Response to CC1:

Authors: Xirui Ma, Yun Zhang, Panyan Ge, Yan Yin, Hepeng Zheng, Tingting Kang, Lingbing Bu, Wenjie Su, Donglin Yang, Qiangyue Xiang and Yinze Ran

We greatly appreciate your valuable time for reviewing our research paper and providing suggestions. ***(The blue text is in response to your comments, and the green text is for specific modifications in the paper. We also highlight revisions in the manuscript.)***

General Review:

The manuscript "Evolution mechanisms of explosive advection sea fog under the influence of transported dust aerosol: a case study over the East China Sea in spring 2025" presents a study on the evolution mechanisms of explosive advection sea fog coupled with long-range dust transport over East Asia. The topic is meaningful and interesting. However, the manuscript suffers from issues regarding the identification of dust events. The manuscript requires a revision before it can be considered for publication.

Answer:

We sincerely appreciate the reviewer's valuable comments and suggestions. We have carefully revised the manuscript and figures in accordance with the specific recommendations provided.

Specific Review:

1. Identification of dust evidence is insufficient:

(1a) The dust is typically characterized by a significant coarse-mode fraction. However, the $PM_{2.5}$ and PM10 concentrations were similar (460 and 469 μg/m³, respectively; Figure 3) during the identified "dust phase" (Stage 2), indicating that the pollution was dominated by $PM_{2.5}$ rather than dust. Additionally, Line 219 claims Section 3.1 satellite data support that Stage 2 is identified as a dust event, but that data only shows sea fog characteristics. Please clarify the "dust" classification. Since there is a high $PM_{2.5}$, how can the author separate the PM2.5 contribution to sea fog and mist?

Answer: We thank the reviewer for this excellent question.

(1) During this event (Stage 2), the near-surface aerosol was indeed dominated by the fine mode ($PM_{2.5}$), rather than by the coarse mode typical of regions near a dust source. We argue that this feature is consistent with long-range transport, rather than contradictory. The physical reason is that coarse-mode particles (>2.5 μm) are preferentially removed along the >1000 km transport path (Fig. 4) because their gravitational settling velocity is far greater than that of fine particles, so that the dust air mass reaching the observation site is dominated by fine particles. This is also a classic characteristic of long-range dust transport, and it is independently reflected in Fig. 6(a). We have added an explanation of this physical process to the analysis of Fig. 6(a).

(2) We sincerely apologize for the obvious typographical error in Line 219 of the original manuscript, where "Section 3.1" was cited. In fact, the core evidence supporting this stage as a dust event is located in Section 3.2 (the Himawari-9 satellite aerosol-component distribution, which clearly shows the transport of dust AOD) and Section 3.5 (the synoptic-scale dynamical analysis illustrating the Mongolian cyclone and the dust transport channel). We have corrected this typo in the revised manuscript.

(3) We are also fully aware that the near-surface PM mass concentration alone is insufficient to uniquely identify dust. We have therefore revised this part in detail. The identification of Stage 2 as the dust phase no longer relies solely on the elevated PM, but on the combination of:

(i) The explosive, synchronous increase of near-surface PM_1/PM2.5/PM_{10} (Fig. 3).

(ii) The strict inverse relationship between visibility and PM, with the PM peak (17:08) synchronous with the wind-speed peak (6.3 m/s), consistent with downward dust transport by mechanical mixing.

(iii) The occurrence of the event in late March during the dust season, accompanied by a southward cold-air intrusion.

(iv) The satellite aerosol composition product in Figure 4 shows the long-distance transport of dust from Mongolia to Qingbang Island via regions including Inner Mongolia, Shaanxi, and Shanxi.

(v) The circulation analysis in Fig. 12 showing that the Mongolian cyclone and the strong westerly jet form an efficient transport channel. It is the convergence of these surface, satellite and circulation lines of evidence that supports Stage 2 as the dust-passage period, rather than any single piece of evidence.

(4) Regarding how to separate the contributions of PM2.5 and of dust to sea fog and mist, we must candidly acknowledge an objective limitation of this study. It should be noted that, based on the PM mass concentrations available in this study, we cannot physically or quantitatively separate the respective contributions of the PM2.5 and the dust. The dust impact discussed hereafter therefore refers to the overall synergistic effect of this long range transported, dust-dominated dust–pollution air mass treated as a whole. We have added an explicit limitation statement in the Fig. 3 analysis of the main text (the Stage 2 identification paragraph in Section 3.1). We thank the reviewer again for this valuable comment, which has made our attribution markedly more rigorous and objective.

The relevant content of Section 3.1 (lines 216–225 of the original manuscript) has been revised. The revised version is as follows:

Stage 2 was affected by strong external disturbance. The PM mass concentrations showed explosive increases during this period. The peak values of PM_1, $PM_{2.5}$, and PM_{10} at 17:08 on March 24 were 267, 460, and 469 μg/m³, respectively (an increase of 11-14 times). This trend is consistent with the explosive input characteristics of dust aerosols (Rodríguez et al., 2024). During this stage, the average visibility was 2.4 km and the relative humidity remained at a low level of 40-65% (Table 2); at the PM peak, the visibility dropped sharply by 28.4% to 1.79 km, showing a strict inverse trend with PM mass concentration changes. The PM mass concentration peak (17:08) was synchronous with the wind speed peak (6.3 m/s). In addition, the event occurred during a concurrent cold-air intrusion in late March, within the dust season. These strongly coupled surface features are similar to those of long-range dust transport. Therefore, in conjunction with the satellite data and circulation analysis evidence presented in subsequent sections (Sections 3.2 and 3.5), this stage is identified as the dust passage period. It should be noted that, based on the PM mass concentrations available in this study, we cannot physically or quantitatively separate the respective contributions of the $PM_{2.5}$ and the dust. The dust impact discussed hereafter therefore refers to the overall synergistic effect of this long range transported, dust-dominated dust–pollution air mass treated as a whole. The cold-air intrusion combined with the dust radiative effects intensified the near-surface temperature drop (a decrease of 5.0°C within 5 hours, with a cooling rate of about 1.0°C/h). In addition, the pressure showed an increase during 16:27-20:00. This may be related to the thermodynamic pressurization effect of aerosol increase on the local boundary layer (Luo et al., 2022).

The relevant content of Section 3.2(Fig. 6) (lines 327–332 of the original manuscript) has been revised. The revised version is as follows:

From Fig. 6(a), during the dust period (Stage 2, 15:00-20:00 on March 24), the proportion of aerosols with particle sizes of 0-1 and 1-2.5 μm significantly increased, while the proportion of aerosols with particle sizes of 2.5-10 μm decreased significantly (by 19%). This phenomenon is related to the typical characteristics of long-distance dust transport. It should be noted that during the dust phase the near-surface $PM_{2.5}$ and PM_{10} concentrations were comparable, i.e., the aerosol was dominated by the fine mode rather than by the coarse mode typical of a dust source region. This is consistent with, rather than contradictory to, long-range-transported dust. During the transport process, the gravitational settling velocity of coarse mode particles (>2.5 μm) is far greater than that of fine particles, the coarse mode is preferentially removed along the >1000 km transport path (Fig. 4), so that the dust air mass arriving at the site is dominated by fine particles. The particle size was mainly concentrated in the 0-2.5 μm. The comparable $PM_{2.5}$ and PM_{10} concentrations are therefore the fine-mode signature expected of long-range-transported dust. In addition, the dust transport passed through regions with strong pollution emissions. Dust particles may have mixed and interacted with regional pollutants, undergoing a certain degree of chemical aging.

(2a) The reported “dust” reached the station on the afternoon of March 24 and then dissipated, while the sea fog did not form until the evening of March 25. How can the dust on March 24 influence the sea fog formed on March 25? Can the author provide evidence proving that the dust was not dispersed before the fog formation?

Answer: We thank the reviewer for this question.

The near-surface PM mass concentration data show that, after the end of Stage 2, the PM mass concentration in Stage 3 had indeed declined. We would clarify that the "dissipation" referred to by the reviewer means the decrease of the dust mass concentration at the 2-m near-surface level, not the removal of dust from the system. The dust was not dispersed, but remained suspended above the sampling height of the weather station and settled slowly. During Stage 3, the dust AOD remained at a relatively high level (Figs. 4c, d; Fig. 5a), while the near-surface PM at 2 m had clearly declined (Fig. 3). These two seemingly different observations are in fact consistent: the weather station samples only at 2 m and can reflect only the near-surface dry-dust mass concentration, whereas the AOD is a column-integrated quantity. Together they indicate that the dust was not dispersed, but remained suspended as fine particles in the layer above the 2-m sampling height, undergoing slow settling. Therefore, "undetectable at 2 m yet still detected in the column" is a manifestation of the complementarity between the column observation and the point observation, not a contradiction.

Furthermore, the dust of 24 March was able to influence the sea fog of 25 March through the inversion layer that it helped establish in advance and that persisted into the following day. Fig. 9 shows that an inversion structure began to form in the near-surface layer at 10:00 on March 24, mainly concentrated at 0.4-1 km. Its occurrence and development were accompanied by both the synoptic-scale cold-air advection at low levels ((Fig. 12(d-1)) and the continuous increase of dust AOD observed by satellite on March 24 (Fig. 5a). With the continuous passage and settling of the dust carried by the cold air, the near-surface inversion progressively strengthened. The maximum inversion reached 9 °C, and the thickness of the inversion layer also expanded significantly. This strong inversion layer was favourable for the accumulation of dust aerosols of sea surface and provided initial thermal conditions for the stabilization of the lower atmosphere. This early inversion (Stage 2) superimposed with the subsequently established warm and moist advection (the SAT-SST was 1.8°C in Stage 3), a continuously stable and deeper inversion layer formed in the boundary layer. This accelerated the continuous accumulation and physicochemical reactions of aerosols, providing sufficient CCN and ideal thermodynamic conditions for the outbreak of sea fog.

We have correspondingly added detailed text to the relevant parts of the manuscript. Revised as follows:

The relevant content of Section 3.2 (lines 275–280 of the original manuscript) has been revised. The revised version is as follows:

Form Fig. 4(a), the dust had not reached the observation site at 08:00 on March 24. At the same time, the aerosols at this site were mainly sulfate aerosols. In Fig. 4(b) at 15:00 on March 24, the dust originated from Mongolia and moved eastward through Inner Mongolia, Shaanxi, Shanxi, Jiangsu, and Shanghai to Qingbang Island in the East China Sea. This result is consistent with the sharp increase of aerosol PM mass concentrations at the near-surface observation site at 15:00 on March 24. This also confirms our conjecture that this increase was caused by dust passage. During Stage 2, the aerosols at this site were mainly dust particles. During Stage 2, the near-surface wind speed was relatively high and the turbulent kinetic energy was enhanced. This led to the strengthening of vertical mixing in the boundary layer. The dust in and above the boundary layer was fully mixed and settled to the near-surface. Therefore, the aerosol PM mass concentrations at the near-surface showed a significant sharp increase. From Fig. 4 (c) and (d), during Stage 3 (pre-formation phase of advection sea fog), dust always existed above the study area. The direct contribution to near-surface PM concentrations was relatively weakened. This indicates that dust aerosols were undergoing a slow settling process. It is necessary to clarify that in Stage 3, the PM mass concentration decreased relatively, referring to the reduction of the dust mass concentration at the near-ground 2 m level, rather than the dust being completely removed from the system. The dust did not disperse but remained suspended above the sampling height of the meteorological station and slowly settled. During Stage 3, the dust AOD remained at a relatively high level (Figures 4(c), (d)), while the PM at the near-ground 2 m level had significantly decreased (Figure 3). These two seemingly different observations are actually consistent. The meteorological station only samples at the 2 m height, which can only reflect the dry dust mass concentration near the ground, while AOD is the integral quantity of the entire column. Together, they indicate that the dust did not disperse but remained suspended in the air layer above the 2 m sampling height and was in a slow settling process. Therefore, the absence of detection at the 2 m level and the detectability of the entire column are manifestations of the complementarity of column observations and point observations, rather than contradictions. Fig. 4 (d) further shows that the dust at the observation site was weakening before sea fog formation. The high-value area of dust AOD was transported to northeastern China. Fig. 4 (e) and (f) indicate that during Stage 7 (dissipation phase of mist), dust passed through the observation site again, which may accelerate its dissipation.

The relevant content of Section 3.3 (lines 431–435 of the original manuscript) has been revised. The revised version is as follows:

Fig. 9 shows that an inversion structure began to form in the near-surface layer at 10:00 on March 24, mainly concentrated at 0.4-1 km. Its occurrence and development were accompanied by both the synoptic-scale cold-air advection at low levels (Fig. 12(d-1)) and the continuous increase of dust AOD observed by satellite on March 24 (Fig. 5a). With the continuous passage and settling of the dust carried by the cold air, the near-surface inversion progressively strengthened. The maximum inversion reached 9 °C, and the thickness of the inversion layer also expanded significantly. This strong inversion layer was favourable for the accumulation of dust aerosols of sea surface and provided initial thermal conditions for the stabilization of the lower atmosphere. From 09:00 to 16:47 on March 25, with the establishment of sea breeze carrying warm and moist airflow over the cold sea surface, a continuously stable and deeper inversion layer formed in the boundary layer. This accelerated the continuous accumulation and physicochemical reactions of aerosols, providing sufficient CCN and ideal thermodynamic conditions for the outbreak of sea fog.

The relevant content of Section 4 (lines 590–598 of the original manuscript) has been revised. The revised version is as follows:

The cold-air intrusion and dust radiative forcing co-acted to change the boundary-layer thermodynamic structure, constructing a favourable background for the formation of advection sea fog. During Stage 2, the solar diurnal cycle together with the co-acting effects of cold-air advection and dust jointly modulated the attenuation of DSR at the surface. This caused the near-surface temperature to drop sharply by 5.0°C within 5 hours, forming an inversion. The inversion was mainly concentrated at 0.4-1 km, with the maximum inversion intensity reaching 9°C. Previous studies on advection sea

fog mostly emphasized the advective cooling effect. However, this study found that under a high-dust background, dust radiative effects combined with synoptic-scale cold-air advection to deepen the inversion during the early stage of Stage 2. This accelerated the continuous accumulation and physicochemical reactions of aerosols. This process enhanced the stability of the boundary layer in advance. This early inversion (Stage 2) superimposed with the subsequently established warm and moist advection (the SAT-SST was 1.8°C in Stage 3), providing favourable thermodynamic conditions and stratification stability for the occurrence of sea fog. During the advection sea fog period (Stage 4), the dense fog layer caused the net radiation (Rn) to remain continuously negative. This kept the MEE at a high level of 70-120 m^2/g, establishing the long-term maintenance of the sea fog system. The study found that DLR was the most sensitive to the state changes of sea fog (fluctuations of fog top height, uneven liquid water content, and fog layer thickness).

(3a) Using satellite AOD in Figure 5 to confirm that the site observed dust is inappropriate, as AOD is a column-integrated property and cannot demonstrate that dust was present at the near-surface level at the site.

Answer: We thank the reviewer for this excellent question. We agree that the satellite AOD in Figure 5, being a column-integrated quantity, is indeed inappropriate for confirming, on its own, the presence of dust at the near-surface level at the observation site. The AOD of the various aerosol components in Figure 5 reflects the column aerosol information over the whole atmosphere above the Qingbang Island site, whereas the PM measured by the weather station is the aerosol mass concentration at the near-surface level; the two represent information at different heights over the same site and are complementary. As we explained in our response to Comment (2a): during the pre-fog Stage 3, Figure 5 shows that the column AOD of dust and the other components over the site remained relatively high, while the near-surface PM at 2 m had clearly declined (Fig. 3). This combination precisely indicates that the dust had not dissipated, but remained suspended, as fine particles, in the column above the 2-m sampling height, undergoing slow settling. Figure 5 and the near-surface PM are therefore not contradictory; rather, they characterize the state of the whole column and of the near-surface, respectively. We also candidly acknowledge that this observation campaign was not equipped with instrumentation for vertical aerosol profiling. The reviewer's suggestion is very helpful and is precisely the direction of our ongoing follow-up work—using a multi-wavelength aerosol lidar to observe the vertical distribution of aerosols and its influence on sea-fog formation.

1. The evidence for aged dust and its enhanced hygroscopicity is insufficient. Please strengthen the discussion by referencing established research, such as: https://doi.org/10.1093/nsr/nwaf221.

Answer: We sincerely thank the reviewer for this valuable suggestion and for pointing us to the important reference Li et al. (2025, National Science Review, nwaf221). We fully agree that the discussion of aged dust and its enhanced hygroscopicity should be supported by more established research, and we have accordingly strengthened the relevant discussion in the manuscript.

This reference provides key mechanistic support for our inference: it shows that, during the transport and aging of Asian dust, water-bearing secondary (sulfate/nitrate) coatings can form on the dust surface, and that such coatings retain liquid water at ambient relative humidity and act as a medium for aqueous-phase heterogeneous reactions, thereby markedly enhancing the hygroscopicity and activation ability of mineral dust. We thank the reviewer again for this suggestion, which has made our argument for the enhanced hygroscopicity of aged dust more substantial.

We must candidly acknowledge that this study did not have direct-observation single-particle chemical analysis and mixing-state characterization instruments (Scanning electron microscopy (SEM), Transmission electron microscopy (TEM) and Nanoscale secondary ion mass spectrometry (NanoSIMS)) that could directly demonstrate that the sulfate aerosol originated from aged dust particles coated with sulfate. For an island-type observation station such as Qingbang Island, deploying such large laboratory-grade single-particle aerosol

instruments faces substantial practical challenges in terms of site space and equipment logistics. This is an objective methodological limitation of this study.

Drawing on the following five mutually independent observational aspects, together with the available literature on Asian dust aging, this study proposes a reasonable speculation:

(1) Fig. 4 shows that the dust was transported from Inner Mongolia through Shaanxi, Shanxi, and Shanghai to Qingbang Island in the East China Sea, passing through regions with elevated SO_2, NO_x, and NH_3 emissions. During long-range transport, dust readily reacts chemically with SO_2 and NO_x, which favours dust aging and sulfate formation. The chemical environment is consistent with the conditions required for heterogeneous sulfate formation on dust surfaces.

(2) Quantitatively usable stages in Fig. 5: During the early periods of Stages 1–3 (before 06:00 on the 25th), dust and sulfate coexisted spatio-temporally, which was conducive to their mixing and chemical reactions. In the late period of Stage 3 (after 06:00 on the 25th, approximately 10.8 hours prior to fog formation), the sulfate AOD increased while the dust component AOD decreased. This scenario aligns well with existing literature reporting that dust aging and the Fe-S coupling mechanism accelerate sulfate formation (Zhuang et al., 1992; Duce et al., 1980; Martin et al., 1994).

(3) Fig. 6(a) shows that during the dust passage period in Stage 2, the proportions of aerosol particles in the 0-1 μm and 1-2.5 μm size ranges increased significantly, with the aerosols mainly concentrated in the 0-2.5 μm range. As the dust transport passed through regions with strong pollution emissions, the dust particles may have mixed and interacted with regional pollutants and undergone some degree of chemical aging.

(4) Figs. 6(a, b) show that from late Stage 3 to early Stage 4, the modal shift reflected the evolution of dry aerosol particles rather than the direct effect of liquid water. This is consistent with the physical process in which aerosols, after undergoing heterogeneous reactions (e.g., sulfate coating onto dust surfaces) and aqueous-phase processing under near-saturated conditions in the atmosphere. Simultaneously, the MEE increased significantly by 2.3 times, reaching 125 m^2/g. This indicates that the extinction efficiency of aerosols in a wet state has significantly improved, which is consistent with the phenomenon that aerosols undergo hygroscopic growth in a high-humidity environment. These two independent observations jointly support that aerosols have undergone chemical and physical evolution in the atmosphere from different physical perspectives.

(5) Fig. 7 shows that sea fog can be triggered at low PM_1, $PM_{2.5}$, and PM_{10} mass concentrations, indicating that the aerosols possess relatively strong hygroscopicity.

Based on these five observational results, together with the literature on long-range transported dust particles (Li et al., 2025; Tobo et al., 2010; Sullivan et al., 2009; Ma et al., 2013; Yin et al., 2007) in which sulfate and nitrate coatings on the surfaces of dust particles have been directly observed as the literature reference. This study proposes the reasonable speculation that the transported dust may have undergone aging, with some particles becoming coated by sulfate to form internally mixed aerosols with a dust-core and sulfate-shell structure that exhibits strong hygroscopicity. This is a reasonable speculation based on the combination of multiple observational results and the literature, rather than a microphysical mechanism directly verified in this study. Direct verification at the aerosol particle level necessitates concurrent single particle chemical and mixing state measurements during similar events in the future. This will be the primary direction of our future research.

A new paragraph (synthesizing the 5 observational points, literature deduction, and explicit uncertainty statement) has been added after Section 3.2 (in the original manuscript):

The results of Fig. 7 (a, b, c) all show that there was a typical exponential decay relationship between visibility and aerosol mass concentration. However, the decay rate was strictly controlled by the RH. During the low RH phase of dust passage (as shown in the blue-purple colour results at around 2-5 km in the figure), the sensitivity of visibility to PM concentration was relatively low. The exponential decay result showed a high exponential decay rate in the sea fog under

high RH conditions. When the visibility was in the range of 0-1 km, the mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} were in the ranges of 26-77, 38-157, and 47-275 μgm^{-3}, respectively. The low critical thresholds for sea fog occurrence were 26, 38, and 47 μgm^{-3}, respectively. This significant result indicates that only a low aerosol mass concentration is needed to trigger sea fog. This suggests that the aerosols are highly hygroscopic.

Combining the results of Figs. 4–7: (1) Fig. 4 shows that the dust was transported from Inner Mongolia through Shaanxi, Shanxi, and Shanghai to Qingbang Island in the East China Sea, passing through regions with elevated SO_2, NO_x, and NH_3 emissions. During long-range transport, dust readily reacts chemically with SO_2 and NO_x, which favours dust aging and sulfate formation. The chemical environment is consistent with the conditions required for heterogeneous sulfate formation on dust surfaces. (2) Quantitatively usable stages in Fig. 5: During the early periods of Stages 1–3 (before 06:00 on the 25th), dust and sulfate coexisted spatio-temporally, which was conducive to their mixing and chemical reactions. In the late period of Stage 3 (after 06:00 on the 25th, approximately 10.8 hours prior to fog formation), the sulfate AOD increased while the dust component AOD decreased. This scenario aligns well with existing literature reporting that dust aging and the Fe-S coupling mechanism accelerate sulfate formation (Zhuang et al., 1992; Duce et al., 1980; Martin et al., 1994). (3) Fig. 6(a) shows that during the dust passage period in Stage 2, the proportions of aerosol particles in the 0-1 μm and 1-2.5 μm size ranges increased significantly, with the aerosols mainly concentrated in the 0-2.5 μm range. As the dust transport passed through regions with strong pollution emissions, the dust particles may have mixed and interacted with regional pollutants and undergone some degree of chemical aging. (4) Figs. 6(a, b) show that from late Stage 3 to early Stage 4, the modal shift reflected the evolution of dry aerosol particles rather than the direct effect of liquid water. This is consistent with the physical process in which aerosols, after undergoing heterogeneous reactions (e.g., sulfate coating onto dust surfaces) and aqueous-phase processing under near-saturated conditions in the atmosphere. Simultaneously, the MEE increased significantly by 2.3 times, reaching 125 m^2/g. This indicates that the extinction efficiency of aerosols in a wet state has significantly improved, which is consistent with the phenomenon that aerosols undergo hygroscopic growth in a high-humidity environment. These two independent observations jointly support that aerosols have undergone chemical and physical evolution in the atmosphere from different physical perspectives. (5) Fig. 7 shows that sea fog can be triggered at low PM_1, PM2.5, and PM_{10} mass concentrations, indicating that the aerosols possess relatively strong hygroscopicity. This is a reasonable speculation based on the combination of multiple observational results and the literature, rather than a microphysical mechanism directly verified in this study. Based on these five observational results, together with the literature on long-range transported dust particles (Li et al., 2025; Tobo et al., 2010; Sullivan et al., 2009; Ma et al., 2013; Yin et al., 2007) in which sulfate and nitrate coatings on the surfaces of dust particles have been directly observed as the literature reference. This study proposes the reasonable speculation that the transported dust may have undergone aging, with some particles becoming coated by sulfate to form internally mixed aerosols with a dust-core and sulfate-shell structure that exhibits strong hygroscopicity. This study did not have direct-observation single-particle chemical analysis and mixing-state characterization instruments (Scanning electron microscopy (SEM), Transmission electron microscopy (TEM) and Nanoscale secondary ion mass spectrometry (NanoSIMS)). These could directly demonstrate that the sulfate aerosol originated from aged dust particles coated with sulfate. For an island-type observation station such as Qingbang Island, deploying such large laboratory grade single particle aerosol instruments faces substantial practical challenges in terms of site space and equipment logistics. Direct verification at the aerosol particle level necessitates concurrent single particle chemical and mixing state measurements during similar events in the future. This will be the primary direction of our future research.

The Abstract has been revised to:

Evolution mechanisms of explosive advection sea fog coupled with long-range dust transport over East Asia remain unclear. This study investigates a dust–advection sea fog event using ground-based observations, Himawari-9 satellite products, and ERA5 reanalysis data. Results show that dust may have undergone aging during transport, promoting sea fog under high humidity (RH > 90%). Before sea fog formation (Stage 3: 12:40-16:47 on the 25th) and during the sea fog period (Stage 4: 16:47-19:30 on the 25th), the proportion of 0-1 μm particles decreased by 18% and 24%, respectively. The proportion of

1-2.5 μm particles increased by 5% and 4%, respectively. The proportion of 2.5-10 μm particles increased by 13% and 20%, respectively. This phenomenon is consistent with aerosols undergoing heterogeneous reactions and aqueous-phase processes, which may be associated with dust aging. Unlike classical advection cooling, radiative forcing of dust and cold air formed a deep inversion (9°C) before fog, which with warm-moist advection suppressed turbulent mixing and provided a favourable thermodynamic background for fog maintenance. The threshold ranges of turbulence parameters (U, TKE, u_*, I_u, I_v, I_w, u_*) were relatively distinct when sea fog maintains visibility within 1 km. The system showed a significant characteristic of turbulence acting first and fog responding later during the late stage of mist. The downward longwave radiation (DLR) was highly sensitive to changes in fog layer structure. Fog dissipation was caused by circulation adjustment and re-invasion of dry-cold dust carried by northerly winds, destroying phase equilibrium. These findings advance understanding of sea fog under complex aerosol backgrounds

The relevant content of the Fig. 5 analysis (lines 289–317 of the original manuscript) has been revised. The revised version is as follows:

From Fig. 5 (a) and (b), it can be seen that dust aerosol particles dominated and contributed the most during Stage 1-3(06:00 on March 25) before the outbreak of sea fog. The aerosol contributions from high to low were dust, sulfate, organic carbon, black carbon, and sea salt aerosols. It is notable that the contribution of sea salt aerosols was the lowest. This indicates that the aerosols at the observation site were mainly dominated by long-distance dust transport during this stage. This indicates that the aerosols at the observation site were mainly dominated by long-distance dust transport during this stage. During this stage, dust and sulfate coexisted spatially and temporally, which was conducive to their mixing and chemical reactions.

During the pre-formation phase of advection sea fog (Stage 3, 06:00-16:47 on the 25th), the dust AOD was gradually decreasing. The sulfate AOD was gradually increasing and became the dominant component. The contribution of sea salt remained at a low level. Previous studies have shown that in the marine atmospheric environment, Fe ions on the surface of dust can accelerate the formation of sulfate through the Fe-S coupling mechanism (Zhuang et al., 1992; Duce et al., 1980; Martin et al., 1994). This is highly consistent with the gradually increasing trend of sulfate AOD observed in our study. Previous studies have shown that dust particles can form a mixed structure of dust core and sulfate shell during the aging process. This internal mixing state can enhance the hygroscopicity of dust and effectively reduce the critical supersaturation required for its activation. This makes it easier to transform into cloud condensation nuclei (CCN) (Li et al., 2025; Tobo et al., 2010; Sullivan et al., 2009; Ma et al., 2013; Yin et al., 2007). In particular, Li et al. (Li et al., 2025) reported that, during the transport and aging of Asian dust, water-bearing secondary (sulfate/nitrate) coatings can form on the dust surface. Such coatings retain liquid water at ambient relative humidity and serve as a medium for aqueous-phase heterogeneous reactions, thereby markedly enhancing the hygroscopicity and activation ability of mineral dust. This mechanism is consistent with the dust-to-sulfate evolution observed before fog onset in the present event (Fig. 5). Such a scenario may have occurred during the event. In addition, the large accumulation of sulfate aerosols can cause a cooling effect on the atmosphere due to its negative forcing on solar radiation. Combined with the continuous moist advection, this further promotes the formation of sea fog.

During the sea fog and maintenance stages (Stage 4-6), the sulfate AOD remained at a high level. This is consistent with the research results of Zhao (Zhao et al., 2022). However, these results are intended strictly as a qualitative reference rather than for quantitative identification. During the mist dissipation phase (Stage 7), the dust AOD increased significantly. This may cause cooling through the combined effect of scattering to reduce surface shortwave radiation and cold air. At the same time, it changed the stratification stability. This finally led to the evaporation of fog droplets, the increase of visibility, and the dissipation of mist. This further verifies the conjecture in Fig. 4 (e) and (f) that the dissipation of sea fog is related to the second passage of dust. In summary, dust aerosols may have played a dual role in this dust-sea fog event. During the pre-formation phase of sea fog (Stage 3) and the mist dissipation phase (Stage 7), the temperatures both showed a decreasing trend. In Stage 3, when the RH increased, dust may have transformed into more hygroscopic mixed-state aerosols through the aging process, promoting the formation of sea fog. In Stage 7, when the RH decreased, dust inhibited the maintenance of mist.

The relevant content of the Fig. 6 analysis (lines 338–341 of the original manuscript) has been revised. The revised version is as follows:

In the early period of Stage 3, aerosols were mainly submicron particles (0-1 μm). However, after the RH increased to 90% at 12:40 on March 25, a significant modal shift occurred in the aerosol particle size distribution. During Stage 3 (12:40-16:47 on March 25) and the early period of Stage 4 (16:47-19:30 on March 25), the proportion of particles with sizes of 0-1 μm decreased by 18% and 24%, respectively, while the proportion of particles with sizes of 1-2.5 μm increased by 5% and 4%, respectively, and the proportion of particles with sizes of 2.5-10 μm increased by 13% and 20%, respectively. This modal shift reflects the actual variation in the dry aerosol mass distribution. This is consistent with aerosols undergoing heterogeneous reactions (e.g., sulfate coating on dust surfaces) and aqueous-phase processing in the atmosphere. In the middle and late period of Stage 4, the proportions of particles with sizes of 0-1 μm and 1-2.5 μm showed oscillating increases, while the proportion of particles with sizes of 2.5-10 μm showed an overall oscillating decrease. This phenomenon was attributed to the gravitational settling and wet removal effect of large fog droplets. During Stage 5, the proportions of all particle sizes showed oscillating variation trends, and the PM mass concentrations showed an overall oscillating decrease. This indicates the dynamic competition between external transport and wet removal by fog droplets, ultimately resulting in the wet removal effect of fog on aerosols.

The relevant content of the Fig. 7 analysis (lines 372–389 of the original manuscript) has been revised. The revised version is as follows:

To understand how aerosol mass concentration and RH affect the macroscopic visibility evolution of this event, the meteorological station observation data (PM mass concentration, Vis, RH) during the entire process were used. This aimed to explore the relationship of visibility to PM mass concentration and its sensitivity to RH (Fig. 7).

The results of Fig. 7 (a, b, c) all show that there was a typical exponential decay relationship between visibility and aerosol mass concentration. However, the decay rate was strictly controlled by the RH. During the low RH phase of dust passage (as shown in the blue-purple colour results at around 2-5 km in the figure), the sensitivity of visibility to PM concentration was relatively low. The exponential decay result showed a high exponential decay rate in the sea fog under high RH conditions. When the visibility was in the range of 0-1 km, the mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} were in the ranges of 26-77, 38-157, and 47-275 μgm^{-3}, respectively. The low critical thresholds for sea fog occurrence were 26, 38, and 47 μgm^{-3}, respectively. This significant result indicates that only a low aerosol mass concentration is needed to trigger sea fog. This suggests that the aerosols are highly hygroscopic.

The relevant content of the Section 4 Conclusions (lines 577–589 of the original manuscript) has been revised. The revised version is as follows:

This event indicates that long-distance transported dust aerosols have a promoting effect on sea fog formation under high RH conditions. Dust aerosols originating from Mongolia passed through the observation site under the guidance of the westerly jet, causing the near-surface PM_{10} mass concentration to explosively increase to 469 μgm^{-3}. Different from the traditional view in sea fog research that sea salt aerosols act as CCN, this study found that during the Stage 3 to early Stage 4, dust and sulfate aerosols showed high coupling in time and space (sulfate AOD showed an increasing trend). During Stage 3 (12:40-16:47 on March 25) and early Stage 4 (16:47-19:30 on March 25), the aerosol particle size distribution showed obvious modal shift. The proportion of 0-1 μm particles decreased by 18% and 24%, respectively, while the proportion of 1-2.5 μm particles increased by 5% and 4%, respectively, and the proportion of 2.5-10 μm particles increased by 13% and 20%, respectively. This modal shift reflects the actual variation in the dry aerosol mass distribution. This is consistent with aerosols undergoing heterogeneous reactions (e.g., sulfate coating on dust surfaces) and aqueous-phase processing in the atmosphere. This also confirms that the cross-modal transformation of aerosols to fog droplets is the core microphysical cause of the sharp drop of Vis to below 1.0 km. The fact that aerosols with a low PM mass concentration threshold can trigger sea fog formation implies their strong hygroscopicity. Based on the independent observations above, and drawing analogies from existing literature on the aging of cross-sea dust, a reasonable speculation is that the long-range transported dust may have undergone aging over the ocean. Some dust particles might be coated by sulfate to form a "dust core–sulfate shell" aerosol structure, exhibiting strong hygroscopicity. Consequently, sulfate aerosols may act as one of the

crucial CCN sources during this sea fog event. While this hypothesis has not yet been directly verified, it will serve as the primary focus of our future research.

2. How doesthe H-9 satellite distinguishes between sea fog and low-level clouds? There are clouds beside the observation station in the satellite imagery in Figure 2 during the entire event.

Answer: We thank the reviewer for this professional question. We must first candidly note that, in passive satellite remote sensing, both sea fog and low-level clouds are essentially low-level liquid-water condensates with similar radiative signatures, so the satellite alone often cannot achieve a complete and unambiguous separation between them; this is also why other clouds appear near the site throughout the event in Fig. 2. We have clarified the respective roles of the satellite and surface observations in the text and have added a description of the H-9 fog/low-cloud identification method, so as to avoid over-reliance on the satellite for this determination.

(1) The H-9 fog/low-cloud identification method. At night, we used the brightness-temperature-difference method ($BTD = BT_{3.89} - BT_{11.24}$), a widely used standard technique for nighttime fog and low-cloud detection (Kim et al., 2019): because fog (and low-level water clouds) differ in emissivity between the 3.89 μm and 11.2 μm channels, their BTD values differ from those of mid- and high-level clouds and clear sky, allowing them to be distinguished from higher clouds. During the daytime, we relied mainly on AHI true-colour composites, in which the fog area appears grey, spatially uniform and smooth-textured, with boundaries conforming to the terrain/coastline relative to the surrounding clouds, for visual identification. We emphasize that the BTD method still has an inherent limitation in separating sea fog from low-level stratus within the "low-level water cloud" category; the satellite results are therefore used in this study only to characterize the macroscopic spatial morphology and evolution of the fog area.

(2) Whether the site was in sea fog rather than low cloud is determined by the surface observations. The satellite cannot confirm whether the low-level water body over the site was grounded sea fog or a non-grounded low cloud; in this study, this determination is made directly by the surface observations. We adopted the WMO and UK Met Office criteria (fog: Vis < 1 km and RH ≥ 95%; mist: 1 km ≤ Vis < 5 km and RH ≥ 95%), and, using the in-situ visibility and RH together with the near-surface PM and other surface measurements, confirmed that the site was indeed within grounded sea fog/mist (Fig. 3, Table 2). In other words, the satellite provides the macroscopic spatial background, while the "grounded fog" is anchored by the surface observations at the site, the two being complementary.

(3) The clouds near the site in Fig. 2. Other cloud systems (e.g., mid/high clouds and non-fog low clouds) did coexist near the site in Fig. 2, which is normal for the real atmosphere. As stated in the text, the satellite fog identification is used for macroscopic morphological reference, whereas whether the site was within sea fog is determined by the surface observations; the coexistence of other clouds in Fig. 2 therefore does not affect the conclusion—established by the surface observations—that the site was within grounded sea fog.

We have added and clarified the above in the manuscript (in the H-9 method description in Section 2.2 and the Fig. 2 analysis in Section 3.1). We thank the reviewer again for this comment, which has made our description of the satellite fog identification more rigorous.

The relevant content of Section 2.2 (the H-9 fog-identification method, lines 136–139 of the original manuscript) has been revised. The revised version is as follows:

For large-scale monitoring, L1 data from Himawari-9 (H-9), the new-generation geostationary meteorological satellite of the Japan Meteorological Agency (JMA), was used in this study. The satellite is equipped with the Advanced Himawari Imager (AHI), which has the capability of high-frequency and multi-spectral observations (Bessho et al., 2016). For fog area identification from the Himawari-9 satellite data, we adopted the brightness-temperature-difference (BTD) method, which is a widely used standard technique for nighttime fog and low-cloud detection (Kim et al., 2019). The BTD was

computed as BTD=BT3.89-BT11.24, where BT3.89 and BT11.24 are the brightness temperatures at the mid-infrared (3.89 μm) and thermal infrared (11.24 μm) channels, respectively. Because fog and low-level water clouds differ in emissivity between the 3.89 μm and 11.24 μm channels, their BTD values differ from those of mid- and high-level clouds and of clear sky, allowing fog and low cloud to be distinguished from higher clouds. We note, however, that passive satellite detection cannot fully and unambiguously separate grounded sea fog from non-grounded low water clouds, since both are low-level liquid-water condensates with similar radiative signatures. Accordingly, the satellite identification is used in this study only to characterize the macroscopic spatial pattern and evolution of the fog area, while whether the observation site itself was within grounded sea fog is determined by the in-situ surface observations (visibility, RH and PM; see Section 3.1). For daytime periods, true-colour composites were utilized primarily for visual confirmation of the sea fog distribution, in which the fog area appears grey, spatially uniform and smooth-textured, with boundaries conforming to the coastline, relative to the surrounding clouds. For aerosol optical depth (AOD) data, the AHI L3 gridded aerosol product provided by JAXA Himawari Monitor (supported by the MASINGAR model system) was used. This product constrains the Meteorological Research Institute (MRI) aerosol transport model by assimilating AOD retrieved from H-9. Hourly AOD for components including sulfate, organic carbon, black carbon, sea salt, and dust can be output. Specifically, only the total AOD is retrieved from H-9. The partitioning into the individual aerosol components is provided by the MASINGAR model and adjusted through the total AOD assimilation. During sea fog occurrences, satellite retrievals may be filtered out or contaminated by cloud screening mechanisms. In this case, model outputs lack direct observational constraints. Therefore, during sea fog occurrences, this AOD data was mainly used as a qualitative or semi-quantitative reference for the regional background aerosol environment. It was not used as an accurate observational basis for aerosol microphysical changes within the fog.

The relevant content of Section 3.1 (the lines 205–206 of the original manuscript) has been revised. The revised version is as follows:

Based on the fog identification criteria of WMO (WMO/GAW, 2003) and the UK Met Office (Met Office, 1994) (Vis < 1 km and RH $\geq 95\%$ is identified as fog, 1 km $\leq$ Vis $<$ 5 km and RH $\geq 95\%$ is identified as mist). This event was divided into 7 detailed stages (Table 2). Table 2 shows the sequence numbers, stage name, time, visibility, and relative humidity of the 7 stages. It should be noted that, although other cloud systems (including mid/high clouds and non-fog low clouds) coexisted near the observation site throughout the event in the satellite imagery (Fig. 2), the satellite imagery is used here only as a reference for the macroscopic spatial morphology of the fog. Whether the site itself was within grounded sea fog is determined by the surface observations: it is confirmed only when the in-situ visibility and RH satisfy the above WMO/Met Office criteria, in combination with the near-surface PM and other surface measurements (Fig. 3, Table 2). The coexistence of other clouds near the site in Fig. 2 therefore does not affect this surface-observation-based determination.

2. It would be good if the authors could discuss the climate impacts of dust, referring to: https://doi.org/10.1126/science.aeb2629.

Answer: We sincerely thank the reviewer for this valuable suggestion and for pointing us to the important reference Wang et al. (2025, Science, doi:10.1126/science.aeb2629). We fully agree that discussing the climate impacts of dust helps to clarify the broader significance of this work, and we have accordingly added the relevant discussion to the manuscript. We thank the reviewer again for this suggestion, which has made the statement of the scientific significance of this work more complete.

The relevant content of Section 1 Introduction (the lines 64–65 of the original manuscript) has been revised. The revised version is as follows:

Due to the very complex interactions of multiple influencing factors between long-range transported dust and sea fog, the details of the effects of long-range transported dust on sea fog processes have not been well understood.

Beyond its effects on air quality and human health, mineral dust is also an important driver of climate. Previous studies have shown that dust exerts a direct radiative effect by scattering and absorbing shortwave and longwave radiation, a semi-direct effect whereby radiative heating within dust layers modifies atmospheric stability and boundary-layer structure, and indirect effects whereby dust—particularly after aging—acts as cloud condensation nuclei and ice nuclei and thereby alters

the microphysics, albedo and lifetime of clouds and fog. In addition, during long-range transport dust drives multiphase chemical reactions and influences surface O_3, and through deposition it affects ocean and ecosystem biogeochemistry (Wang et al., 2025). In recent years, Asian dust storms have increased in intensity and frequency and their pathways have shifted eastward and southward, so that dust increasingly reaches the densely populated and economically developed coastal regions of eastern China, including the East China Sea region examined here; effectively addressing Asian dust has accordingly been emphasized as a contribution to climate adaptation and sustainable development (Wang et al., 2025). These climate-relevant effects motivate a closer examination of how transported dust interacts with the coastal marine boundary layer and low-level fog.

The radiative forcing of aerosols can alter the thermodynamic and dynamic structure of the boundary layer (Deaconu et al., 2019; De Graaf et al., 2020), which can change the formation and dissipation conditions as well as the life cycle of fog

The relevant content of Section 4 (the lines 619–620 of the original manuscript) has been revised. The revised version is as follows:

This event is a typical coupled case of dust-advection sea fog with synergistic effects of multiple influencing factors. The large-scale circulation background provided sufficient water vapor, dust transport channels, and suitable air-sea conditions. Aerosols and radiation can change the microphysical properties of sea fog and the thermodynamic structure of the boundary layer, regulating the life cycle of sea fog. The turbulence process directly determined the maintenance and dissipation of the sea fog system. The long-distance transport of dust to the ocean and its exchange process at the air-sea interface have an important impact on the mechanism of sea fog formation and dissipation. This result supplements the impact of dust aerosols on the mechanism of sea fog formation and dissipation. Given that Asian dust storms are intensifying and that their pathways are shifting toward the densely populated coastal regions of eastern China (Wang et al., 2025), such dust–boundary-layer and dust–fog interactions over the downstream marginal seas may become more frequent, with compound implications for the regional radiation balance, marine visibility hazards and coastal air quality. This broader context underscores the value of integrated dust and air-quality monitoring over coastal and marine regions. At the same time, this research also holds practical reference significance for a deeper understanding of the mechanisms underlying the formation and dissipation of sea fog in a complex aerosol environment.

Minor comments:

1. Abbreviations in the abstract should be defined upon first appearance, such as U, TKE, u_*, I_u, I_v, and I_w.

Answer: We thank the reviewer for this careful comment. We have revised this content. The revised result is as follows:

Abstract. Evolution mechanisms of explosive advection sea fog coupled with long-range dust transport over East Asia remain unclear. This study investigates a dust–advection sea fog event using ground-based observations, Himawari-9 satellite products, and ERA5 reanalysis data. Results show that dust may have undergone aging during transport, promoting sea fog under high humidity (RH>90%). Before sea fog formation (Stage 3: 12:40-16:47 on the 25th) and during the sea fog period (Stage 4: 16:47-19:30 on the 25th), the proportion of 0-1 μm particles decreased by 18% and 24%, respectively. The proportion of 1-2.5 μm particles increased by 5% and 4%, respectively. The proportion of 2.5-10 μm particles increased by 13% and 20%, respectively. This phenomenon is consistent with aerosols undergoing heterogeneous reactions and aqueous-phase processes, which may be associated with dust aging. Before fog formation, the cold air advection and radiative forcing of dust co-acted to deepen a 9°C inversion, which with warm-moist advection suppressed turbulent mixing and provided a favourable thermodynamic background for fog maintenance. The threshold ranges of turbulence parameters (horizontal wind speed (U), turbulent kinetic energy (TKE), friction velocity (u_*), turbulence intensities (I_u, I_v, I_w)) were relatively distinct when sea fog maintains visibility within 1 km. The system showed a significant characteristic of

turbulence acting first and fog responding later during the late stage of mist. The downward longwave radiation (DLR) was highly sensitive to changes in fog layer structure. Fog dissipation was caused by circulation adjustment and re-invasion of dry-cold dust carried by northerly winds, destroying phase equilibrium. These findings advance understanding of sea fog under complex aerosol backgrounds.

2. There is a discrepancy between the use of "3912" in Eq. (2) and "3.912" in Line 160. While the authors intend to maintain consistency with the unit Mm^{-1} for the extinction coefficient (σext), the notation should be uniform throughout the text.

Answer: We thank the reviewer for this careful check. Upon verification, we confirm that the constant in Eq. (2) should be 3912, which equals 3.912×10^3, where 3.912 is the Koschmieder constant (Lee and Shang, 2016) and the factor of 10^3 arises from converting the extinction coefficient σext from km^{-1} (consistent with Vis expressed in km) to Mm^{-1}, the unit adopted in this study. We note that this constant had been mistyped as 3921 in the original Eq. (2); it has now been corrected to 3912. In addition, we now state explicitly the relationship between 3912 and 3.912 in the text defining the constant, so that the notation is consistent throughout. We thank the reviewer again for this comment, which has improved the accuracy and consistency of the formulation.

The relevant content of Section 2.3 (the Eq. (2) of lines 158 of the original manuscript) has been revised. The revised version is as follows:

$$\sigma_{ext} = 3912/\mathrm{Vis}$$

The relevant content of Section 2.3 (the lines 160 of the original manuscript) has been revised. The revised version is as follows:

Where σ_{ext} is the aerosol extinction coefficient with a unit of Mm^{-1}, $\rho(PM_{2.5})$ is the mass concentration of $PM_{2.5}$ with a unit of $\mu g \cdot m^{-3}$, and the unit of Vis is km. The factor 3912 in Eq. (2) equals 3.912×10^3, where 3.912 is the Koschmieder constant (Lee and Shang, 2016) and the factor of 10^3 converts the extinction coefficient from km^{-1} (consistent with Vis expressed in km) to Mm^{-1}.

3. Line 229-230: The authors claim the near-surface wind direction changed from land to sea breeze between 04:30 and 09:00 on March 25. What is the evidence for this? The wind direction data in Figure 3 shows almost no variation.

Answer: We thank the reviewer for this careful check. We have re-examined the near-surface wind-direction data in Figure 3 and confirm that, during the early morning to forenoon of 25 March (including 04:30–09:00), the 2-m wind direction was mainly southerly, and there was no significant daily change reversal from land breeze to sea breeze. The original statement that "the near-surface wind direction changed from land to sea breeze" was indeed not supported by Figure 3, for which we apologize, and we have revised this sentence.

The relevant content of Section 3.1 (the lines 228-229 of the original manuscript) has been revised. The revised version is as follows:

The system then entered the coupling period of the core mechanism of sea fog outbreak, including Stage 3 and Stage 4. At the beginning of Stage 3, the residual dust aerosols showed a gentle oscillating decrease. The settling rate of PM_{10} was about 1.8 $\mu g/m^3/h$, which is consistent with the gravitational settling model. The PM mass concentrations increased during 12:32-16:47 on March 25. This may be related to the hygroscopic growth of aerosol particles. During 04:30-09:00 on March 25, the near-surface wind at the site remained predominantly southerly. After 09:00 on March 25, the wind speed continued to increase to 6.0 $m \cdot s^{-1}$ with continuous warm and moist advection. This provided sufficient water vapor transport

for sea fog outbreak. It was favourable for the hygroscopic growth of settled dust and other aerosols to prepare for sea fog outbreak. At the end of Stage 3 (16:20-16:47), the thermodynamic conditions changed obviously. The temperature cooling rate was about 2.89°C/h, and the RH jumped to 100%. At the same time, the pressure turned to a weak increase after reaching the bottom since 15:30 on March 25. This indicates that the overall environmental field (thermal and dynamic background) changed. The combined effect of thermal and dynamic condition changes finally led to a sharp decrease in visibility to 1.0 km at 16:47 on March 25. During Stage 4, the visibility decreased sharply. The minimum visibility was 0.31 km. The aerosol concentrations showed a significant increase with multi-peak fluctuation characteristics.