged AR over the IIA region, increasing from 0.03 mm at 60 min to 0.35 mm at 120 min after the end of seeding. This enhancement was likely associated with reduced cloud-water mixing ratios and increased rainwater mixing ratios, indicating enhanced microphysical growth of fog droplets into raindrops. Visibility initially decreased at 60 min after the end of seeding owing to enhanced near-surface moistening, evaporative cooling, and increased liquid-phase extinction, but improved at 120 min after the end of seeding as the cloud-water mixing ratio and liquid-phase extinction decreased and surface precipitation increased. The vertical analysis further indicated that the visibility improvement extended downward toward the surface under weakened upward motion and enhanced low-level subsidence. Sensitivity experiments showed that seeding at 23 m produced a greater improvement in near-surface visibility than seeding at 410 m and 672 m. Thus, low-level hygroscopic cloud seeding may be an effective strategy for mitigating winter sea fog and improving airport visibility under similar meteorological conditions.

Several uncertainties remain in the quantitative assessment of the effects of cloud seeding on sea fog dissipation. Direct observational validation was limited owing to the absence of in situ measurements for the 2017 sea fog event, although comparisons with the NIMS drone-based cloud-seeding experiment provided partial support for the simulated AR enhancement. Uncertainties in key model inputs, particularly the particle-size distribution, also limit the accurate representation of seeding-induced microphysical processes, including droplet activation, growth, and sedimentation. In addition, the sensitivity experiments mainly focused on seeding altitude; therefore, further studies are required to investigate the effects of seeding location, duration, and application rate. Despite these limitations, atmosphere–ocean coupling improved the representation of marine boundary layer processes relevant to sea fog dissipation, thereby enabling more realistic simulations of cloud-seeding impacts. Future work should integrate field observations with improved cloud-seeding parameterizations to enhance the realism of numerical simulations. These improvements will support more effective sea fog mitigation strategies and early warning systems, thereby reducing flight delays, shipping disruptions, traffic hazards, and socioeconomic losses in coastal regions. Overall, air–sea interactions and seeding altitude are critical factors in the development of effective cloud-seeding strategies for sea fog mitigation.

Declarations

Acknowledgements

This work was funded by the Korea Meteorological Administration Research and Development Program “Research on Weather Modification and Cloud Physics” under Grant (KMA2018-00224). This research was also supported by Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries, Korea (RS-2025-02217872), and the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (RS-2026-25478568).

Author contributions

S.-H. M. performed the formal analysis, validation, and software development, and wrote the original draft of the manuscript. Y.-K. L. developed the methodology and contributed to the conceptualization and discussions. S.-K. S. conceived the study, developed the methodology, supervised the research, and contributed to manuscript review and editing. K.-Y. H., S.-B. L., S.S. L., and J.H. K. contributed to the formal analysis and commented on the methods and the manuscript.

Competing interests

All authors declare no financial or non-financial competing interests.

Data availability

Observed data from the Automated Synoptic Observing System, Aerodrome Meteorological Observation System, Automatic Weather Station, Ocean buoys and tidal stations were obtained from <https://data.kma.go.kr/cmmn/main.do> and <https://www.khoa.go.kr/oceangrid/khoa/intro.do>. The ERA5 reanalysis fields on single levels and pressure levels were obtained from <https://doi.org/10.24381/cds.adbb2d47> and <https://doi.org/10.24381/cds.bd0915c6>. The HYCOM analysis fields are available at <https://www.hycom.org/>.

Code availability

The underlying code for this study is not publicly available for proprietary reasons.

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Figures

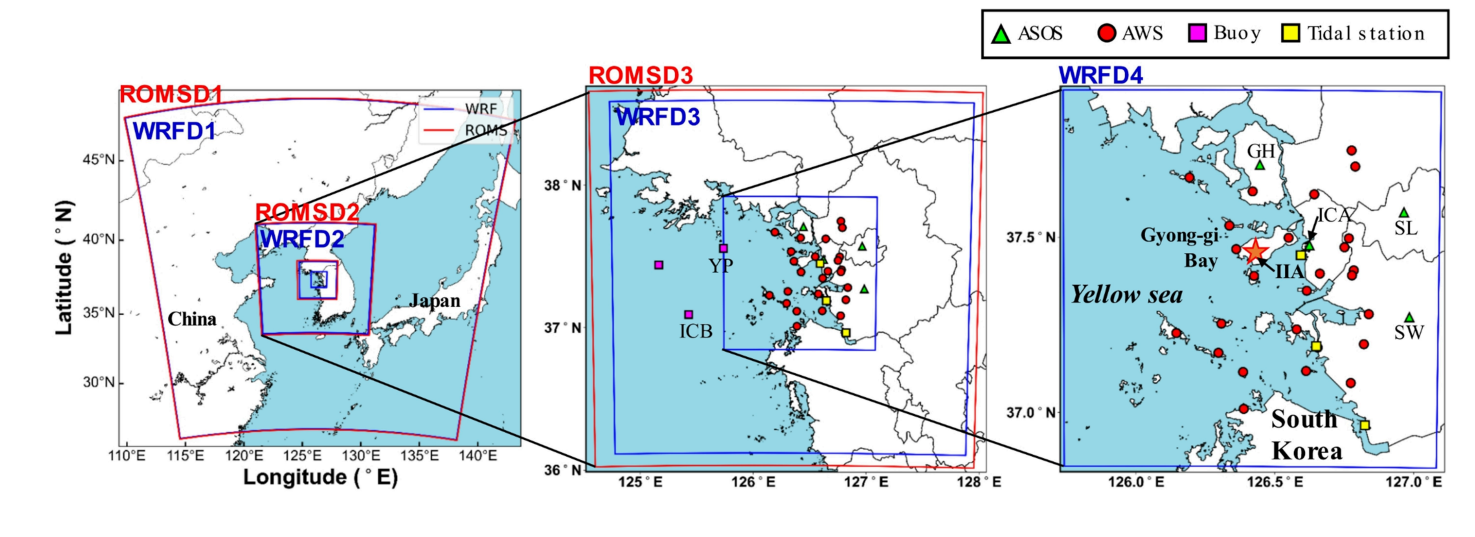


Figure 1

Nested model domains of the coupled atmosphere–ocean model (WRF, blue solid frames); ROMS, red solid frames) and locations of the observation sites in western South Korea. Meteorological variables were observed at 27 sites (one AMOS station, star; four ASOS stations, green triangles; 22 AWS sites, red

circles), whereas SST was observed at six marine sites (three buoy stations, magenta rectangles; three tidal stations, yellow rectangles).

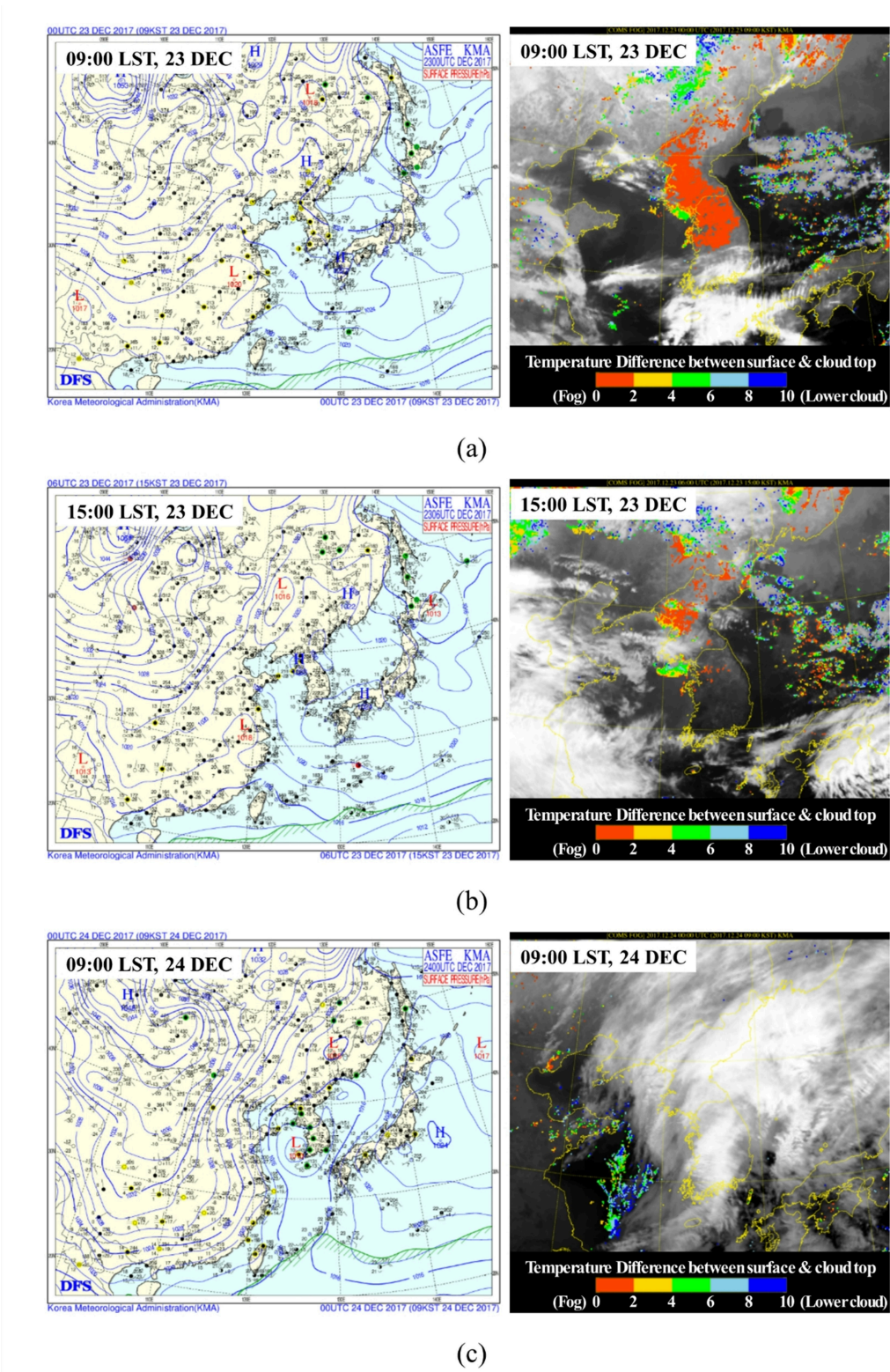


Figure 2

Synoptic weather charts and satellite-derived fog imagery from the Communication, Ocean and Meteorological Satellite (COMS) at (a) 09:00 LST and (b) 15:00 LST on December 23, and (c) 09:00 LST

on December 24, 2017.

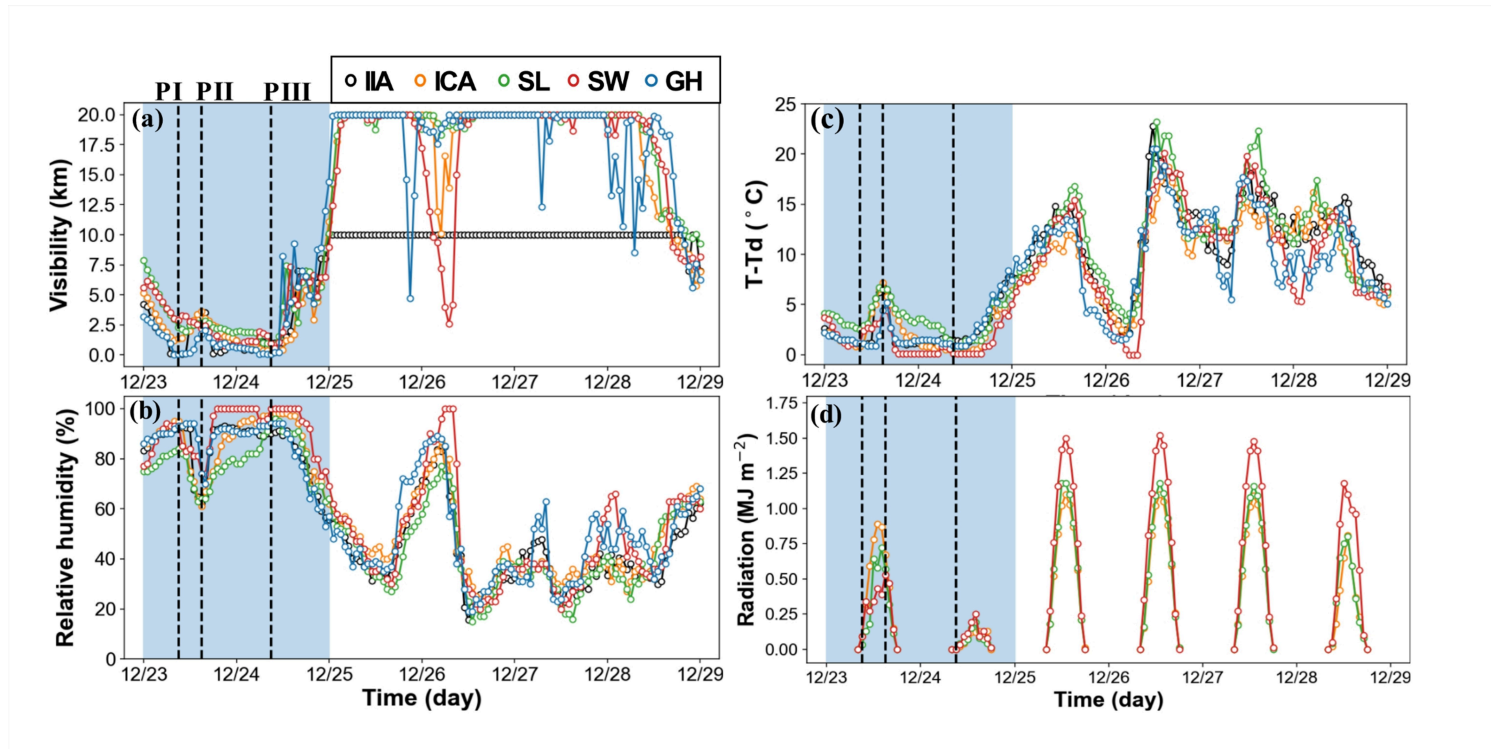


Figure 3

Time series of the observed meteorological variables: (a) visibility, (b) relative humidity, (c) air–dew point temperature difference (ADTD, $T-T_d$), and (d) solar radiation at Incheon international airport (IIA), Seoul (SL), Incheon (ICA), Suwon (SW), and Ganghwa (GH) meteorological sites during the analysis period of December 23–29, 2017. At IIA, visibility measurements were capped at 1 km, and solar radiation data were unavailable. The blue shaded box indicates the severe fog event (December 23–24, 2017). PI, PII, and PIII denote three representative stages of the event: 09:00 LST on December 23 (PI), 15:00 LST on December 23 (PII), and 09:00 LST on December 24 (PIII).

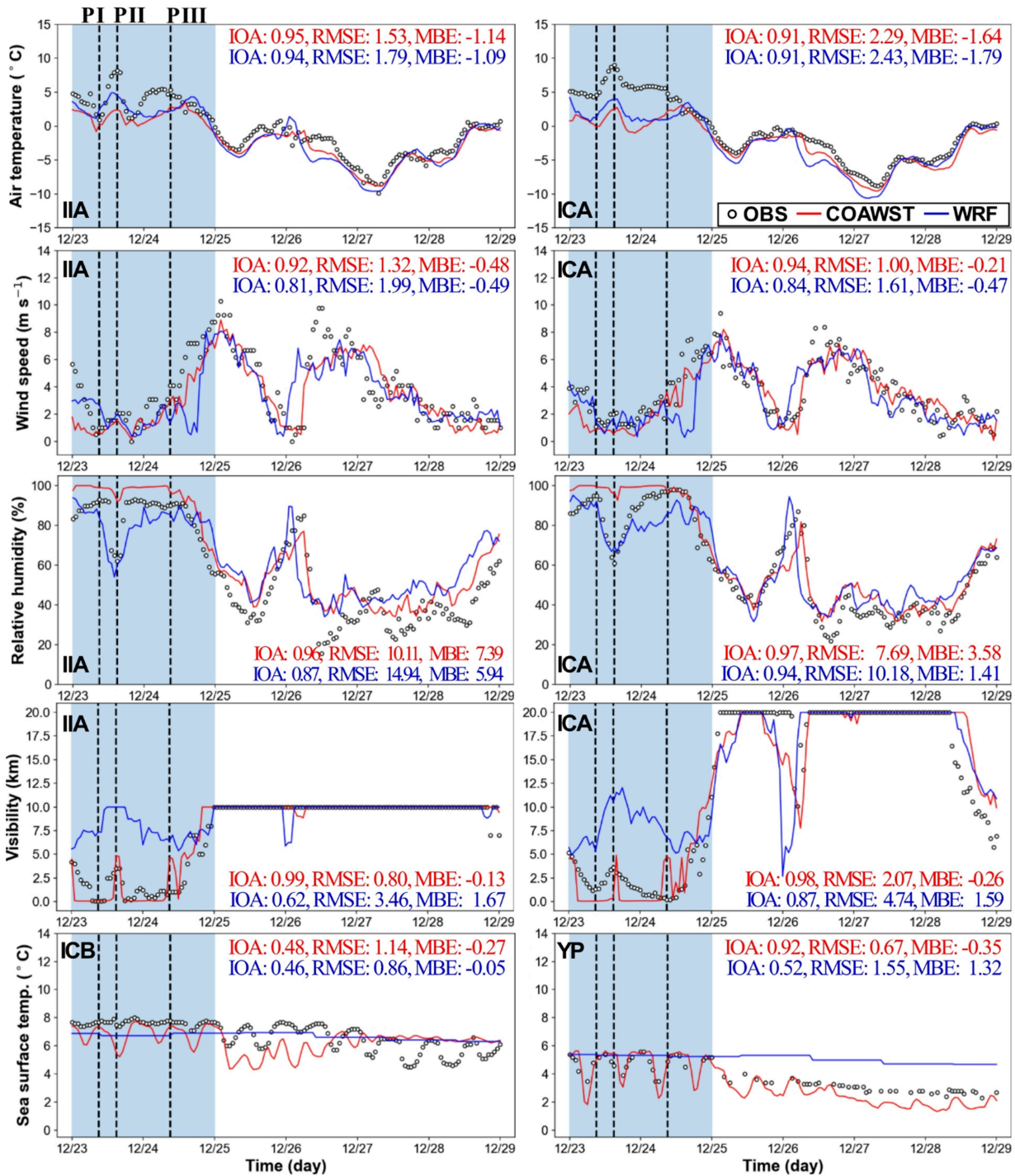


Figure 4

Time series of observed and model-simulated variables from the coupled (COAWST) and uncoupled (WRF) models: air temperature, wind speed, relative humidity, visibility, and sea surface temperature. The blue shaded box indicates the severe sea fog event (December 23–24, 2017). IIA and ICA denote the meteorological monitoring sites at Incheon international airport and Incheon, respectively. At IIA,

visibility measurements were capped at 1 km. ICB and YP denote the marine buoy stations at Incheon and Yeonpyeong, respectively (Fig. 1).

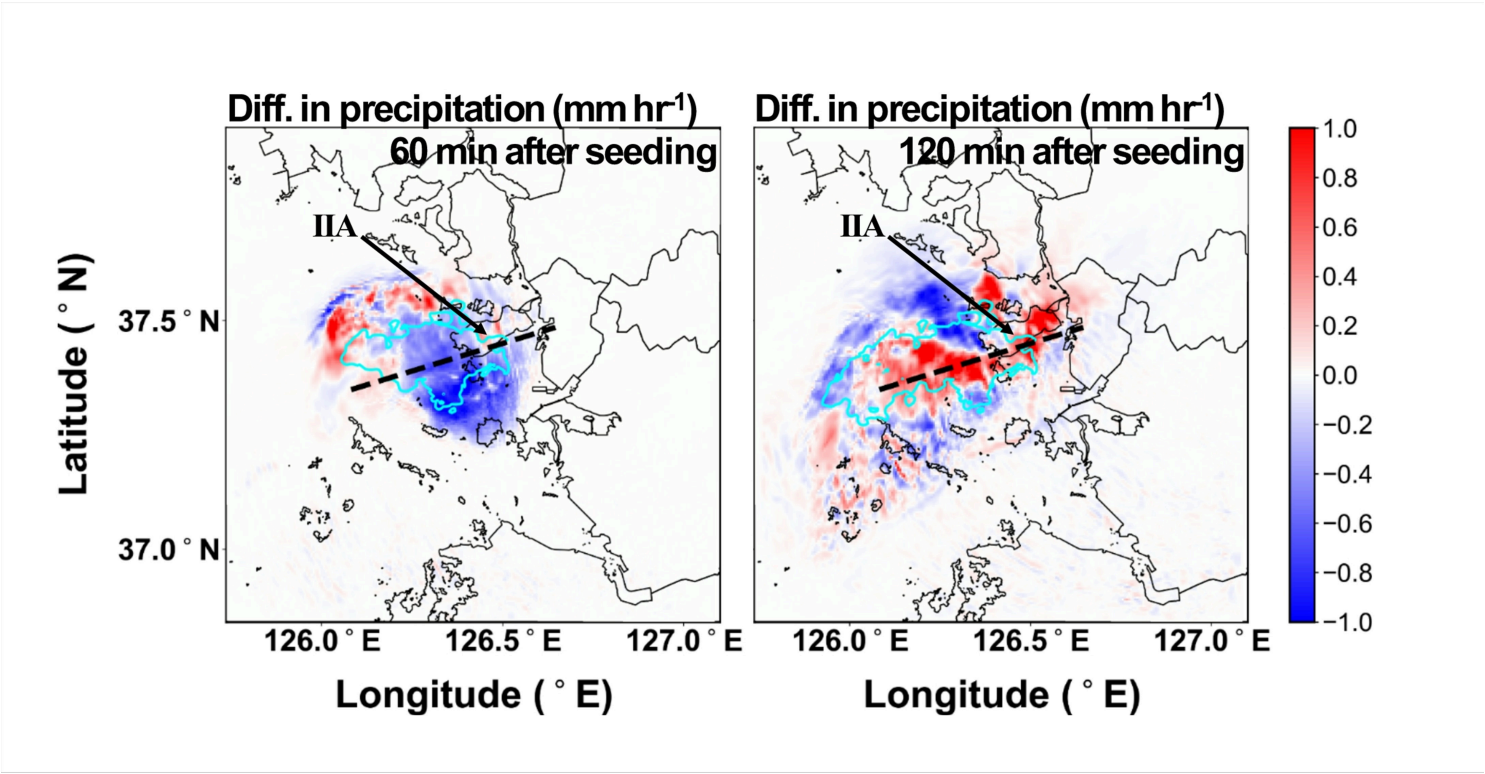


Figure 5

Spatial distributions of AR (mm hr⁻¹; SEED - UNSD) at 60 and 120 min after the end of seeding. Cyan contours indicate the simulated transport pathway of the seeding material. Black dashed lines denote the locations of the vertical cross sections.

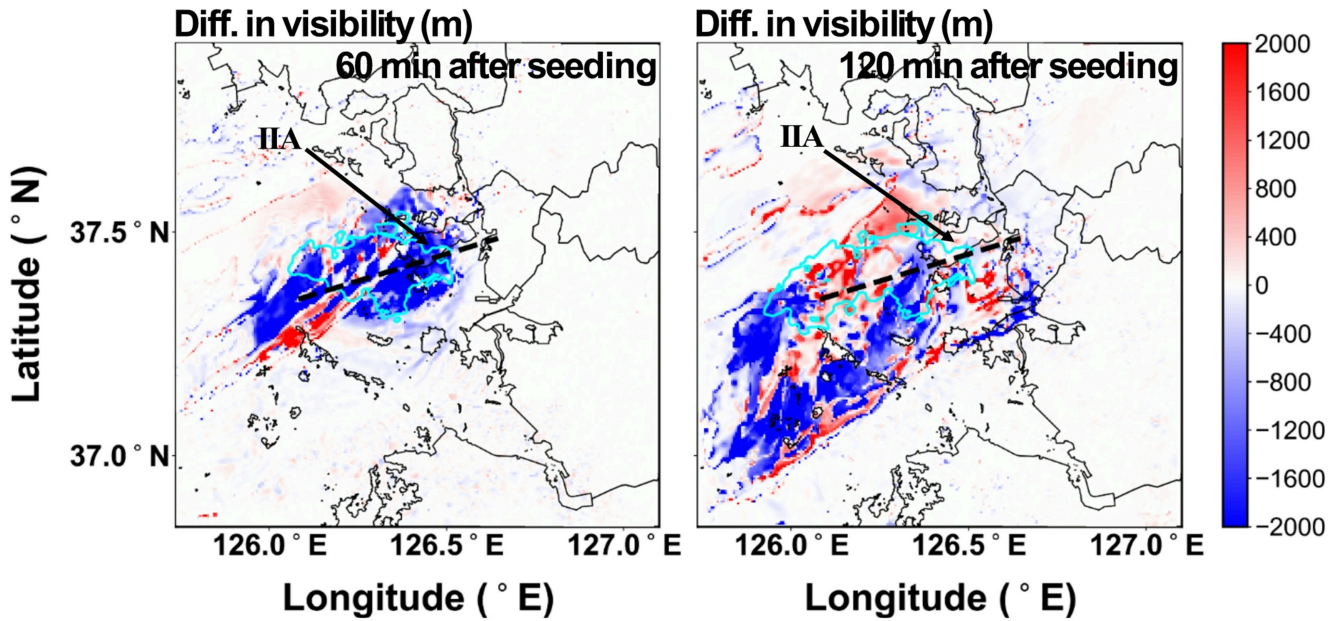


Figure 6

Spatial distributions of near-surface visibility differences (m) between the SEED and UNSD simulations (SEED - UNSD) at 60 and 120 min after the end of seeding. Cyan contours indicate the simulated transport pathway of the seeding material. Black dashed lines denote the locations of the vertical cross-sections.

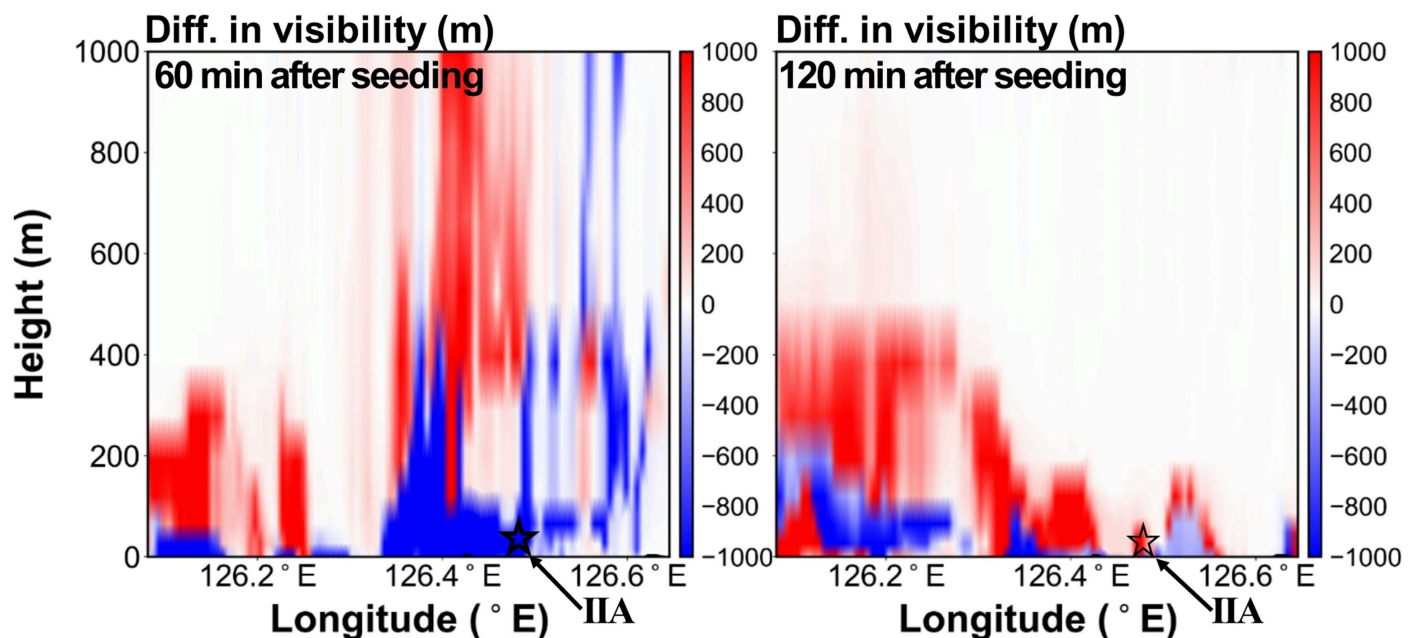


Figure 7

Longitude–height cross-sections (along the lines shown in Fig. 5) of visibility differences (m) between the SEED and UNSD simulations (SEED – UNSD) at 60 and 120 min after the end of seeding.

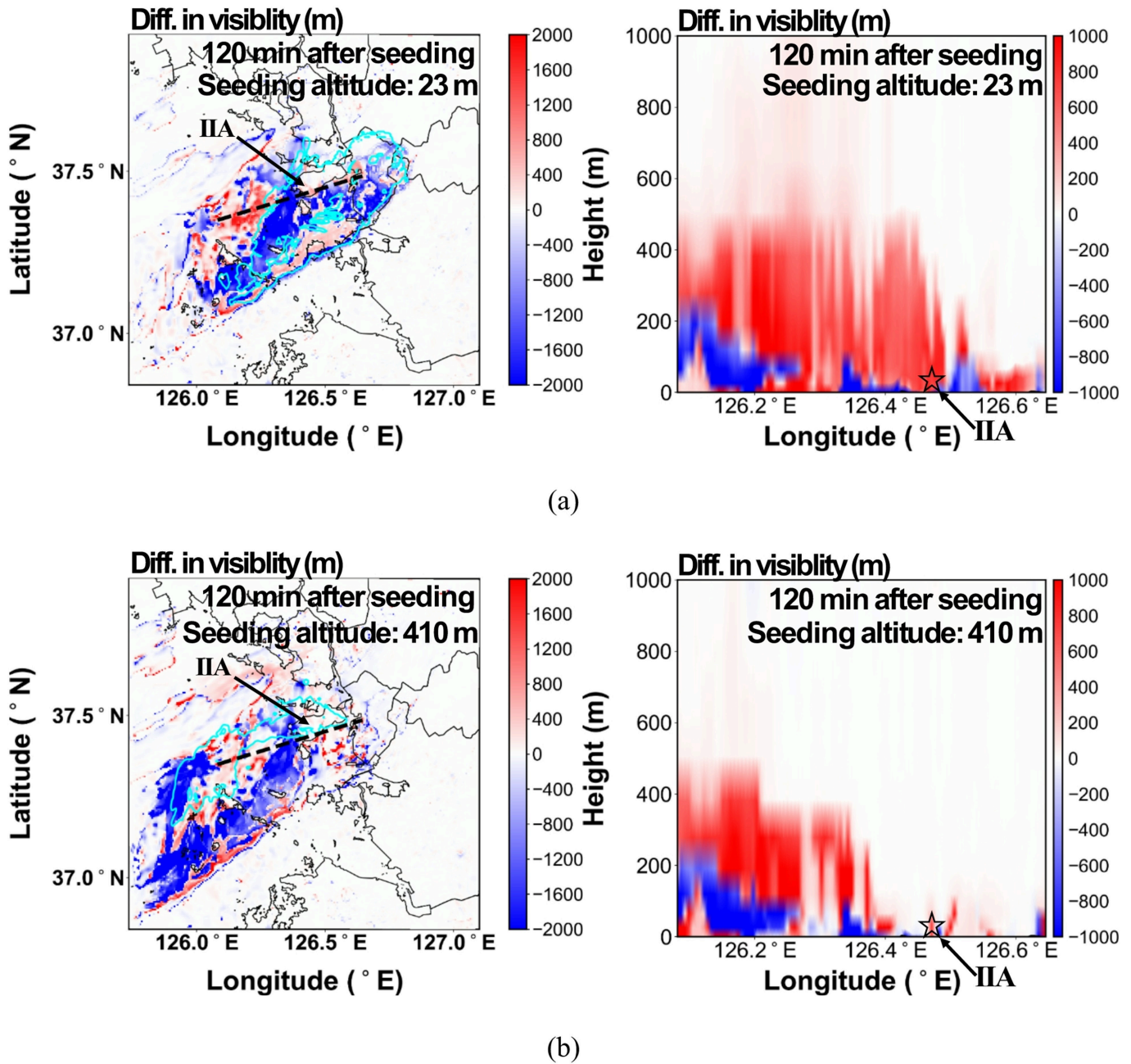


Figure 8

Spatial distributions and longitude–height cross-sections (along the lines shown in Fig. 5) of visibility differences (m) from the seeding-altitude sensitivity experiments at 120 min after the end of seeding, relative to the UNSD simulation. (a) 23-m seeding altitude and (b) 410-m seeding altitude.

Supplementary Files

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- [202677CloudseedingonSeafogSupplementaryMaterialNewV2.docx](#)