

A coherent two-interface scattering model for Bohai Sea ice observed by C-band SAR*

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Abstract The Bohai Sea, China's only seasonally ice-covered sea, exhibits complex backscattering signatures in C-band Synthetic Aperture Radar (SAR) observations, particularly in nearshore areas influenced by high concentrations of suspended sediments. Using Sentinel-1 C-band Vertical-Vertical (VV)-polarized data, this study investigates the regional-scale incidence-angle-dependent scattering behavior of seasonal sea ice in the nearshore Huanghe (Yellow) River estuary. A first-order Small Perturbation Method (SPM) is employed to construct an electromagnetic scattering model for finite thickness layered sea ice, representing the ice cover as a three-layer air-ice-seawater medium with two rough scattering interfaces. The model explicitly accounts for scattering contributions from the air-ice interface, the ice-seawater interface attenuated by propagation through the ice layer, and their coherent coupling effects, while the dielectric properties of sediment-laden sea ice are described using the De Loor model combined with effective medium theory. Incidence-angle-conditioned regional mean normalized radar cross section (NRCS) is derived through statistical averaging to characterize stable scattering behavior under realistic SAR observation conditions. Comparison between modeled and Sentinel-1 observed NRCS demonstrates that the proposed coherent layered scattering framework successfully reproduces the dominant incidence-angle-dependent behavior of VV-polarized C-band NRCS at the statistical level, with validation results mainly concentrated around a global correlation coefficient (R) of 0.71 and the root mean square error (RMSE) of approximately 0.9 dB. Tile-wise analysis reveals multiple angular-response types, including increasing, decreasing, convex, concave, and weakly varying responses, indicating that the observed NRCS cannot be reduced to a single monotonic angular trend. Model comparison further shows that explicitly separating the upper and lower interface contributions and including their coherent cross term improves the reproduction of the observed VV NRCS-incidence angle response. Forward sensitivity experiments show that sediment volume fraction mainly changes the NRCS amplitude while largely preserving the angular-response type. These results provide a physically consistent basis for interpreting regional-scale SAR backscattering behavior of sediment-influenced seasonal sea ice in complex nearshore environments.

Keyword: Synthetic Aperture Radar (SAR); Bohai Sea ice; normalized radar cross section (NRCS); two-interface scattering

1 INTRODUCTION

Bohai Sea is the only seasonally ice-covered sea in China and is characterized by a semi-enclosed, shallow-water environment (Sun et al., 2020). Sea ice in the Bohai Sea mainly develops in coastal and shallow regions during winter, and long-term satellite observations have shown that it is generally dominated by thin seasonal ice (Shi and Wang,

2012; Ouyang et al., 2019). The spatial distribution and annual severity of Bohai Sea ice exhibit strong variability, reflecting its high sensitivity to local environmental conditions (Sun et al., 2020; Zhu et al., 2022). The complexity of sea ice remote sensing

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in the Bohai Sea is further enhanced by the nearshore environmental background. Previous studies have shown that Bohai Bay and areas adjacent to the Huanghe River estuary remain under persistently high concentrations of suspended particulate matter during winter, with spatial patterns governed by wind-wave forcing, sediment resuspension, and nearshore circulation (Zhu et al., 2022). Sediment-laden sea ice has also been reported in Arctic and sub-Arctic coastal or shelf regions, including the Chukchi Sea, Laptev Sea, Sea of Okhotsk, Baltic Sea, and southern Hudson Bay, indicating that sediment incorporation into sea ice is not unique to the Bohai Sea (Huck et al., 2007; Barber et al., 2021; Waga et al., 2022). Optical remote-sensing studies have shown that sediment-bearing sea ice differs from clean ice in spectral reflectance and surface albedo, which enables satellite-based mapping of particle-laden ice and assessment of its sediment loading (Huck et al., 2007; Waga et al., 2022). For Bohai Sea ice, suspended material or sediment content has also been shown to affect transmission, reflection, and scattering characteristics (Xu et al., 2010). In the context of sea ice remote sensing in the Bohai Sea, suspended sediments in the water column and sediment incorporated into sea ice may alter the optical and electromagnetic responses of the ice-seawater system. Consequently, when interpreting radar observations of nearshore sea ice in the Bohai Sea, the persistently high-turbidity environment in the Huanghe River estuary and adjacent nearshore areas should be regarded as an important background factor, and its potential impact on the observed backscattering characteristics should be carefully considered.

Synthetic Aperture Radar (SAR) has become a primary tool for long-term sea-ice monitoring, owing to its high sensitivity to surface roughness and dielectric properties of sea ice (Dierking, 2013; Qiu et al., 2024). Recent review studies have further summarized the extensive use of spaceborne SAR, especially polarimetric SAR, for sea-ice classification, ice-type discrimination, motion tracking, thickness-related retrievals, and scattering-mechanism analysis (Lyu et al., 2022; Shokr and Dabboor, 2023). Sea ice studies based on radar backscattering are generally grounded in a forward electromagnetic scattering framework, in which physical parameters such as surface morphology, internal structure, and interface characteristics are linked to radar observables, including normalized radar cross section (NRCS), to interpret sea-ice states (Jezek et al., 1998). Previous

studies have demonstrated that microwave backscattering from sea ice is jointly controlled by surface geometry, salinity distribution, and near-surface structure through their influence on the effective dielectric constant, and systematic differences in these physical-dielectric properties among ice types lead to distinct scattering responses in C-band SAR observations (Scharien et al., 2010). Multi-frequency comparative studies over the Bohai Sea and other seasonal ice-covered regions further indicate that, compared with higher frequency bands that are more sensitive to near surface conditions and lower frequency bands that provide different penetration and thin-ice separability, C-band provides a practical trade-off between surface scattering sensitivity and electromagnetic penetration depth (Zhang et al., 2013). As a result, C-band SAR has been widely employed for observing and analyzing thin ice and first-year ice in seasonal ice regimes (Nandan et al., 2017; Qiu et al., 2024). Multi-frequency SAR studies of newly formed and freeze-up sea ice further show that C-band signatures contain useful information on early-stage ice conditions, but are also affected by frequency, polarization, incidence angle, ice type, surface roughness, salinity, and near-surface dielectric properties (Johansson et al., 2018; Mahmud et al., 2022). In nearshore regions of the Bohai Sea, where environmental conditions are highly complex and ice-seawater interactions are pronounced, C-band SAR derived NRCS often exhibits pronounced spatial heterogeneity and clear incidence angle dependence. In view of these characteristics, this study adopts an electromagnetic scattering framework, with particular emphasis on regional-scale averaged scattering behavior, to investigate how interface related scattering terms are manifested in observed SAR NRCS under realistic observation conditions.

At present, electromagnetic scattering models can be broadly classified into two categories: analytical or semi-analytical models based on approximate scattering theories, and numerical electromagnetic models that directly solve Maxwell's equations. Within the analytical and semi-analytical category, the Integral Equation Model (IEM), as a classical surface scattering theory, has been widely applied to interpret microwave backscattering from sea ice and other natural surfaces (Fung, 1994). However, this approach typically incorporates the ice-seawater interface into an effective dielectric response and neglects interfacial propagation phase and coherent interference

effects (Golden et al., 1998). For thin to moderately thick sea ice, such simplifications may be insufficient to describe the continuous modulation of NRCS by the lower interface, internal propagation phase, and coherent interference effects, thereby limiting the physical interpretability of multi-interface scattering mechanisms. Within the framework of analytical electromagnetic scattering theories, the Small Perturbation Method (SPM) provides a systematic analytical description for multi-interface scattering problems. Under the first-order perturbation approximation, a unified electromagnetic scattering theory applicable to arbitrary layered structures with an arbitrary number of rough interfaces was established, demonstrating that the total scattering power can be consistently expressed as the sum of individual interface contributions and their cross terms (Imperatore et al., 2009). Building upon this general formulation, subsequent studies have specialized the theory to layered ice-snow systems by explicitly introducing multiple rough interfaces and accounting for internal propagation and reflection effects, and have conducted forward numerical analyses to verify the physical feasibility of multi-interface scattering under different parameter configurations (Komarov et al., 2014). These studies provide a theoretical basis for representing finite thickness sea ice as a multi-interface scattering system rather than as a single effective boundary. Complementary to analytical approaches, numerical electromagnetic methods provide an independent means of investigating multi-interface scattering by directly solving Maxwell's equations. Finite-element-based studies have shown that roughness at the ice-seawater interface can substantially enhance the total backscattered power, further indicating that the contribution of the lower interface should not be neglected in sea-ice scattering processes (Xu et al., 2018). Nevertheless, such numerical simulations are typically restricted to prescribed geometries and limited parameter combinations, involve high computational cost, and are therefore difficult to extend to the wide incidence-angle ranges and spatial scales commonly encountered in satellite SAR observations. As a result, their applicability to the stable statistical characterization of NRCS behavior at regional scales remains limited.

Despite substantial progress in analytical and numerical investigations of multi-interface electromagnetic scattering in layered media, most existing studies focus on the physical interpretation

of individual scattering realizations or idealized configurations (Tsang et al., 2000). Under realistic spaceborne SAR observation conditions, however, radar measurements rarely correspond to a single deterministic scattering scenario. Instead, the observed signal represents a spatially aggregated response from heterogeneous sea-ice fields, within which surface roughness, ice thickness, salinity, and sub-grid structural variability coexist (Oliver and Quegan, 2004). As a result, SAR observables are more naturally characterized in terms of regionally averaged or statistically aggregated NRCS, together with their conditional dependence on incidence angle over finite spatial supports (Ulaby et al., 1982). From this observational perspective, the physical interpretation of stable incidence-angle-dependent behavior of statistically averaged NRCS within an electromagnetic scattering framework remains insufficiently addressed, particularly with respect to the respective contributions from the upper and lower ice interfaces and their coherent interactions. Although coherent multi-interface scattering effects are well understood at the level of individual realizations, it remains unclear whether and how such effects manifest themselves in regionally averaged NRCS derived from spatially heterogeneous sea-ice regions.

To address this issue, this study focuses on seasonal sea ice in the nearshore Huanghe River estuary of the Bohai Sea and formulates a coherent two-interface SPM framework for interpreting C-band Vertical-Vertical (VV) polarized SAR NRCS. Within this framework, the sea-ice cover is represented as a finite thickness air-ice-seawater layered medium with two rough interfaces, namely the air-ice interface and the ice-seawater interface. The respective contributions of the upper interface, the lower interface, and their coherent cross term are explicitly formulated and statistically examined using incidence-angle-conditioned regional NRCS observations. By combining a physically based scattering model with incidence-angle-conditioned NRCS statistics, this study investigates how coherent two-interface scattering mechanisms are manifested in regional-scale Sentinel-1 NRCS under realistic nearshore sea-ice conditions.

The remainder of this paper is organized as follows. Section 2 presents the physical scattering model for finite thickness sea ice. Section 3 describes the study area, datasets, and preprocessing procedures. Section 4 introduces the tile-based sample screening, material parameterization, parameter

search, and validation strategy. Section 5 reports and discusses the regional-scale validation results, tile-wise angular-response behavior, effective roughness parameters, sediment-volume-fraction sensitivity, and model comparison. Section 6 summarizes the main conclusions and limitations.

2 PHYSICAL SCATTERING MODEL

2.1 Physical assumptions and layered air-ice-seawater representation

As illustrated in Fig.1, the sea-ice system is represented as a horizontally stratified three-layer air-ice-seawater medium consisting of air (0), a finite thickness sea ice layer (1), and the underlying seawater (2). The mean coordinate system is defined with the horizontal plane parallel to the mean ice surface and the vertical axis pointing upward. Throughout this study, the sea-ice system is treated as a three-layer (air-ice-seawater) medium, in which microwave backscattering is governed by two rough scattering interfaces, namely the air-ice and ice-seawater boundaries. The radar observation is considered under a monostatic SAR geometry, and the local incidence angle is denoted by θ .

The top interface, separating air and sea ice, is characterized by a rough surface described by the height function

$$z_t(x, y) = \eta_t(x, y), \quad (1)$$

while the bottom interface, separating sea ice and seawater, is described by

$$z_b(x, y) = -h + \eta_b(x, y), \quad (2)$$

where h denotes the mean ice thickness, and $\eta_t(x, y)$ and $\eta_b(x, y)$ represent zero-mean random height fluctuations of the top and bottom interfaces. For the subsequent tile-scale implementation, both interfaces are assumed to be locally statistically stationary within each retained tile. To reduce the number of free parameters and maintain model interpretability, isotropic roughness spectra are adopted as a first-order approximation in the baseline model.

Each layer is characterized by a complex dielectric constant ε_j ($j=0, 1, 2$), representing air, sea ice, and seawater. The dielectric properties of the ice and seawater layers are introduced here as symbolic material inputs to the scattering formulation. Their numerical parameterization and resulting effective values are described in Section 4.2 and are then treated as fixed inputs in the scattering calculation.

Based on these material inputs, the corresponding planar-interface Fresnel coefficients are introduced as electromagnetic response terms.

For a three-medium geometry (Fig.1), the vertical wavenumber k_{zj} ($j=0, 1, 2$) follows from Snell's law and the dispersion relation

$$k_{zj} = k_0 \sqrt{\varepsilon_j - \sin^2 \theta}, \quad (3)$$

where $k_0 = 2\pi/\lambda$ is the free-space wavenumber, ε_j is the complex relative permittivity of layer j and θ is the local incidence angle. For the sea-ice layer, k_{z1} is complex and can be written as $k_{z1} = \beta_1 + i\alpha_1$, where $\beta_1 = \text{Re}\{k_{z1}\}$ represents the phase constant and $\alpha_1 = |\text{Im}\{k_{z1}\}|$ represents the attenuation coefficient.

Based on the electromagnetic boundary conditions at a planar interface, the Fresnel reflection coefficients for VV polarization can be written as

$$F_{VV}^{01} = \frac{\varepsilon_1 k_{z0} - \varepsilon_0 k_{z1}}{\varepsilon_1 k_{z0} + \varepsilon_0 k_{z1}}, \quad (4)$$

$$F_{VV}^{12} = \frac{\varepsilon_2 k_{z1} - \varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1} + \varepsilon_1 k_{z2}}. \quad (5)$$

The associated transmission coefficients (for the tangential electric-field amplitude) are

$$T_{VV}^{01} = \frac{2\varepsilon_1 k_{z0}}{\varepsilon_1 k_{z0} + \varepsilon_0 k_{z1}}, \quad (6)$$

$$T_{VV}^{10} = \frac{2\varepsilon_0 k_{z1}}{\varepsilon_1 k_{z0} + \varepsilon_0 k_{z1}}. \quad (7)$$

These coefficients define the reflection/transmission behavior of the layered medium under the planar interface assumption and will be used to construct the effective top and bottom interface scattering amplitudes in the following sections. Within this layered configuration, the incident radar wave interacts with both the top and bottom rough interfaces through scattering, while undergoing

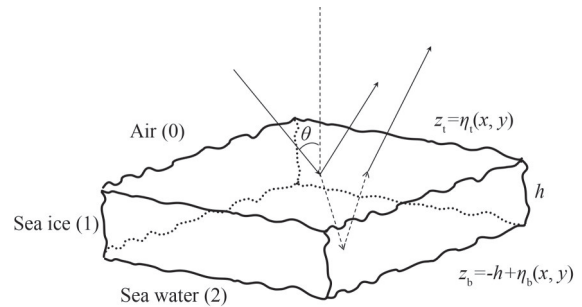


Fig.1 Schematic of the monostatic SAR scattering geometry for a three-layer air-ice-seawater system

transmission, attenuation, and phase accumulation inside the ice layer. This formulation provides a consistent physical basis for describing multilayer scattering contributions and remains compatible with first-order surface scattering theory.

2.2 Single interface scattering under the first-order perturbation approximation

Following the classical first-order SPM, radar backscattering from a randomly rough surface can be described, in a statistical sense, by separating the geometric scaling factor, the electromagnetic response of the interface, and the surface roughness spectrum. In this study, the classical single-interface Bragg formulation is used as a rough-interface scattering basis rather than as a complete physical description of finite-thickness sea ice.

Under monostatic illumination, the NRCS for a single rough interface can be expressed in the generic form

$$\sigma_{VV}^0(\theta) = G(\theta) |A_{VV}(\theta)|^2 W(q), \quad (8)$$

where θ denotes the local incidence angle, $q=2k\sin\theta$ is the Bragg resonant wavenumber, and $k=2\pi/\lambda$ is the electromagnetic wavenumber corresponding to the radar wavelength λ . For monostatic backscattering, the geometry-related factor is written as

$$G(\theta)=4\pi k^4 \cos^4\theta. \quad (9)$$

It originates from the first-order perturbation expansion of the surface scattering problem and accounts for the angular dependence of the scattering efficiency (Iodice and Imperatore, 2024). The term $A_{VV}(\theta)$ denotes the VV-polarized electromagnetic response of the rough interface. For a single dielectric boundary, it reduces to the corresponding Fresnel-type scattering coefficient; for a layered medium, it can be generalized to include transmission, reflection, attenuation, and phase effects. The surface roughness contribution is described by the roughness power spectrum $W(q)$, evaluated at the Bragg wavenumber. In this study, $W(q)$ follows the two-dimensional roughness spectral-density normalization used in the Bragg formulation adopted here. Therefore, the numerical prefactor should be interpreted together with the definition of $W(q)$. Different Fourier-transform or spectrum-normalization conventions may lead to alternative prefactors without changing the physical dependence on the electromagnetic coefficient and roughness

spectrum.

Equation 8 provides a physically transparent description of microwave scattering from a single randomly rough interface under the first-order small-perturbation assumption. In this baseline formulation, the backscattered power is governed by the Fresnel reflection coefficient of the interface and the corresponding surface roughness spectrum (Ulaby et al., 1986). However, finite-thickness sea ice differs from the single-interface case because the observed SAR return may contain contributions from both the air-ice and ice-seawater boundaries. In addition, waves scattered from the lower interface must undergo transmission through the upper boundary, propagation within the ice layer, attenuation, and phase accumulation. These effects cannot be fully represented by a single rough boundary.

Accordingly, the single-interface SPM form in Eq.8 is used as the starting point for the two-interface sea-ice formulation developed in the next subsection. The key extension is to replace the single-interface electromagnetic response by the coherent superposition of the scattering amplitudes from the air-ice and ice-seawater interfaces.

2.3 Extension of the SPM framework to a two-interface sea-ice configuration

For a sea-ice layer of finite thickness, the scattering system consists of two rough interfaces: the top air-ice interface and the bottom ice-seawater interface. Compared with a single rough boundary, this layered configuration introduces additional transmission, attenuation, and phase-accumulation processes within the ice layer. Therefore, the finite thickness sea-ice layer is not treated as a single rough interface in the present formulation. Instead, the total scattered field is represented by the coherent superposition of the contributions from the two rough boundaries. The total complex scattering amplitude at incidence angle θ is written as

$$S(\theta)=S_t(\theta)+S_b(\theta), \quad (10)$$

where $S_t(\theta)$ and $S_b(\theta)$ denote the scattering amplitudes associated with the top and bottom interfaces. Taking the second-order moment of the total scattering amplitude gives

$$E\{|S(\theta)|^2\}=E\{|S_t(\theta)|^2\}+E\{|S_b(\theta)|^2\}+2\text{Re}\{E\{S_t(\theta)S_b^*(\theta)\}\}. \quad (11)$$

The first two terms in Eq.11 represent the independent power contributions from the top and

bottom interfaces, whereas the third term represents the coherent cross contribution between them. This cross contribution accounts for the constructive or destructive interference caused by the finite propagation phase inside the ice layer.

Consistent with the standard radar equation for distributed targets, the NRCS can be expressed as a geometry-scaled version of the second-order moment of the complex scattering amplitude (Fung, 1994)

$$\sigma_{VV}^0(\theta) = G(\theta) E\{|S_{VV}(\theta)|^2\}, \quad (12)$$

which preserves the first-order SPM separation between the geometric factor and the second-order moment of the rough-interface scattering amplitude, while allowing the latter to include multiple interface contributions.

For the top (air-ice) interface, the scattered wave is controlled by the Fresnel reflection response at the upper boundary and by the roughness spectrum of the top interface.

$$E\{|S_t(\theta)|^2\} = |F_{VV}^{01}|^2 W_t(q), \quad (13)$$

where F_{VV}^{01} is the Fresnel reflection coefficient at the air-ice interface for VV polarization, and $W_t(q)$ denotes the roughness power spectrum of the top interface evaluated at the Bragg wavenumber.

For the bottom (ice-seawater) interface, the scattered wave undergoes transmission into the ice layer, propagation to the lower boundary, reflection, and propagation back toward the radar. Accordingly, the ensemble-averaged scattered power can be written as

$$E\{|S_b(\theta)|^2\} = |T_{VV}^{01} T_{VV}^{10} F_{VV}^{12}|^2 e^{-4\alpha_i h} W_b(q), \quad (14)$$

where T_{VV}^{01} and T_{VV}^{10} are the transmission coefficients across the air-ice interface, F_{VV}^{12} is the Fresnel reflection coefficient at the ice-seawater interface. The exponential term $e^{-4\alpha_i h}$ accounts for the two-way propagation loss through the ice.

In addition to the independent contributions, the coherent superposition of $S_t(\theta)$ and $S_b(\theta)$ gives rise to a cross term. This term contains the one-way propagation attenuation, the phase accumulation within the ice layer, the phase difference between the top- and bottom-interface electromagnetic responses, and the cross spectrum between the two rough interfaces. In the present formulation, the cross contribution is written as

$$2\text{Re}\{E\{S_t(\theta)S_b^*(\theta)\}\} = 2e^{-2\alpha_i h} |F_{VV}^{01}| |T_{VV}^{01} T_{VV}^{10} F_{VV}^{12}| |W_{tb}(q)| \cos(2\beta_i h - \Delta\phi), \quad (15)$$

where $\beta_i = \text{Re}\{k_{zi}\}$ is the phase constant in the ice layer, and $W_{tb}(q)$ denotes the cross spectrum between the height fluctuations of the top and bottom interfaces. The phase difference $\Delta\phi$ is defined as

$$\Delta\phi = \arg(F_{VV}^{01}) - \arg(T_{VV}^{01} T_{VV}^{10} F_{VV}^{12}). \quad (16)$$

The term $\cos(2\beta_i h - \Delta\phi)$ describes the phase-controlled interference between the top and bottom interface scattering amplitudes. A positive value enhances the total scattered power, whereas a negative value leads to partial cancellation.

Substituting Eqs. 13–15 into Eq. 11 and then into Eq. 12, gives the two-interface first-order scattering representation for the finite thickness sea-ice layer. This formulation extends the single-interface SPM basis by explicitly retaining the air-ice contribution, the ice-seawater contribution, and their coherent cross contribution. It therefore provides a physically interpretable framework for examining how finite ice thickness, dielectric contrast, propagation attenuation, and interface roughness jointly control the VV-polarized NRCS.

2.4 Roughness spectra of the air-ice and ice-seawater interfaces

The surface roughness of the top (air-ice) and bottom (ice-seawater) interfaces is characterized by their corresponding roughness power spectra, denoted by $W_t(q)$, $W_b(q)$, and $W_{tb}(q)$. Following standard random rough-surface scattering theory, the roughness statistics of each interface are described using parametric isotropic power spectra that relate the surface height variance and correlation structure to the spectral distribution of roughness energy. These spectra serve as material-independent statistical inputs to the first-order small-perturbation scattering formulation.

Within each analysis tile, the top and bottom interfaces are allowed to exhibit different roughness characteristics (Komarov et al., 2014). Therefore, they are parameterized using separate root mean square heights and correlation lengths. The roughness power spectra of the two interfaces are written as

$$W_t(q) = \sigma_t^2 \widetilde{W}_t(q), \quad (17)$$

$$W_b(q) = \sigma_b^2 \widetilde{W}_b(q), \quad (18)$$

where σ_t^2 and σ_b^2 denote the height variances (mean square heights) of the top and bottom interfaces, $\widetilde{W}_t(q)$ and $\widetilde{W}_b(q)$ are the corresponding normalized spectral shape functions describing the correlation

structure of each interface. This parameterization explicitly separates the overall roughness strength from the spectral shape, allowing the scattering formulation to remain independent of a specific roughness model.

For the coherent cross term in Eq.15, the cross spectrum $W_{tb}(q)$ describes the statistical coupling between height fluctuations at the top and bottom interfaces. Because direct observations of the joint top-bottom roughness statistics are not available, the magnitude of the cross spectrum is approximated using the geometric mean of the two interface spectra,

$$|W_{tb}(q)| = \sigma_t \sigma_b \left[\widetilde{W}_t(q) \widetilde{W}_b(q) \right]^{\frac{1}{2}}. \quad (19)$$

This treatment provides a simple closure approximation for the coherent cross contribution when only the marginal roughness spectra of the two interfaces are specified. It should be noted that this approximation does not imply that the true top and bottom interface height fields are fully known or directly measured. Rather, it is used to represent the potential contribution of statistically coupled two-interface scattering within the present effective SPM framework.

To represent relatively smooth interfaces with short-range spatial correlations, the Gaussian roughness spectrum is adopted (Pinel and Bourlier, 2013). This spectrum has been widely used in microwave scattering studies of natural surfaces within the first-order small-perturbation framework, particularly for interfaces whose roughness energy is dominated by small-scale height fluctuations.

$$\widetilde{W}_G(q) = \pi L^2 \exp\left(-\frac{q^2 L^2}{4}\right), \quad (20)$$

where L denotes the surface correlation length. The rapid exponential decay of the Gaussian spectrum at high spatial wavenumbers reflects the absence of pronounced long-range correlations, making it suitable for describing relatively smooth air-ice or ice-seawater interfaces under weak-roughness conditions. The top and bottom interface spectral shapes are specified as

$$\widetilde{W}_t(q) = \widetilde{W}_G(q, L_t), \quad (21)$$

$$\widetilde{W}_b(q) = \widetilde{W}_G(q, L_b), \quad (22)$$

where L_t and L_b are the effective correlation lengths of the top and bottom interfaces. It should be emphasized that σ_t , σ_b , L_t , and L_b are treated as tile-

scale effective roughness parameters in this study. They are not direct in situ measurements of the physical sea-ice surface or underside roughness. Instead, they represent the effective roughness statistics required for the first-order scattering model to reproduce the observed NRCS-incidence-angle behavior within each selected tile.

3 STUDY AREA AND DATA

3.1 Study area and sea-ice condition

The study area is situated north of the Huanghe River estuary (approximately 37.78°N–37.80°N, 119.22°E–119.24°E (Fig.2a)), in the southern Bohai Sea near the northwestern Laizhou Bay. The Bohai Sea is one of the southernmost seasonally frozen seas in the Northern Hemisphere, and sea-ice formation there is mainly controlled by the regional geographic setting and hydrometeorological conditions. With an average water depth of approximately 18 m, the basin is affected by cold Siberian air masses in winter and generally experiences a sea-ice season from December to March (Yan et al., 2022). Long-term satellite-based retrievals from 2000 to 2016 further indicate that Bohai winter sea ice is generally thin, with a mean ice thickness of 5.58 ± 0.86 cm, and that the maximum ice thickness and maximum ice extent usually occur around late January and early February (Ouyang et al., 2019). Sea-ice conditions in the Bohai and northern Yellow Seas also exhibit substantial interannual variability, and winter temperature and cold-wave frequency have been identified as important local climatic factors controlling sea-ice variation during 2001–2020 (Yan et al., 2023). In addition, the Huanghe River estuary is characterized by strong sediment input and high turbidity. Large amounts of sediment are delivered by the Huanghe River to the Bohai Sea, deposited near the estuary, and resuspended and transported offshore during winter; sea-ice cover can also modify local hydrodynamics and sediment transport processes (Liu et al., 2024).

The SAR and optical images analyzed in this study were acquired on 15–16 January 2025. As shown in Fig.2, the Sentinel-2B optical image reveals bright continuous ice-covered areas, narrow linear fracture-like features, and fragmented or drifting ice patches within the study area. The corresponding Sentinel-1A VV-polarized NRCS image also shows clear bright-dark spatial contrasts. These image features indicate that the study area is not a uniform ice cover, but a spatially

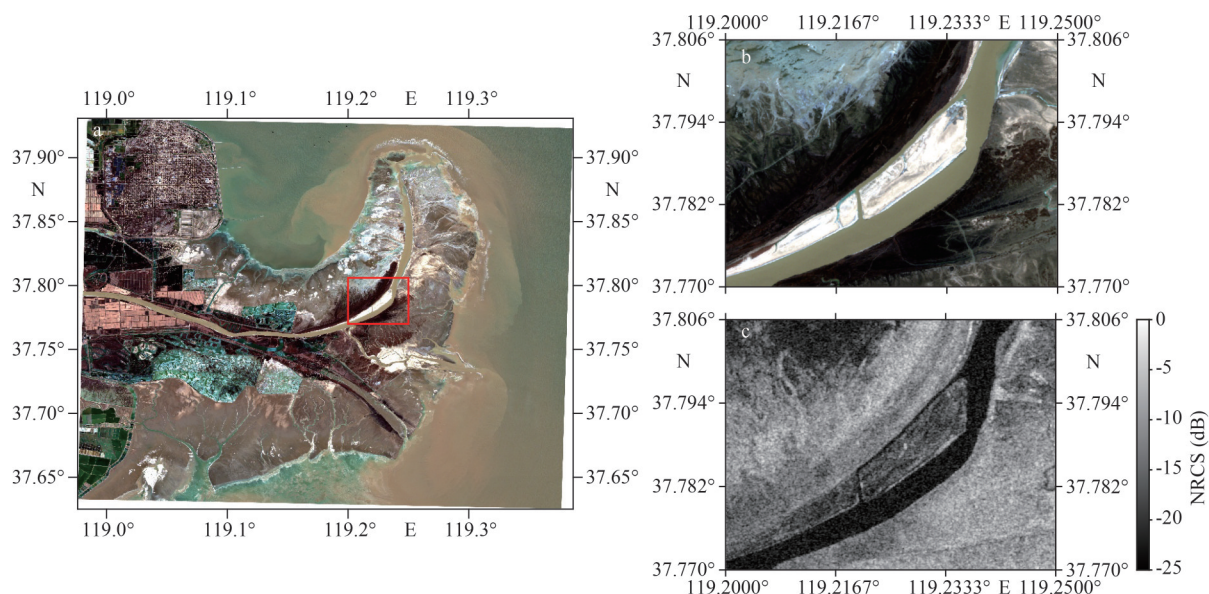


Fig.2 Overview of the study area near the Huanghe River estuary

a. Sentinel-2B Multispectral Instrument (MSI) true-color composite (January 2025) covering the Huanghe River estuary, with a marked box highlighting the study area; b. enlarged view of the selected study area from Sentinel-2B; c. Sentinel-1A Ground Range Detected (GRD) High vertical-vertical (VV)-polarized NRCS over the same area.

heterogeneous thin-ice scene with variable surface texture and backscattering response. Numerical sea-ice modelling studies for the Bohai Sea have shown that the formation and evolution of Bohai Sea ice involve both thermodynamic and dynamic processes, and that ice floes can drift under the forcing of winds, tides, and ocean current (Yan et al., 2022). Field observations of Bohai landfast ice further showed that cold-air events can lead to rapid sea-ice growth, with growth rates reaching 3.7 cm/d under very cold conditions (Ma et al., 2024). Ma et al. (2024) also reported that in a normal ice winter, the seasonal ice cover in the Bohai Sea lasts for about three months and that drift-ice thickness ranges from approximately 10 cm for undeformed ice floes to 50 cm for rafted ice floes. Therefore, the continuous ice-covered areas, fragmented ice patches, and fracture-like features observed in Fig.2 can be interpreted as the image expression of nearshore thin ice affected by both thermodynamic growth and local dynamic modification.

According to the mid and late January 2025 ice-condition forecasts and 72 h marine forecasts issued by the Dongying Municipal Bureau of Marine Development and Fisheries, a small amount of drift ice occurred in the Dongying nearshore waters in mid-January 2025, while a small amount of fast ice appeared around coastal shoals and the estuarine

area. The reported level-ice thickness was generally 3–5 cm in mid-January and approximately 5 cm in late January. The ice thickness parameter used in this study is therefore mainly based on the local level-ice thickness reported in the Dongying nearshore ice-condition forecasts. It also refers to the 2000–2016 satellite-based Bohai winter sea-ice thickness retrievals (Ouyang et al., 2019), the Moderate Resolution Imaging Spectroradiometer (MODIS)-based analysis of sea-ice thickness evolution during the severe 2009/2010 Bohai ice season (Shi and Wang, 2012), and the field observations of Bohai landfast-ice growth reported (Ma et al., 2024). Accordingly, $h=5$ cm is adopted as the representative ice thickness for nearshore level-ice conditions in the baseline scattering simulation.

3.2 Data and preprocessing

3.2.1 Data source and acquisition

The primary dataset used in this study consists of C-band SAR observations acquired by the Sentinel-1A satellite operated by the European Space Agency. Sentinel-1A operates at a center frequency of 5.405 GHz and provides systematic wide-area SAR coverage suitable for sea-ice observation. All SAR images were acquired in Interferometric Wide-Swath mode with VV polarization, which has been widely used for characterizing sea-ice surface

roughness and dielectric variations. The SAR data were collected during January 2025, corresponding to the peak seasonal ice-development period in the Bohai Sea.

To support sea-ice identification and visual interpretation, multispectral optical imagery from the Sentinel-2B satellite was additionally employed. Sentinel-2B Multispectral Instrument (MSI) data provide high-resolution observations in visible and near-infrared bands, which are effective for distinguishing sea ice, open seawater, and fracture zones under cloud-free conditions. Optical images temporally close to the Sentinel-1A acquisitions were selected to ensure spatial and temporal consistency between the SAR and optical datasets. In this study, Sentinel-2B imagery is used as an auxiliary data source for ice masking and regional context, while SAR data constitute the primary input for quantitative NRCS analysis.

3.2.2 Preprocessing

Sentinel-1A SAR data were processed following a standard radiometric and geometric correction workflow to ensure the reliability and consistency of the NRCS measurements. Precise orbit ephemerides were applied to refine satellite geometry and improve geolocation accuracy. Thermal noise and border-noise removal were then performed to suppress low-signal edge artifacts inherent to Ground Range Detected (GRD) products. Radiometric calibration was subsequently conducted to generate VV-polarized NRCS, while auxiliary parameters such as local incidence angle, latitude, and longitude were retained for subsequent scattering analysis. Finally, Range-Doppler terrain correction was applied, and the SAR data were reprojected to the Universal Transverse Mercator (UTM) Zone 51N coordinate system, yielding geocoded NRCS products with a spatial resolution of 10 m (Torres et al., 2012; GMV Innovating Solutions, 2025a).

Sentinel-2B MSI data were processed in parallel to ensure spatial consistency with the SAR dataset. Optical bands in the visible and near-infrared range were selected to facilitate ice-seawater discrimination. To match the spatial resolution and map projection of the Sentinel-1A data, the 20 m near-infrared band (B8A) was resampled to 10 m, and all selected bands were reprojected to the same UTM coordinate system. The resulting Sentinel-2B products provide spatially aligned optical information that supports sea-ice masking and regional visualization in the

subsequent analysis (GMV Innovating Solutions, 2025b).

3.2.3 Optical-assisted sea-ice masking and sample selection

To ensure that the proposed two-interface scattering framework in a three-layer configuration is applied only to physically meaningful sea-ice regions, an optical-assisted sea-ice masking procedure is introduced prior to SAR-based analysis. The purpose of this step is to exclude open seawater and non-ice surfaces, thereby avoiding the contamination of scattering statistics by fundamentally different backscattering mechanisms.

The sea-ice mask is derived from Sentinel-2B multispectral imagery, exploiting the strong contrast between sea ice and open seawater in the visible and near-infrared spectral ranges under cloud-free conditions. Optical snow and ice products derived from sensors such as MODIS have been widely used in previous studies to support sea-ice identification in SAR-based analyses (Hall et al., 2002). In the present study, Sentinel-2B imagery is adopted as a higher-resolution optical reference, providing improved spatial detail and geometric consistency with Sentinel-1A SAR data. The resulting binary ice mask is spatially aligned with the Sentinel-1A SAR data and applied directly to the geocoded NRCS products.

After masking, only SAR samples located within optically identified sea-ice regions are retained for subsequent analysis. This step effectively restricts the dataset to areas where the assumed two-interface sea-ice scattering configuration—comprising an air-ice surface and an ice-seawater interface—is physically valid, while suppressing contributions from open seawater and mixed boundary pixels.

Following sea-ice masking, the remaining SAR samples still exhibit spatial variability due to incidence-angle dependence and local surface heterogeneity. Rather than treating this variability as noise, it is regarded as an intrinsic physical characteristic of sea-ice backscattering. To preserve spatial locality while ensuring sufficient angular information for model inversion, the masked SAR samples are subsequently organized into spatial tiles, within which statistical screening and parameter estimation are performed. This tile-based sample organization forms the basis for the incidence-angle-dependent scattering analysis of regional mean NRCS presented in the following section.

4 METHOD

4.1 Tile-based screening of SAR sea-ice samples

After optical-assisted sea-ice masking, the remaining VV-polarized SAR samples still exhibit substantial spatial and angular variability within the ice-covered region. Such variability is expected in sea-ice SAR observations because microwave backscatter is jointly controlled by radar parameters, including frequency, polarization, and incidence angle, as well as by sea-ice geophysical and thermodynamic properties (Mahmud et al., 2020). Previous Sentinel-1A sea-ice studies have further shown that SAR backscatter and texture features can vary systematically with incidence angle, and that this dependence may differ among surface or ice classes (Lohse et al., 2021). Similarly, recent SAR sea-ice classification studies have explicitly incorporated class-dependent incidence-angle effects into the classification framework (Guo et al., 2023), while C-band Sentinel-1A backscatter has also been shown to exhibit statistical relationships with sea-ice physical parameters that depend on ice type, incidence angle, spatial scale, and locality (Liu et al., 2025). This variability primarily reflects the intrinsic incidence-angle dependence of NRCS and the coexistence of multiple scattering contributions associated with heterogeneous sea-ice surfaces, rather than random noise or measurement artifacts. However, when SAR samples within a local region are unevenly distributed over the incidence-angle domain, direct inversion of incidence-angle-dependent scattering models may become ill-conditioned and physically ambiguous.

To address this issue, a tile-based screening strategy is adopted to ensure that subsequent model inversion is supported by spatially localized samples with sufficient and well-distributed incidence-angle information. The masked SAR dataset is partitioned into regular geographic tiles, within which samples are treated as approximately homogeneous in terms of surface properties while retaining natural angular variability. The tile size was selected as a compromise between local spatial representativeness and statistical stability. Smaller tiles better preserve local ice-surface homogeneity but often fail to provide enough samples and angular diversity. Larger tiles improve sample support but increase the risk of mixing different surface states, fracture features, or drifting ice patches within one statistical unit. Preliminary tests over tile sizes from 0.002° to

0.005° showed that the 0.003° – 0.004° range provided a practical balance between spatial locality and angular sampling. Therefore, a geographic tile size of $0.004^\circ \times 0.004^\circ$ was adopted in this study. This scale was not selected as the spatial unit that minimized the root mean square error (RMSE), but rather as a spatial support for incidence-angle-conditioned NRCS statistics and subsequent model inversion.

For each tile, basic usability conditions are first imposed, including a minimum number of valid SAR samples and a minimum span of local incidence angles. The minimum sample-size threshold was determined from the statistical stability of angle-bin-averaged NRCS. Sentinel-1A mission specifications report a radiometric stability of 0.5 dB (3σ) and a radiometric accuracy of 1 dB (3σ), and subsequent Sentinel-1A constellation calibration studies have also emphasized the importance of radiometric consistency and noise effects, particularly over low-backscatter targets such as ice areas (Torres et al., 2012; Schmidt et al., 2020). Accordingly, $E=0.5$ dB was used as a conservative practical uncertainty target for the angle-bin mean NRCS. Let s_k and n_k denote the standard deviation and sample number of σ_{VV}^0 in the k^{th} incidence-angle bin. The standard error of the bin mean is

$$SE_k = \frac{s_k}{\sqrt{n_k}}. \quad (23)$$

For a 95% confidence half-width target of $E=0.5$ dB, the required sample size is $n_k \geq \left(\frac{1.96s_k}{E}\right)^2$.

For all valid angle bins in the candidate tiles, the median and 75th percentile of s_k were 2.160 dB and 2.492 dB. Substituting these values gives a required sample size of approximately 72–96 samples per effective angle bin. Because at least four effective angle bins are required to constrain an incidence-angle-dependent response, the corresponding total sample requirement is approximately 288–384. Therefore, $N_{\min}=350$ was adopted as a practical minimum sample-size threshold.

The minimum incidence-angle span is directly related to the angular dependence of the scattering model. In the first-order perturbation framework, the NRCS depends explicitly on incidence angle. The geometric factor $G(\theta)$ varies with θ and the Bragg wavenumber sampled by the roughness spectrum, q also changes with incidence angle. This theoretical dependence is consistent with recent observational

and classification studies showing that sea-ice SAR backscatter or texture features exhibit incidence-angle-dependent behavior (Lohse et al., 2021; Guo et al., 2023; Liu et al., 2025). Therefore, if the incidence-angle span within a tile is too small, even a large number of samples can only provide a nearly single-angle constraint and cannot robustly determine the angular response of σ_{VV}^0 . To define a practical angular threshold, a regression between binned σ_{VV}^0 and incidence angle was performed for the retained tiles. The median absolute angular sensitivity was 0.277 dB/deg. Under the uncertainty target $E=0.5$ dB, a 3° incidence-angle span corresponds to a typical NRCS change of approximately $0.277 \times 3 = 0.831$ dB, which is larger than the target uncertainty of the bin-mean NRCS. Therefore, $\Delta\theta_{\min}=3^\circ$ was used as a practical lower bound for incidence-angle-dependent fitting.

Beyond total sample count and angular span, additional angular-distribution quality metrics are introduced to identify and exclude tiles dominated by a narrow range of incidence angles. Let N_k denote the number of SAR samples falling into the k^{th} incidence-angle bin within a tile, and let $N=\sum_k N_k$ be the total number of samples in that tile. Two complementary metrics are defined to characterize the angular distribution quality:

$$p_{\max} = \frac{\max_k N_k}{\sum_k N_k}, \quad (24)$$

$$N_{\text{eff}} = \frac{\left(\sum_k N_k\right)^2}{\sum_k N_k^2}. \quad (25)$$

The metric $p_{\max}$ quantifies the dominance of a single incidence angle bin, while N_{eff} represents the effective number of incidence-angle bins contributing to the inversion. When samples are excessively concentrated in one or two angular bins, the inversion problem becomes effectively single angle dominated, even if the total sample count is relatively large. In such cases, the angular dependence of the scattering model parameters cannot be robustly constrained. Therefore, tiles were retained only when $p_{\max} \leq 0.4$ and $N_{\text{eff}} \geq 4$.

The incidence-angle bin width was set to 0.45° . Preliminary binning tests showed that a 0.5° bin width could generate sparsely populated edge bins in some retained tiles when fixed bin edges were not well aligned with the local incidence-angle range.

The 0.45° setting provided slightly finer angular discretization and more balanced bin occupation.

Through this screening procedure, only tiles with spatially localized scattering behavior, sufficient sample support, and informative angular sampling are retained for subsequent model fitting and independent validation. The final tile selection results are illustrated in Fig.3, where retained tiles are highlighted over the masked SAR backscatter field. The screening parameters are summarized in Table 1.

4.2 Material parameterization and fixed model inputs

The scattering formulation described in Section 2 requires several material and electromagnetic inputs before the roughness parameters are fitted. In this study, the mean ice thickness, dielectric constants of the sea-ice and seawater layers, sediment volume fraction, and radar frequency are prescribed as fixed

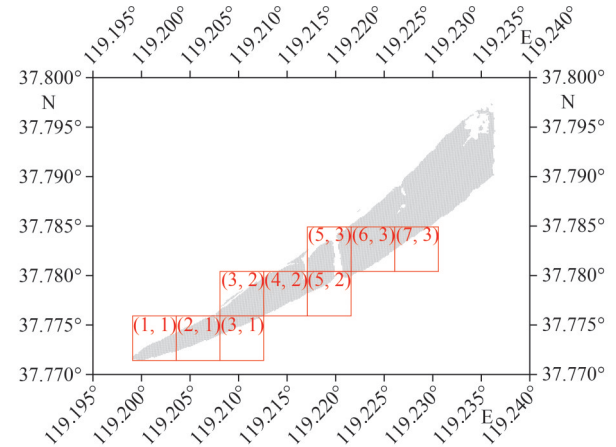


Fig.3 Tile-based partitioning and screening of SAR sea-ice samples

Gray dots indicate VV-polarized SAR backscatter samples after sea-ice masking, while red boxes denote the tiles retained for subsequent model inversion. Tile indices (i, j) are labeled for reference.

Table 1 Screening parameters for tile-based SAR sea-ice sample selection

Parameter	Value
Tile size	$0.004\ 5^\circ \times 0.004\ 5^\circ$
Minimum valid samples	$N_{\min} = 350$
Minimum incidence-angle span	$\Delta\theta_{\min} = 3^\circ$
Incidence-angle bin width	0.45°
Maximum bin-occupation ratio	$p_{\max} \leq 0.4$
Effective angle-bin criterion	$N_{\text{eff}} \geq 4$

baseline inputs. In contrast, the interface roughness parameters L_i , L_b , σ_i , and σ_b are not prescribed as fixed values. They are optimized within the search ranges described in Section 4.3 for each retained tile and each repeated half-split realization. The mean sea-ice thickness is fixed at $h=5$ cm. This value is selected according to the local ice-condition forecasts for the Dongying nearshore waters during the Sentinel-1 acquisition period as discussed in Section 3.1.

The dielectric constant of air is assumed to be $\epsilon_0 \approx 1.00$, while the dielectric properties of the sea-ice and seawater layers are parameterized using established models and regional winter conditions, as specified below.

For the sea-ice layer, sediment particles are included as one of the dielectric inclusion phases because coastal Bohai Sea ice near the Huanghe River estuary may contain suspended mineral particles, as discussed in the Introduction and Study Area sections. The purpose of including sediment is not to retrieve the exact sediment concentration from SAR observations, but to represent the possible modification of the effective dielectric response of coastal sea ice. Previous studies have shown that in contrast to dry sand particles, moist mineral soils and sediments exhibit substantially higher and lossy dielectric constants at C-band frequencies (Matzler, 1998; Gadani and Vyas, 2015).

The effective dielectric constant of sediment-laden sea ice is evaluated using a De Loor-type multiphase dielectric mixing model. In this formulation, the phase with the largest volume fraction and spatial continuity is treated as the host medium, while brine, air, and sediment are represented as inclusion phases (De Loor, 1954; Scharien et al., 2010). For model simplification and physical consistency, the inclusions are approximated as randomly oriented spherical particles. Under the low-volume-fraction condition considered in this study, the reference permittivity is taken as that of the host medium. The mixing model is used only to provide the effective sea-ice permittivity required by the scattering calculation, rather than as an independent inversion module. Because direct in situ measurements of sediment content within sea ice are not available for the study area, a representative sediment volume fraction is prescribed rather than retrieved from the SAR data. The adopted value is constrained using reported suspended-material concentrations in Bohai Sea ice. Xu et al. (2010) reported that the suspended

material, or sediment content, in Bohai Sea ice can be separated after melting and that sea ice with different sediment contents exhibits distinct spectral transmission, reflection and scattering characteristics. They further reported suspended-material concentration ranges of 40–1 668 mg/L for level ice and 67–4 972 mg/L for rafted or deformed ice at the Bohai Bay station (Xu et al., 2010). Assuming a representative mineral-particle density of $\rho_{\text{sed}} = 2\,650$ kg/m³, the sediment volume fraction can be approximated as $v_{\text{sed}} = \frac{C_{\text{sed}} \times 10^{-3}}{\rho_{\text{sed}}}$ where C_{sed} is

expressed in mg/L. This conversion gives a plausible range from approximately 1.5×10^{-5} to 1.88×10^{-3} . Therefore, $v_{\text{sed}} = 1.0 \times 10^{-3}$ is adopted as a representative baseline sediment-laden scenario within this range. The effect of v_{sed} is further examined through sensitivity experiments. With the adopted mixing configuration and material parameters, the resulting effective permittivity of sediment-laden sea ice is $\epsilon_{\text{ice}} = 6.44 - 0.66i$, which is used as the fixed effective permittivity of the sea-ice layer in the baseline scattering simulations.

For the seawater layer, the complex permittivity is evaluated under representative winter conditions of the Bohai Sea using standard microwave seawater permittivity models that account for frequency, temperature, and salinity dependence (Klein and Swift, 1977; Yao and Liu, 2015). In winter, the Bohai Sea is characterized by near-freezing water temperatures and salinity typically ranging from approximately 28 to 31.5, with reduced salinity in coastal regions influenced by Huanghe River estuary discharge. Using the Sentinel-1A C-band frequency $f = 5.405$ GHz, and representative winter conditions, the resulting seawater permittivity is $\epsilon_{\text{sea}} = 60.15 - 37.30i$, which is consistent with widely used microwave seawater permittivity formulations.

4.3 Parameter search space and fitting procedure

After the fixed material and electromagnetic inputs were specified, the roughness parameters of the air-ice and ice-seawater interfaces were fitted. The parameters L_i , L_b , σ_i , and σ_b were not prescribed as fixed physical values. Instead, they were selected within prescribed search ranges for each retained tile and each half-split repetition. Here, L_i and L_b denote the correlation lengths of the air-ice and ice-seawater interfaces, while σ_i and σ_b denote the corresponding root mean square heights. Because no simultaneous in situ roughness measurements of the

two interfaces are available for the study area, these fitted parameters are interpreted as tile-scale effective roughness parameters used to reproduce the incidence-angle-dependent NRCS response, rather than as direct measurements of physical interface roughness.

The search ranges were defined by considering both reported sea-ice roughness observations and the spectral response of the Gaussian roughness model used in this study. Terrestrial light detection and ranging (LiDAR) measurements of centimeter-scale sea-ice roughness have shown that sea-ice surface roughness can be parameterized using RMS height, correlation length, and autocorrelation-function form. That study also found strongly anisotropic correlation lengths, indicating that sea-ice surface spectra may vary with the azimuthal direction of the incident microwave radiation (Landy et al., 2015). C-band scatterometer and in situ observations over level first-year sea ice further show that bare ice can have millimeter-scale RMS height and centimeter-scale correlation length, and that such roughness statistics are relevant to assessing the validity domains of Bragg and IEM scattering models (Scharien et al., 2014).

For the Gaussian roughness spectrum adopted in this study, the spectral response at a fixed Bragg wavenumber is mainly controlled by the dimensionless product qL . The response reaches its maximum at $qL=2$. The Sentinel-1A local incidence-angle range in this study gives $q \approx 1.03\text{--}1.47/\text{cm}$, corresponding to a peak-response correlation length of approximately $L_* = 2/q = 1.36\text{--}1.94\text{ cm}$. This calculation is used only as an internal scale check to ensure that the selected L_t and L_b search range covers the main Gaussian spectral response scale under the present observation geometry.

Considering the reported roughness scales, the Gaussian spectral response, possible differences between the upper and lower interfaces, and the uncertainty associated with tile-scale effective parameters, the candidate correlation lengths are set as $L_t, L_b = 0.5\text{--}6.0\text{ cm}$. The candidate RMS heights are set as $\sigma_t, \sigma_b = 0.4\text{--}6.0\text{ mm}$.

To avoid parameter combinations that clearly violate the weak-roughness assumption, the RMS-height range is further examined with reference to the first-order perturbation condition. For a smooth or weakly rough interface, a commonly used roughness condition is $k\sigma < 0.3$ (Fung, 1994). For Sentinel-1A C-band, $\lambda \approx 5.55\text{ cm}$, giving $k \approx 1.13/\text{cm}$. Therefore, for $\sigma = 0.4\text{--}6.0\text{ mm}$, the corresponding $k\sigma$ range is approximately $0.045\text{--}0.68$. This range

covers millimeter-scale roughness values within the strict weak-roughness regime while also retaining somewhat rougher tile-scale effective interface states. To further exclude excessively steep roughness combinations, a small-slope constraint is imposed: $\sigma_t/L_t \leq 0.30$ and $\sigma_b/L_b \leq 0.30$. The search ranges and constraints are summarized in Table 2.

For each half-split repetition, all admissible parameter combinations within the prescribed search space are tested, and the combination yielding the minimum calibration error is selected as the best-fit effective roughness parameter set for that tile. The roughness statistics reported in the Results section are therefore interpreted in this effective-parameter sense.

4.4 Bin-wise random half-split validation and global metric aggregation

To evaluate the model against samples not used for parameter calibration, a bin-wise random half-split validation strategy was adopted. For each retained tile, the SAR samples were first grouped into local incidence-angle bins with a bin width of 0.45° . Within each usable incidence-angle bin, the samples were randomly divided into a calibration subset and a validation subset. Because the split was performed within each incidence-angle bin, the two subsets shared the same angle-bin structure, thereby reducing additional bias caused by inconsistent incidence-angle coverage.

In each half-split repetition, the effective roughness parameters L_t, L_b, σ_t , and σ_b for each tile were determined only from the calibration-bin statistics of that tile. The fitted parameters were then used to predict the NRCS of the corresponding validation bins, and the predictions were compared with the validation-bin mean observations. This produced tile-wise validation metrics for each repetition, denoted as $R_{r,t}$, $\text{RMSE}_{r,t}$, and $\text{Bias}_{r,t}$, where r denotes the repetition index and t denotes the tile index. These tile-wise metrics were used to examine local fitting behavior and spatial variability among

Table 2 Search ranges and constraints for the effective roughness parameters of the air-ice and ice-seawater interfaces

Parameter	Symbol	Range
Correlation lengths of the air-ice and ice-seawater interfaces	L_t, L_b	0.5–6.0 cm
RMS heights of the air-ice and ice-seawater interfaces	σ_t, σ_b	0.4–6.0 mm
Small-slope constraint	$\sigma_t/L_t, \sigma_b/L_b$	≤ 0.30

the retained tiles.

For the regional-scale validation, all validation-bin observations and predictions from the retained tiles were pooled for each repetition. For the r^{th} repetition, let

$$y_r = (y_{r,1}, y_{r,2}, \dots, y_{r,M_r}), \quad (26)$$

and

$$\hat{y}_r = (\hat{y}_{r,1}, \hat{y}_{r,2}, \dots, \hat{y}_{r,M_r}), \quad (27)$$

denote the pooled observed and predicted VV NRCS values from all validation bins. Here, M_r is the number of pooled validation-bin points in the r^{th} repetition, and all NRCS values are expressed in dB. The global validation metrics for the r^{th} repetition are then computed as

$$R_r^{\text{global}} = \text{corr}(y_r, \hat{y}_r), \quad (28)$$

$$\text{RMSE}_r^{\text{global}} = \sqrt{\frac{1}{M_r} \sum_{m=1}^{M_r} (\hat{y}_{r,m} - y_{r,m})^2}, \quad (29)$$

$$\text{Bias}_r^{\text{global}} = \frac{1}{M_r} \sum_{m=1}^{M_r} (\hat{y}_{r,m} - y_{r,m}). \quad (30)$$

This procedure was repeated $N_{\text{rep}}=1\,000$ times. For the overall regional-scale validation, the distributions of R_r^{global} , $\text{RMSE}_r^{\text{global}}$, and $\text{Bias}_r^{\text{global}}$ over the 1 000 repetitions were summarized using both robust and moment-based statistics. Specifically, the median and interquartile range were reported to describe the central tendency and spread of the repeated validation results, while the mean and standard deviation were also provided for direct numerical comparison. The representative validation scatter plot was selected from the repetition whose global R and global RMSE were closest to their corresponding median values after normalization by their interquartile ranges.

5 RESULT AND DISCUSSION

5.1 Overall validation statistics at the regional scale

Based on the data screening, model-input specification, parameter search, and repeated validation procedure described in Section 4, the regional-scale validation performance of the coherent two-interface model is first evaluated.

Figure 4 shows the validation-bin observed-predicted scatter plot for a representative half-split repetition. This representative repetition was

selected as the case whose global R and global RMSE are closest to their corresponding median values among the 1 000 repetitions. It is therefore used to illustrate the bin-level prediction behavior under a typical repeated-validation condition. For this representative repetition, the validation-bin observations and predictions from all retained tiles are generally distributed around the 1:1 line, with $R=0.712$, $\text{RMSE}=0.929$ dB, and $\text{Bias}=-0.096$ dB. Most points are distributed around approximately -18–-16 dB and its neighboring range, and they broadly follow the 1:1 line. This indicates that the model can reproduce the validation-bin-scale variation of VV NRCS over the Huanghe River estuary sea-ice region. However, some scatter remains in the higher-NRCS range and in several individual tiles, suggesting that local ice-surface heterogeneity, residual within-bin variability, and unmodeled variations in interface roughness or dielectric properties still affect the prediction accuracy of individual bins.

Figure 5 further presents the distribution of regional-scale global metrics over the 1 000 repetitions. The global R values are mainly concentrated around 0.7, the RMSE values are mostly within approximately 0.9–1.0 dB, and the Bias distribution is slightly negative. The consistency among the median, interquartile range (IQR), mean, and standard deviation (SD) statistics indicates that the

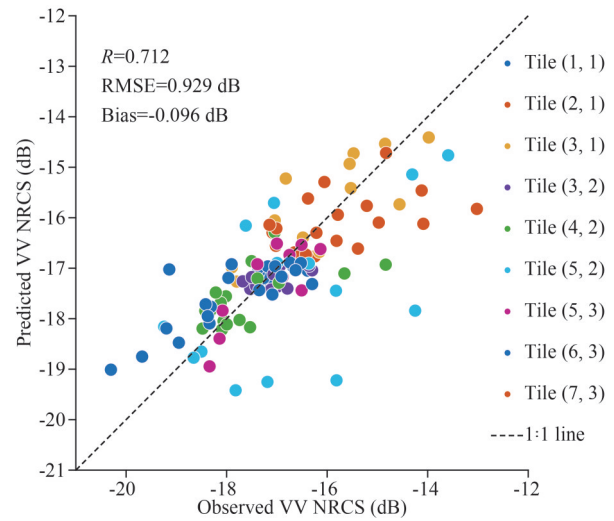


Fig.4 Representative observed-predicted comparison of validation-bin NRCS for the coherent two-interface model

Colored points represent paired observed and predicted VV-polarized NRCS values from the nine retained tiles, and the dashed line denotes the 1:1 reference line. The overall correlation coefficient (R), root mean square error (RMSE), and Bias values are shown in the upper-left corner.

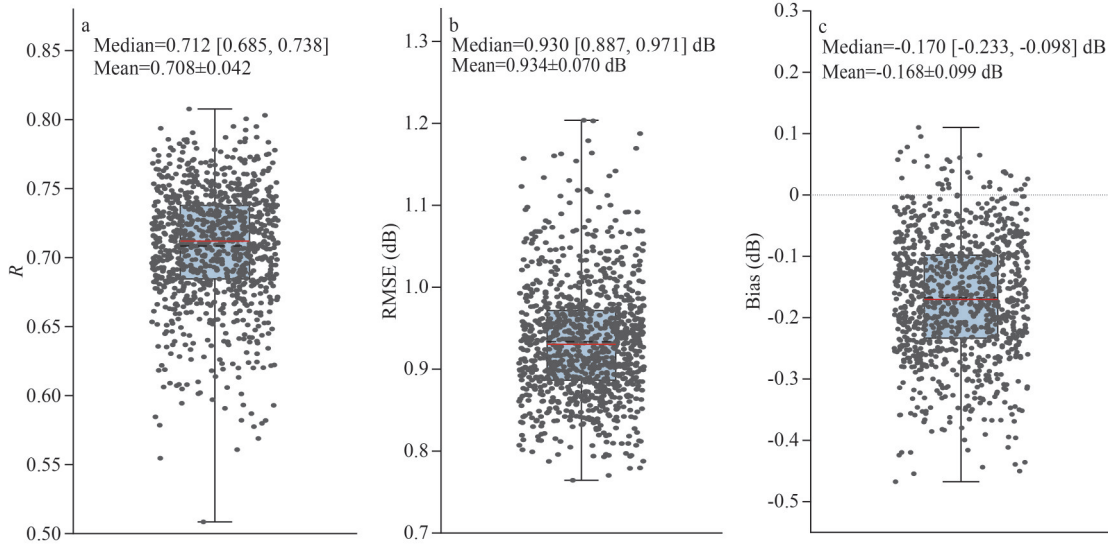


Fig.5 Distribution of regional-scale validation metrics over 1 000 half-split repetitions

a. correlation coefficient (R); b. root mean square error (RMSE); c. Bias. Gray dots represent individual repetitions. Boxes indicate the interquartile ranges, red solid lines indicate the medians, and black dashed lines indicate the means.

validation results have relatively low sensitivity to the random half-split process and remain stable at the regional scale. The slightly negative Bias suggests a weak overall underestimation of the observed NRCS.

5.2 Tile-wise validation and incidence-angle response types

Table 3 first summarizes the tile-wise validation statistics over the 1 000 half-split repetitions. Different from the regional-scale global metrics discussed in the previous section, the R , RMSE, and Bias values reported here were calculated separately for each retained tile and then summarized using

their median and mean values over the repeated validations. These statistics are used to evaluate the local model performance in different spatial units. Overall, the median RMSE values range from 0.400 to 1.293 dB, and the Bias values are mostly negative, indicating different degrees of local underestimation. Meanwhile, the tile-wise R values vary substantially, from nearly zero to approximately 0.767. This suggests that the amplitude and shape of the local NRCS-incidence angle response strongly affect the correlation metric. Therefore, the tile-wise validation statistics should be interpreted together with the angular-response curves rather than based on R alone.

Figure 6 shows the VV NRCS-incidence angle responses for the retained tiles. For each tile and each fixed incidence-angle bin, the horizontal coordinate is the mean local incidence angle of the samples within that bin, while the vertical coordinates are the median observed and predicted validation-bin VV NRCS values over the 1 000 repeated validations. Therefore, the curves represent relatively stable tile-bin-scale angular responses after repeated half-split validation, rather than the result of a single random split. It should be noted that although the incidence-angle bin width is fixed at 0.45° , the spacing between adjacent plotted points is not necessarily exactly 0.45° . This is because the plotted horizontal coordinate is the actual mean incidence angle within each bin. When the within-

Table 3 Tile-wise validation statistics over the 1 000 half-split repetitions

Tile	R		RMSE (dB)		Bias (dB)	
	Median	Mean	Median	Mean	Median	Mean
(1, 1)	0.009	-0.019	0.400	0.414	-0.021	-0.024
(2, 1)	0.200	0.148	0.732	0.763	-0.173	-0.177
(3, 1)	0.731	0.723	1.017	1.021	-0.145	-0.154
(3, 2)	0.224	0.152	0.689	0.718	-0.158	-0.150
(4, 2)	0.652	0.609	0.748	0.770	-0.105	-0.095
(5, 2)	0.631	0.662	1.273	1.311	-0.382	-0.407
(5, 3)	0.767	0.748	0.677	0.696	-0.021	-0.031
(6, 3)	0.738	0.728	0.895	0.904	-0.053	-0.057
(7, 3)	0.300	0.201	1.293	1.307	-0.536	-0.530

bin angle distribution is uneven or when samples are concentrated near bin edges, the mean angles of adjacent bins may show non-uniform spacing. This can be seen, for example, in Tiles (3, 1) and (7, 3). Such non-uniform spacing reflects the statistical distribution of actual SAR samples after binning, rather than an error in the angle-binning scheme.

The curves reveal several typical NRCS-incidence angle response types among the retained tiles. Tile (5, 3) shows an increasing type, with VV NRCS increasing with incidence angle. Tile (3, 1) shows a decreasing type. Tiles (1, 1), (2, 1), and (3, 2) exhibit weakly varying or nearly flat responses, with relatively small NRCS changes over the sampled incidence-angle range. Tile (4, 2) shows a concave response, with NRCS first decreasing and then increasing, whereas Tile (6, 3) shows a convex response, with NRCS first increasing and then decreasing. These different response types indicate that, even within a compact nearshore thin-ice

region, the VV NRCS response to incidence angle is not limited to a single monotonic form. Instead, it may reflect different relative contributions from the air-ice interface, the ice-seawater interface, and the coherent cross term, together with local variations in surface state and ice conditions. Similar incidence-angle-dependent and surface-type-dependent behaviors have also been emphasized in previous Sentinel-1A sea-ice studies (Lohse et al., 2021; Guo et al., 2023). The representative response types identified here are therefore used in the subsequent sensitivity analysis to examine how ice thickness and sediment volume fraction affect different angular-response forms.

Combining Fig.6 with Table 3 further clarifies the local validation behavior of different response types. For tiles with more evident angular responses, such as Tiles (5, 3), (6, 3), (3, 1), and (4, 2), the model generally follows the main direction of the observed angular variation. Tile (5, 3), representing the increasing type, has a median $R=0.767$, $RMSE=$

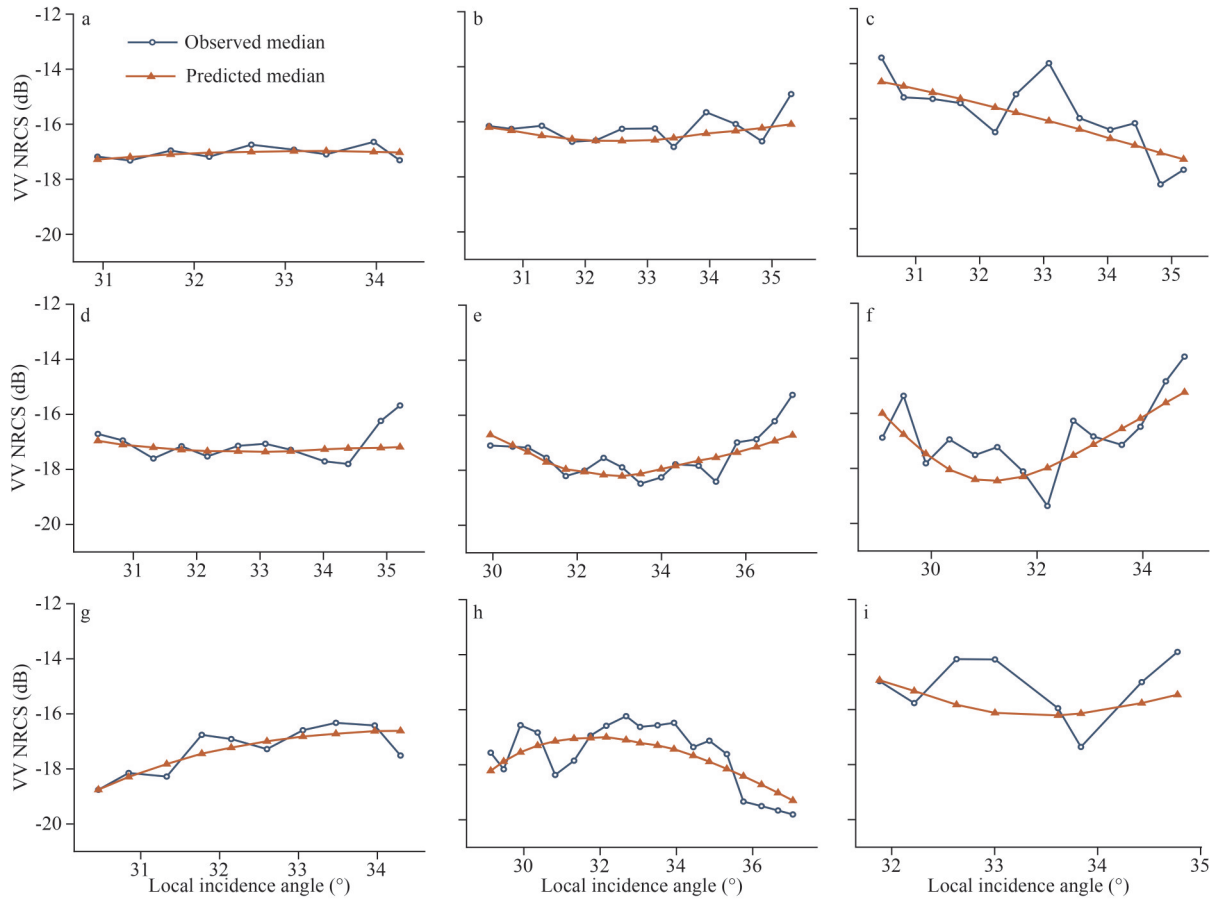


Fig.6 Tile-wise VV NRCS-incidence angle responses for the retained sea-ice tiles

Tile (1, 1) (a), Tile (2, 1) (b), Tile (3, 1) (c), Tile (3, 2) (d), Tile (4, 2) (e), Tile (5, 2) (f), Tile (5, 3) (g), Tile (6, 3) (h), and Tile (7, 3) (i). Blue lines with circular markers indicate the observed median values, and orange lines with triangular markers indicate the predicted median values.

0.677 dB, and Bias=-0.021 dB, indicating good local agreement. Tiles (6, 3) and (3, 1), corresponding to convex and decreasing responses, both have median R values above 0.73, suggesting that the model can capture pronounced non-flat angular responses. Tile (4, 2) also shows a stable reproduction of the concave response, with a median $R=0.652$ and RMSE=0.748 dB. In contrast, Tiles (1, 1), (2, 1), and (3, 2) have relatively low R values, but this should be interpreted in relation to their weak NRCS dynamic ranges. For example, Tile (1, 1) has an almost flat observed angular response. Its median R is close to zero, but the median RMSE is only 0.400 dB and the Bias is -0.021 dB. This indicates that a low correlation coefficient does not necessarily imply a large absolute prediction error. Rather, under nearly flat-response conditions, R becomes more sensitive to small bin-to-bin fluctuations and residual within-bin variability. Similar caution is needed when interpreting the low R values of Tiles (2, 1) and (3, 2).

Tile (5, 2) shows a relatively moderate correlation but has a larger RMSE and a more negative Bias, with median values of $R=0.631$, RMSE=1.273 dB, and Bias=-0.382 dB. As shown in Fig.6, its observed curve contains stronger local fluctuations, whereas the predicted curve is smoother. This suggests that the model can capture part of the overall angular tendency but is less able to reproduce local peaks or rapid NRCS changes over a narrow incidence-angle interval. Tile (7, 3) is more difficult to interpret within the two-interface framework, with median $R=0.300$, RMSE=1.293 dB, and Bias=-0.536 dB. Its observed response shows irregular non-monotonic bin-to-bin variations, and the local NRCS fluctuations appear to dominate over a stable angle-consistent trend. As a result, the model fails to capture a clear angular response for this tile. This behavior may be associated with local ice-surface heterogeneity, fragmented or drifting ice patches, fracture zones, or mixed scattering states within the tile. Previous SAR sea-ice studies have shown that backscatter can be strongly affected by ice type, roughness, deformation, young ice, leads, environmental conditions, and radar geometry. Therefore, highly heterogeneous local ice conditions may produce complex NRCS-incidence angle relationships that cannot be fully represented by a simple tile-scale equivalent parameterization (Dierking, 2013; Mahmud et al., 2020; Lohse et al., 2021; Qiu et al., 2024). This result indicates that the coherent two-interface

model can reproduce the major angular-response types for most retained tiles, but its effective parameterization remains limited for locally complex or mixed ice conditions.

5.3 Effective roughness parameter and physical interpretation

To further examine the physical meaning of the fitted coherent two-interface model, Table 4 summarizes the effective roughness parameters retrieved for the retained tiles under the coherent SPM framework. It should be emphasized that these parameters are not direct in situ measurements of the actual morphology of the sea-ice surface or underside. Instead, they represent the effective roughness statistics required by the first-order SPM scattering model to reproduce the incidence-angle-dependent VV-polarized NRCS within each tile. Therefore, the fitted correlation lengths and root mean square heights should be interpreted as tile-scale, model-dependent effective parameters, rather than being directly equated with the morphological roughness of the actual sea-ice surface or underside.

Overall, the correlation lengths of both the upper and lower interfaces are mainly at the centimeter scale, whereas the root mean square heights are generally at the millimeter scale. Meanwhile, the fitted results indicate that the effective roughness characteristics of the air-ice and ice-seawater interfaces are not identical. In most retained tiles, the effective root mean square height of the ice-seawater interface is larger than that of the air-ice interface, while its effective correlation length is usually smaller than or comparable to that of the

Table 4 Tile-wise fitted effective roughness parameters of the air-ice and ice-seawater interfaces

Tile	L_t (cm)		L_b (cm)		σ_t (mm)		σ_b (mm)	
	Median	Mean	Median	Mean	Median	Mean	Median	Mean
(1, 1)	4.70	3.72	2.70	2.69	3.20	3.21	3.80	3.79
(2, 1)	2.70	2.40	2.10	2.03	2.00	2.03	5.00	4.82
(3, 1)	5.10	4.38	3.30	3.32	3.80	3.51	5.00	4.93
(3, 2)	1.90	2.07	2.30	2.19	1.40	1.84	4.60	4.34
(4, 2)	2.10	1.90	2.10	2.11	1.80	1.91	4.20	4.67
(5, 2)	3.50	3.39	1.70	1.71	3.20	3.25	4.60	4.55
(5, 3)	4.70	4.54	2.90	2.70	5.40	4.97	4.40	4.15
(6, 3)	5.10	5.03	3.30	3.31	5.80	5.75	5.00	5.19
(7, 3)	3.70	3.64	1.70	1.77	5.80	5.62	5.00	5.08

upper interface. Previous morphological studies of sea-ice surface and underside profiles have shown that, from the perspective of profile-scale geometrical morphology, the underside of sea ice can exhibit stronger undulations than the upper surface (Li et al., 2022). Although the effective roughness parameters fitted in this study cannot be directly equated with morphological roughness, this existing understanding provides a relevant physical background for the stronger effective roughness contribution associated with the lower interface.

These results suggest that, within the present coherent two-interface SPM framework, reproducing the observed regional-scale VV NRCS-incidence angle response requires the lower interface, or the scattering terms associated with the lower interface, to exhibit stronger effective height variability and a shorter effective correlation scale. This further indicates that, for nearshore seasonal thin ice in the Huanghe River estuary, the scattering contribution from the ice-seawater interface and its coherent coupling with the air-ice interface should not be simply neglected.

5.4 Forward sensitivity of VV NRCS to sediment volume fraction

Previous studies have shown that sediment inclusions can affect multiple types of remote-sensing signals from sea ice. Optical remote-sensing studies have demonstrated that sediment-laden ice differs from clean ice in spectral reflectance and surface albedo, enabling satellite-based mapping of sediment-laden sea ice and assessment of particle loading (Huck et al., 2007; Waga et al., 2022). Passive microwave studies have further suggested that dirty or sediment-laden ice can alter microwave emissivity and brightness temperature, potentially leading to errors in sea-ice concentration retrievals (Tikhonov et al., 2025). Compared with optical and passive microwave observations, however, the direct influence of sediment inclusions on C-band SAR backscatter remains less well quantified. Therefore, in this study, sediment volume fraction is treated as a dielectric-modification factor, and the following experiment evaluates only the forward sensitivity of VV NRCS to sediment-content variation, rather than attempting to retrieve sediment concentration from SAR observations.

Considering the high suspended-sediment background of the Huanghe River estuary in the Bohai Sea, the influence of sediment volume

fraction on VV-polarized NRCS was further evaluated using a forward sensitivity experiment based on the SPM model. The purpose of this experiment was to examine the possible NRCS response induced by changes in sediment volume fraction under fixed model structure and fixed effective roughness parameters. Because the retained tiles exhibit different incidence-angle response patterns, five representative tiles were selected for this analysis, corresponding to increasing, convex, concave, decreasing, and weakly varying angular responses. For each representative tile, the median fitted effective roughness parameters were used and only the sediment volume fraction v_{sed} was varied.

The values of sediment volume fraction were converted from the suspended-material concentrations in Bohai Sea ice reported by Xu et al. (2010), as described in Section 4.2. The low-sediment case corresponds to $C_{\text{sed}}=40$ mg/L, giving $v_{\text{sed}}=0.001$ 51%, whereas the high-sediment case corresponds to $C_{\text{sed}}=4$ 972 mg/L, giving $v_{\text{sed}}=0.187$ 621%. In addition, $v_{\text{sed}}=0.10\%$ was used as a representative reference case to characterize the model response under an intermediate sediment-content condition.

As shown in Fig.7, when v_{sed} increases from the low-sediment case to the high-sediment case, the simulated VV NRCS changes by different magnitudes among the five representative tiles. Overall, the variation in sediment volume fraction mainly modifies the amplitude of the NRCS curves, while the original incidence-angle response type of each tile is largely preserved. For example, Tile (5, 3) still shows an increasing response with incidence angle, Tile (6, 3) remains convex, Tile (4, 2) remains concave, Tile (3, 1) retains a decreasing response, and Tile (1, 1) remains weakly varying. This indicates that, under the present model configuration, sediment volume fraction can affect the absolute magnitude of VV NRCS, but it is not the only factor controlling the shape of the incidence-angle response.

To quantify the NRCS response induced by sediment-volume-fraction variation, the signed difference between the high- and low-sediment cases was first calculated. For a representative tile, let $\sigma_{\text{low}}^0(\theta_k)$ and $\sigma_{\text{high}}^0(\theta_k)$ denote the simulated NRCS values at incidence angle θ_k under the low- and high-sediment cases. The sediment-induced difference is defined as

$$\Delta\sigma^0(\theta_k) = \sigma_{\text{high}}^0(\theta_k) - \sigma_{\text{low}}^0(\theta_k). \quad (31)$$

The bar value in Fig.7f represents the mean

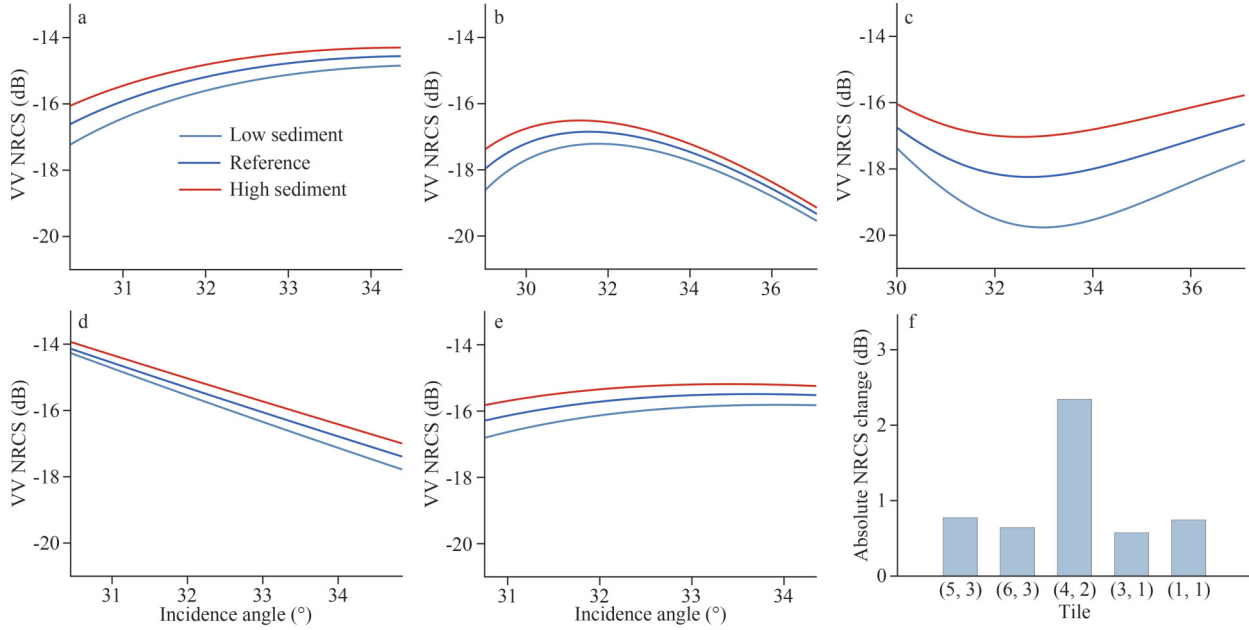


Fig.7 Sensitivity of SPM-simulated VV NRCS to sediment volume fraction

a. increasing response for Tile (5, 3); b. convex response for Tile (6, 3); c. concave response for Tile (4, 2); d. decreasing response for Tile (3, 1); e. weakly varying response for Tile (1, 1); f. absolute NRCS changes from low- to high-sediment conditions for the five representative tiles.

absolute change over the incidence-angle range of each tile:

$$\left| \overline{\Delta\sigma^0} \right| = \left| \frac{1}{N_\theta} \sum_{k=1}^{N_\theta} (\sigma_{\text{high}}^0(\theta_k) - \sigma_{\text{low}}^0(\theta_k)) \right|, \quad (32)$$

where N_θ is the number of incidence-angle samples used in the forward simulation for that tile. The vertical cap above each bar indicates the 95th percentile of $\left| \overline{\Delta\sigma^0} \right|$, which characterizes the magnitude of the stronger sediment-sensitive response within the corresponding tile.

From the low- to high-sediment cases, the mean absolute NRCS change of the five representative tiles ranges from 0.57 to 2.34 dB, and the 95th-percentile absolute change ranges from 0.77 to 2.77 dB. Among the selected tiles, Tile (4, 2) is the most sensitive to sediment-volume-fraction variation, with a mean absolute change of 2.34 dB and a 95th-percentile change of 2.77 dB. In contrast, the other four tiles show mean absolute changes of approximately 0.57–0.77 dB. These results indicate that the NRCS response induced by sediment-content variation is not spatially uniform, but is modulated by the local effective roughness configuration, the lower-interface scattering contribution, and the coherent coupling between the upper and lower interfaces.

Physically, changing v_{sed} modifies the effective

permittivity of the sea-ice layer, which further affects the Fresnel responses of the air-ice and ice-seawater interfaces, the propagation attenuation inside the ice layer, and the phase relationship of the coherent cross term. Therefore, even if sediment-volume-fraction variation appears only as a change in the dielectric parameter, its effect on the total NRCS can be either enhanced or weakened through the two-interface scattering structure. In particular, tiles with stronger effective lower-interface roughness and more pronounced cross-term contribution may exhibit larger VV NRCS responses to sediment-volume-fraction variation.

5.5 Forward sensitivity of SPM components to sea-ice thickness

To further examine the influence of sea-ice thickness h on the coherent two-interface SPM response, a forward thickness-sensitivity experiment was conducted following the sediment-volume-fraction sensitivity analysis. Similar to the v_{sed} experiment, this test was not intended to retrieve the true ice thickness from Sentinel-1A data. Instead, it was designed to evaluate how changes in h affect the top-interface term, bottom-interface term, coherent cross term, and total VV NRCS under a fixed model structure and fixed effective roughness parameters.

The experiment used the same Gaussian

roughness spectrum as that adopted in the parameter inversion. For each representative tile, the effective correlation lengths L_t , L_b and the RMS heights σ_t , σ_b were fixed to the median fitted values of that tile. This setting avoids mixing the effect of thickness variation with roughness re-fitting. The sediment volume fraction was fixed at the reference case, $v_{\text{sed}} = 1.0 \times 10^{-3}$, corresponding to an effective sea-ice permittivity of $\epsilon_{\text{ice}} = 6.4437 - 0.6628i$. Only the sea-ice thickness was varied, with h scanned from 3 to 8 cm at an interval of 0.1 cm. This range covers representative thin-ice conditions in the nearshore Huanghe River estuary during the study period and is centered around the baseline value of $h = 5$ cm.

To maintain consistency with the preceding sediment-sensitivity experiment, the same five representative tiles were used, corresponding to increasing, convex, concave, decreasing, and weakly varying VV NRCS-incidence angle responses. This design allows the thickness effect to be compared among different angular-response types. Figure 8 shows the variation of the top air-ice term, bottom ice-seawater term, coherent cross term, and total VV NRCS as functions of h .

The air-ice interface term is almost insensitive to changes in sea-ice thickness and appears as a nearly horizontal response curve. As can be seen from Eq.13, the top-interface term is mainly controlled by the electromagnetic response of the air-ice interface, the effective roughness spectrum of the upper interface, and the incidence angle. When the other parameters are fixed, this term does not explicitly

contain the ice thickness h , and therefore remains nearly unchanged as h varies. Different from the two independent interface terms, the coherent cross term exhibits a clear oscillatory response to changes in thickness. As shown in Eq.15, the cross term contains both the propagation attenuation factor $\exp(-2ah)$ and the phase modulation factor $\cos(2\beta h - \Delta\phi)$, where β is the real part of the propagation constant in the ice layer and $\Delta\phi$ denotes the phase difference between the scattering coefficients of the upper and lower interfaces. Therefore, as h changes, the scattering amplitudes from the two interfaces may undergo either coherent enhancement or coherent cancellation. This phase-dependent behavior leads to the non-monotonic variation of the cross term and the total VV NRCS.

These results indicate that sea-ice thickness mainly affects the total scattering response by modulating the propagation attenuation of the lower-interface contribution and the coherent phase relationship between the upper and lower interfaces. For single-frequency C-band VV-polarized NRCS, the effects of ice thickness, interface roughness, dielectric properties, and the coherent cross term are coupled. Therefore, h cannot be uniquely constrained using VV NRCS alone. For this reason, h was not treated as a free inversion parameter in this study. Instead, a representative nearshore thin-ice thickness derived from external ice-condition information was used as a fixed input. The role of the thickness-sensitivity experiment is to verify the physical response of the component terms to h in the

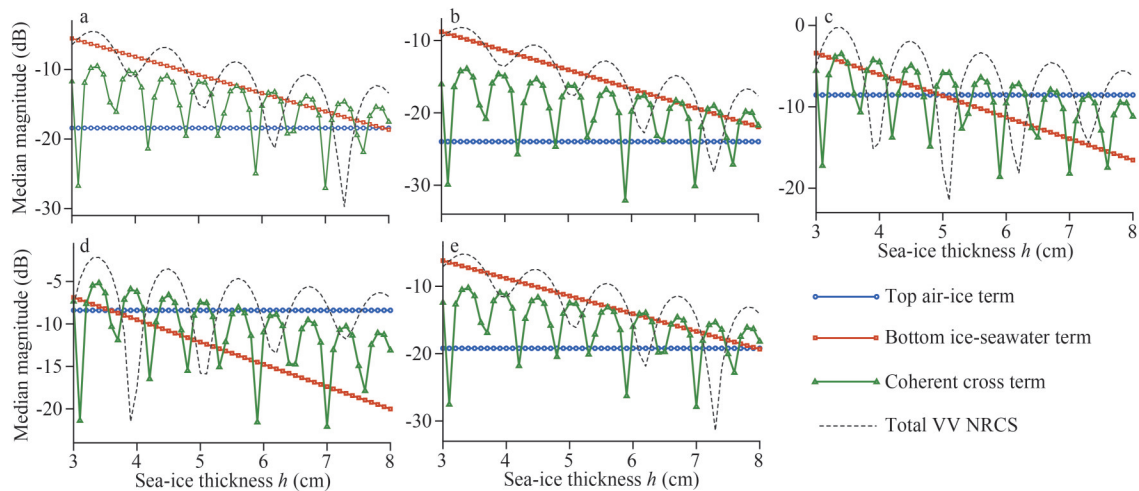


Fig.8 Forward sensitivity of SPM component terms and total VV NRCS to sea-ice thickness for representative tiles

a. increasing response for Tile (5, 3); b. convex response for Tile (6, 3); c. concave response for Tile (4, 2); d. decreasing response for Tile (3, 1); e. weakly varying response for Tile (1, 1).

coherent two-interface model, rather than to retrieve sea-ice thickness.

5.6 Model comparison and role of the coherent cross term

In addition to the complete coherent two-interface model adopted in this study, two reference models were further constructed to evaluate the influence of different physical representations on the reproduction of the VV NRCS angular response. The three models are defined as the effective-medium model, the incoherent two-interface model, and the coherent two-interface model. For convenience, they are hereafter referred to as Model 1, Model 2, and Model 3.

Model 1 is the effective-medium model, in which the layered sea-ice medium is treated as an integrated effective dielectric response, without explicitly separating the air-ice and ice-seawater interfaces or including the coherent cross term between the two interfaces. Similar concepts have been applied in previous studies of layered-medium scattering. For example, previous work represented an air-sea surface film-seawater three-layer medium as an air-effective medium two-layer scattering problem and established an NRCS equivalence relationship between the layered medium and the effective-medium representation based on an effective dielectric constant model (Xie et al., 2017, 2023). Therefore, Model 1 in this study is used as a reference method representing the treatment of the sea-ice layer as an integrated effective-medium

response. Model 2 is the incoherent two-interface model, which explicitly retains the air-ice and ice-seawater interface terms but removes the coherent cross term between them, thereby testing the model performance when only two independent interface-scattering contributions are considered. Model 3 is the complete coherent two-interface model adopted in this study, which includes the top-interface term, the bottom-interface term, and the coherent cross term, and is used to describe the coherent coupling between scattering amplitudes from the two interfaces of finite thickness sea ice.

To ensure a fair comparison, the same tile-screening strategy, parameter-search procedure, and repeated half-split validation framework were applied to all three models. As shown in Fig.9, the results of Model 1 indicate that treating the sea-ice layer as an integrated effective-medium response is insufficient to reproduce the regional statistical characteristics of the observed VV NRCS variation with incidence angle. In contrast, Model 2 shows a clear improvement after explicitly separating the air-ice and ice-seawater interfaces, indicating that introducing the ice-seawater interface scattering term can substantially improve the reproduction of the regional-scale VV NRCS-incidence angle response. With the coherent cross term further included on the basis of Model 2, Model 3 achieves the best validation performance among the three models. In addition, the distributions of repeated half-split validation results show that Model 3

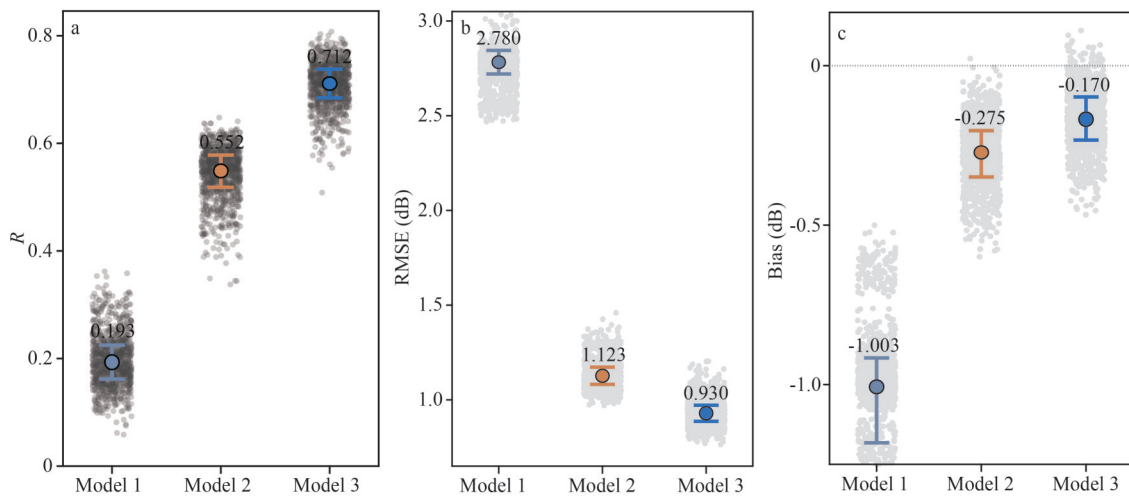


Fig.9 Repeated half-split validation comparison of three SPM formulations

a. global correlation coefficient (R); b. root mean square error (RMSE); c. Bias. Models 1, 2, and 3 represent the effective-medium, incoherent two-interface, and coherent two-interface formulations, respectively. Gray dots represent individual repetitions. Colored circles indicate the medians, and error bars indicate the interquartile ranges.

outperforms the other two reference models in R , RMSE and Bias, indicating that this improvement is not caused by a single random split but remains stable across repeated validations.

These results demonstrate that, compared with the effective-medium reference model, explicitly separating the air-ice and ice-seawater interfaces improves the reproduction of the observed VV NRCS-incidence angle response. The additional improvement obtained by Model 3 indicates that the coherent cross term provides a non-negligible contribution to the regional-scale scattering statistics. Therefore, the improvement of Model 3 mainly arises from the explicit finite thickness two-interface representation and its coherent coupling relationship, rather than from arbitrary empirical parameter adjustment. It should be noted that this model comparison is intended to evaluate the explanatory capability of different scattering structures for regional-scale NRCS statistics, and does not imply that all fitted parameters can be uniquely interpreted as true sea-ice morphological parameters.

6 CONCLUSION

Using Sentinel-1A C-band VV-polarized SAR observations, this study developed a coherent two-interface SPM framework to interpret the regional-scale incidence-angle-dependent NRCS response of nearshore seasonal sea ice in the Huanghe River estuary. The sea-ice cover was represented as a finite thickness air-ice-seawater medium with two rough interfaces, allowing the contributions from the air-ice interface, the ice-seawater interface, and their coherent cross term to be examined within a unified scattering framework.

The regional-scale validation results show that the coherent two-interface model can reproduce the main statistical characteristics of the Sentinel-1A observed VV NRCS variation with incidence angle. In the repeated half-split validation, the global R values are mainly concentrated around 0.71, the RMSE values are mostly within approximately 0.9–1.0 dB, and the Bias is generally slightly negative. This indicates that the model can stably reproduce the dominant angular variation of the observed NRCS at the regional scale, although a weak overall underestimation remains. The tile-wise results further show that the VV NRCS-incidence angle responses of the retained tiles are not limited to a single monotonic pattern, but include several

typical response types, including increasing, decreasing, convex, concave, and weakly varying responses. For tiles with pronounced angular responses, the model generally follows the main direction of the observed curves. These results indicate that the coherent two-interface model can reproduce not only monotonic responses, but also non-monotonic responses such as convex and concave patterns, suggesting that the upper- and lower-interface scattering terms and their coherent coupling make practical contributions to regional-scale SAR backscatter.

Considering the high suspended-sediment background of the nearshore Huanghe River estuary, this study further conducted a sensitivity analysis of sediment volume fraction. The results show that different representative tiles exhibit different degrees of NRCS response to changes in sediment volume fraction. This response is mainly expressed as a change in scattering amplitude, while the original incidence-angle response type of each tile is largely preserved. From the low- to high-sediment cases, the mean absolute NRCS change of the five representative tiles is approximately 0.57–2.34 dB, indicating that sediment-content variation can exert a non-negligible influence on C-band SAR backscatter from nearshore sea ice. This result suggests that, in sediment-rich coastal environments such as the Huanghe River estuary, the influence of sediment on the effective dielectric properties of sea ice and its SAR scattering response should not be simply ignored.

Overall, the results demonstrate that, in a regional statistical sense, the coherent two-interface SPM framework provides a physically reasonable interpretation of the C-band VV NRCS-incidence angle response of nearshore seasonal thin ice in the Huanghe River estuary. The model is not intended for pixel-level retrieval of the microstructural properties of sea ice. Instead, it is designed to explain the statistical manifestation of the air-ice interface, the ice-seawater interface, and their coherent coupling in regionally averaged SAR backscatter under finite spatial support and incidence-angle conditions. The ability of the model to reproduce the major angular-response types in most retained tiles further indicates that, under nearshore thin-ice conditions, the scattering contribution from the ice-seawater interface and its coherent coupling with the upper interface should

not be simply neglected.

Several limitations should also be noted. First, the fitted roughness parameters are model-dependent effective parameters. They should not be interpreted as unique in situ measurements of the actual air-ice or ice-seawater interface morphology. Second, the present analysis is based mainly on single-frequency VV-polarized Sentinel-1A observations, which cannot uniquely constrain the coupled effects of sea-ice thickness, dielectric properties, and upper- and lower-interface roughness. Third, local variations in ice-surface state, fragmented or drifting ice patches, fracture structures, mixed boundary pixels, and spatially variable sediment incorporation may produce short-scale scattering anomalies that cannot be fully represented by the current tile-scale effective-parameter model. Future work should incorporate multi-temporal, multi-polarization, or multi-frequency SAR observations, together with independent measurements of ice thickness, salinity, sediment content, and interface roughness. Such data would help further constrain the coupled model parameters and evaluate the applicability of the coherent two-interface scattering framework across different seasonal ice stages, ice types, and nearshore environments.

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