

Article

An Improved Scheme for FY-3E/HIRAS-II Radiance Simulation at Large Scan Angles

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Abstract

To address the bias in radiative simulation caused by the horizontal inhomogeneity of atmospheric parameters under large scan angles for the HIRAS-II (Hyperspectral Infrared Atmospheric Sounder-II) onboard the Fengyun-3E satellite, this study proposes a method for constructing slant-path atmospheric parameter profiles along the satellite's line-of-sight (Exp.2). In contrast to the conventional method (Exp.1) based on the assumption of horizontally homogeneous vertical atmospheric profiles, this method accurately calculates the intersection points between the satellite's line-of-sight and the various altitude layers of the ECMWF reanalysis data version-5 (ERA5). It employs a hybrid interpolation algorithm combining inverse distance weighting and spline interpolation to obtain a continuous distribution of atmospheric parameters along the slant path, thereby accounting for the actual observation geometry of the satellite. The results show that when the satellite zenith angle exceeds 30°, the simulation differences between Exp.2 and Exp.1 increase significantly. Specifically, in the CO₂ absorption band, the differences between the two methods are mainly concentrated between −0.1 K and 0.1 K, whereas in the water vapor absorption band, this range expands to between −0.5 K and 0.5 K. Notably, biases are concentrated near the scan edges and exhibit a strong latitudinal dependence, with high-latitude areas showing more prominent deviations due to steeper atmospheric parameter gradients and asymmetric orbital geometry. Moreover, a comparison with the measured satellite-observed brightness temperature further demonstrates that Exp.2 effectively reduces simulation biases near the scan edge. The mean bias is reduced by up to 0.1 K in water vapor absorption channels, a more significant improvement compared to the 0.03 K reduction in CO₂ absorption channels. These results indicate that the proposed slant-path profile construction method significantly enhances the accuracy and reliability of infrared hyperspectral radiative transfer forward simulations under complex observation geometries by providing a more realistic representation of the three-dimensional slant-path radiative transfer process. This advancement holds important implications for improving the atmospheric correction of remote sensing data.



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Keywords: FY-3E/HIRAS-II; satellite line-of-sight path tracing; brightness temperature simulation bias; atmospheric parameter profile

1. Introduction

The hyperspectral infrared sounder provides critical atmospheric temperature and humidity profile information for numerical weather prediction and climate research by

detecting radiation emitted from the Earth–atmosphere system across multiple channels with high spectral resolution. As the world’s first early-morning polar-orbiting meteorological satellite, it fills a crucial gap in the global observing system for this orbital timeframe [1]. The HIRAS-II (Hyperspectral Infrared Atmospheric Sounder-II) onboard FY-3E features significant improvements over its predecessors in terms of spectral coverage, spectral resolution, and spatial resolution [2–4], providing a new data foundation for high-precision atmospheric sounding.

The ultimate goal of satellite quantitative remote sensing is to accurately retrieve geophysical parameters of the land surface and atmosphere from the apparent radiance signals received by the sensor. Achieving this objective hinges on high-precision atmospheric correction, the accuracy of which fundamentally depends on the precision of radiative transfer forward modeling. This reliance exists because the forward model serves as the physical bridge connecting the atmospheric state to satellite observations. Scholars worldwide have conducted extensive research in this field, developing various forward simulation and atmospheric correction methods based on radiative transfer models (such as LBLRTM, 6S, LOWTRAN, MODTRAN, and FASCODE) [5–9]. However, current mainstream forward modeling methods largely rely on a key assumption: using a single vertical atmospheric profile from the satellite nadir point’s projected location to represent the atmospheric state for an entire pixel’s field of view [10–12]. This approach is approximately valid at small satellite zenith angles (near the nadir point), as the observation path closely aligns with the vertical column. As the scan angle increases, however, the satellite’s actual line-of-sight path (the slant path) deviates significantly from the local vertical direction, causing it to traverse a substantially expanded horizontal range of the atmosphere [13,14]. Under these conditions, persisting with simulations based on the nadir-point vertical profile fails to accurately characterize the real, three-dimensional atmospheric structural variations along the slant path, which are caused by strong horizontal gradients of atmospheric elements like temperature and water vapor. Consequently, significant radiative simulation errors are introduced at the edges of the scan line [13,14]. These errors are directly propagated into the atmospheric correction process, leading to distorted estimates of the atmospheric contribution. This, in turn, severely constrains the accuracy of retrieving atmospheric parameters from the corrected data, rendering the valuable observational data at the scan edges difficult to utilize effectively.

To address the aforementioned issue, this study proposes and implements a method for constructing slant-path atmospheric profiles along the actual observation line-of-sight, specifically tailored to the cross-track scanning geometry of FY-3E/HIRAS-II. It is worth noting that foundational work exists regarding slant-path representation: Guo et al. [13], neglecting Earth’s curvature, calculated the horizontal offset within each pressure layer based on the inter-layer height difference and satellite zenith angle, subsequently employing bilinear interpolation of NWP fields to construct temperature and water vapor profiles for FY-3D/MWHS-II observational paths. Bormann [14], under the plane-parallel atmosphere assumption, estimated the horizontal displacement of the line-of-sight based on the satellite zenith angle and the vertical distance between atmospheric layers. By selecting several vertical profiles within the satellite azimuthal plane for horizontal interpolation, the study improved radiance simulations of sounders within assimilation systems. In contrast to these previous studies, the primary distinction of this work lies in the following: based on a series of coordinate transformations, we solve for the three-dimensional intersection points between the satellite line-of-sight and atmospheric isosurfaces layer by layer. By integrating horizontal inverse-distance weighting with vertical spline interpolation, we reconstruct atmospheric parameter profiles—including temperature, water vapor, and ozone—along the actual viewing path of HIRAS-II. This approach provides inputs for

brightness temperature forward modeling that more accurately reflect the true infrared hyperspectral observation geometry. To systematically evaluate the effectiveness and improvement of the new method, a rigorous comparative experiment is designed. This experiment comprehensively compares the new method (Exp.2: slant-path profile method) with the conventionally widely-used vertical profile method based on the satellite nadir point projection (Exp.1). The focus is on quantifying the differences between the two methods in terms of the constructed atmospheric temperature and humidity profiles as well as the final simulated HIRAS-II radiance brightness temperature. The core objective of this study is to demonstrate that by more accurately representing the three-dimensional slant-path radiative transfer process, the physical foundation for forward simulation accuracy under complex observation geometries can be enhanced. This, in turn, provides key technical support for improving atmospheric correction of remote sensing data at large scan angles and ultimately enhancing the reliability of atmospheric parameter retrieval.

The structure of this paper is as follows: Section 2 provides a detailed introduction to the FY-3E/HIRAS-II Level 1 radiance data, the collocated MERSI-LL cloud mask (CLM) product, and the ERA5 reanalysis data used in this study. It also elaborates on the theoretical basis, geometric model, and interpolation algorithm of the newly developed slant-path retrieval method, along with the design of comparative experiments with traditional methods. Section 3 systematically presents and analyzes the statistical results of the two methods in simulating brightness temperature, with a focus on the distribution patterns of biases across scan angles, spectral channels, and latitudes, as well as comparisons with observed brightness temperature. Section 4 will provide an in-depth discussion of the main results and summarize the key findings of this study, along with prospects for future research.

2. Materials and Methods

2.1. FY-3E/HIRAS-II Data

FY-3E is the world's first meteorological satellite in a dawn-dusk sun-synchronous orbit, designed and built by the Shanghai Academy of Spaceflight Technology (Shanghai, China). It carries the HIRAS-II, an advanced version of the HIRAS instrument onboard FY-3D. This new instrument demonstrates comprehensive improvements in several aspects, including spectral coverage and spatial resolution [2–4]. The satellite operates at an altitude of 836 km and covers 3041 continuous channels across the infrared band of 3.92–15.38 μm . Detailed parameters of the HIRAS-II instrument are provided in Table 1.

Table 1. Spectral parameters of FY-3E/HIRAS-II.

Band Name	Spectral Range (cm^{-1})	Spectral Resolution (cm^{-1})	Number of Channels (Apodized)	Radiometric Calibration Accuracy (K) (Minimum/Expected)
Long-Wave	650~1168.125	0.625	830	650~667
				667~689
				689~1000
				1000~1136
Medium-Wave	1168.75~1920	0.625	1203	1210~1538
				1538~1750
				2155~2300
Short-Wave	1920.625~2550	0.625	1008	2300~2550

The HIRAS-II scan mirror observes the Earth using a cross-track, side-scanning method. Each scan line observes 32 fields of regard (FORs), which consist of 28 consecutive Earth targets, including 2 cold space targets and 2 onboard blackbody targets, covering a scan angle range of $\pm 50.4^\circ$. Each FOR comprises 9 detector elements (fields of view, FOV)

arranged in a 3×3 array. Each individual FOV has an Earth observation angular diameter of 1° , corresponding to a nadir instantaneous field of view of approximately 14 km on the ground. The data used in this study are Level 1 radiance observations from HIRAS-II (<http://satellite.nsmc.org.cn/portalsite/default.aspx> accessed from 1–31 July 2023). In practical applications, in addition to rigorous quality control of the radiance data, apodization is also required to reduce the side-lobe effects caused by the sinc function. After apodization, the radiance R_n for the n -th channel is given by:

$$R_n = 0.23 \times R_{n-1} + 0.54 \times R_n + 0.23 \times R_{n+1} \quad (1)$$

In the formula, R_{n-1} represents the radiance of the $(n - 1)$ th channel, and R_{n+1} represents the radiance of the $(n + 1)$ th channel. The radiance values for the first and last channels are not apodized [15].

Furthermore, in selecting the channels, we specifically focus on two absorption bands. Five channels (numbers 35, 51, 67, 83, and 99) are chosen from the CO_2 absorption band, with central wavenumbers of 670 cm^{-1} , 680 cm^{-1} , 690 cm^{-1} , 700 cm^{-1} , and 710 cm^{-1} , respectively. Another five channels (numbers 373, 453, 533, 613, and 693) are selected from the water vapor absorption band, with central wavenumbers of 1400 cm^{-1} , 1450 cm^{-1} , 1500 cm^{-1} , 1550 cm^{-1} , and 1600 cm^{-1} , respectively. These channels are used for an in-depth comparison and analysis of the brightness temperature simulations. The aforementioned channels are located in characteristic spectral bands that are highly sensitive to variations in atmospheric temperature and humidity. This makes them more effective in representing and highlighting the changing characteristics of atmospheric parameters under slant-path observation conditions, rendering them particularly suitable for satellite remote sensing research.

2.2. FY-3E/MERSI-LL Data

The MERSI-LL (Medium-Resolution Spectral Imager-Low Light) onboard the FY-3E satellite platform employs a multi-detector parallel scanning method. It possesses the capability for continuous and integrated multispectral observations in the low-light and infrared bands along the dawn-dusk orbit. Its spectral coverage ranges from 0.7 to $12.0 \text{ }\mu\text{m}$, including one low-light channel and six thermal infrared channels. Among these, the spatial resolution of the two infrared split-window channels is 250 m , while the remaining channels have a resolution of 1 km . Each channel scans simultaneously with either 10 or 40 detector elements, covering a ground scanning field of view ranging from -54.7° to 50° [16,17]. The data used in this study are the MERSI-LL cloud mask (CLM) products from 1–31 July 2023.

This study selected clear-sky ocean samples from HIRAS for analysis. This move aims to control surface homogeneity and exclude cloud contamination in order to isolate and highlight differences in atmospheric parameters resulting from variations in observation geometry. The identification of clear-sky ocean fields of view was based on the precise instrument field-of-view matching algorithm proposed by Wang et al. [18], which was applied to spatially match the MERSI-II and HIRAS-II instruments on the same platform. The specific procedure is as follows: first of all, the projection range of the HIRAS pixel is calculated. Then, the observation vectors of both instruments are computed, and the matrix of vector angles is recorded. If the angle between the observation vectors is less than half of the angular width of the HIRAS field of view (i.e., 0.5°), the pixel is considered to fall within the HIRAS pixel range. A field of view is deemed to meet the criteria only if all pixels within it are identified as clear-sky over the ocean.

$$\frac{\text{LOS}_{\text{HIRAS-II}} \cdot \text{LOS}_{\text{MERSI-LL}}}{\|\text{LOS}_{\text{HIRAS-II}}\| \|\text{LOS}_{\text{MERSI-LL}}\|} > \cos(\beta/2) \quad (2)$$

In the formula, β represents the fixed observation angular width of the HIRAS-II detector element, while $\text{LOS}_{\text{HIRAS-II}}$ and $\text{LOS}_{\text{MERSI-II}}$ denote the line-of-sight vectors of the two instruments, respectively.

2.3. ERA5 Data

ERA5, the fifth-generation atmospheric reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), is based on the Cy41r2 Integrated Forecasting System implemented in 2016 [19]. It represents substantial improvements over the previous ERA-Interim reanalysis product. The temporal resolution has been enhanced from 6-hourly to hourly, and the horizontal resolution has been increased from approximately 83 km to 30 km. The data simulate the atmosphere across 137 levels from the surface up to 80 km, with significantly improved accuracy in representing meteorological parameters such as temperature and humidity in the troposphere [19,20]. The dataset is accessible at <https://cds.climate.copernicus.eu/cdsapp#!/home> (accessed on 31 July 2023). The “ERA5 hourly data on pressure levels from 1940 to present” dataset used in this study has an hourly temporal resolution, a spatial resolution of $0.25^\circ \times 0.25^\circ$, and covers 37 pressure levels from 1000 hPa to 1 hPa. This research utilizes global data from all time slots between 1 and 31 July 2023, which include parameters such as atmospheric temperature, relative humidity, and ozone mixing ratio.

Spatiotemporal matching between ERA5 reanalysis data and HIRAS-II observations is performed as follows: spatially, the ERA5 gridded data with a $0.25^\circ \times 0.25^\circ$ resolution are interpolated onto the HIRAS-II field of view (FOV) using bilinear interpolation; temporally, the observation time difference between the two datasets is constrained to within 30 min.

2.4. Method for Constructing Slant-Path Atmospheric Parameter Profiles

Calculate the satellite-to-ground LOS vector in the ENU (East, North, Up) coordinate system using the satellite zenith angle (θ), azimuth angle (A), and range (r).

$$\text{LOS}_{\text{ENU}} = \begin{pmatrix} E \\ N \\ U \end{pmatrix} = \begin{pmatrix} r \sin \theta \sin A \\ r \sin \theta \cos A \\ r \cos \theta \end{pmatrix} \quad (3)$$

where $r = h/\cos\theta$, and h is the orbital altitude of the Fengyun-3E satellite (836 km).

By applying Equation (4) along with the satellite’s initial longitude (λ) and latitude (φ), the initial position S_0 of the satellite in the Earth-Centered, Earth-Fixed (ECEF) coordinate system can be determined.

$$S_0 = \begin{pmatrix} S_{X_0} \\ S_{Y_0} \\ S_{Z_0} \end{pmatrix} = \begin{pmatrix} (N + h_0) \cos \varphi \cos \lambda \\ (N + h_0) \cos \varphi \sin \lambda \\ ((1 - e^2)N + h_0) \sin \varphi \end{pmatrix} \quad (4)$$

where $N = \frac{\alpha}{\sqrt{1 - e^2 \sin^2 \varphi}}$, $\alpha = 6,378,137(\text{m})$, $f = 1/298.257$, $e^2 = f(2 - f)$.

In the above formula, N represents the radius of curvature in the prime vertical, α denotes the semi-major axis of the WGS84 ellipsoid, e^2 indicates the square of the first eccentricity of the ellipsoid, and f represents the flattening of the Earth’s ellipsoid. Since the target point is on the Earth’s surface, h_0 is simplified to 0 here.

Based on the rotation matrix R from Equation (5), convert the LOS_{ENU} to the satellite-to-ground line-of-sight vector LOS_{ECEF} (LOS_X , LOS_Y , LOS_Z) in the ECEF coordinate system. Then, calculate the position S of the ground target point using the following Equation (6).

$$R = \begin{bmatrix} -\sin \lambda & \cos \lambda & 0 \\ -\sin \varphi \cos \lambda & -\sin \varphi \sin \lambda & \cos \varphi \\ \cos \varphi \cos \lambda & \cos \varphi \sin \lambda & \sin \varphi \end{bmatrix} \quad (5)$$

$$LOS_{ECEF} = \begin{pmatrix} LOS_X \\ LOS_Y \\ LOS_Z \end{pmatrix} = R^T \begin{pmatrix} E \\ N \\ U \end{pmatrix}, S = \begin{pmatrix} S_X \\ S_Y \\ S_Z \end{pmatrix} = \begin{pmatrix} S_{X_0} \\ S_{Y_0} \\ S_{Z_0} \end{pmatrix} + \begin{pmatrix} LOS_X \\ LOS_Y \\ LOS_Z \end{pmatrix} \quad (6)$$

The coordinates (S_X , S_Y , S_Z) of a ground target point in the ECEF coordinate system are converted into its geographical coordinates ($\lambda_{HIRAS-II}$, $\varphi_{HIRAS-II}$, $h_{HIRAS-II}$) through an iterative convergence method.

$$\lambda_{HIRAS-II} = \arctan\left(\frac{S_Y}{S_X}\right), h_{HIRAS-II} = \frac{\sqrt{S_X^2 + S_Y^2}}{\cos \varphi_{HIRAS-II}} - N \quad (7)$$

$$\varphi_{HIRAS-II} = \arctan\left[\frac{S_Z}{\sqrt{S_X^2 + S_Y^2}} \left(1 - e^2 \frac{N}{N + h_{HIRAS-II}}\right)^{-1}\right] \quad (8)$$

Based on the satellite line-of-sight path tracing algorithm, the positions of all intersection points between the satellite line-of-sight and the ERA5 vertical layers are calculated, obtaining multiple sets of latitude, longitude, and height coordinates along the path. Within the ERA5 three-dimensional grid coordinate system, a hybrid interpolation method is designed. If a path point falls exactly on an ERA5 grid point, the atmospheric parameter value at that grid point is directly extracted. If a path point does not fall on a grid point, in the horizontal space, the Inverse Distance Weighting (IDW) method from Equation (9) is adopted [21]. This method uses a rigorous mathematical model to characterize the nonlinear weight relationship between the path point and the grid points, accurately interpolating the atmospheric parameter distribution of the target point across all height levels. In the vertical direction, the continuity and smoothness advantages of the spline interpolation method are leveraged to further enhance the interpolation accuracy.

$$v_e = \sum_{i=1}^m \frac{v_i}{d_i^n} / \left(\sum_{i=1}^m \frac{1}{d_i^n} \right) \quad (9)$$

where v_e is the estimated value at the interpolation point, v_i represents the parameter value (such as temperature, water vapor density, pressure, or ozone) at the i -th grid point (where i ranges from 1 to m), and d_i is the distance between that i -th grid point and the point to be interpolated. The total number of known grid points used in the calculation, m , is set to 4. The exponent n , which is typically chosen as 2, controls the rate at which the weight coefficient decreases as the distance between the interpolation point and the sample grid points increases.

The slant-path atmospheric profile (Exp.2) and the traditional vertical atmospheric profile (Exp.1) obtained from the above steps are uniformly interpolated onto the fixed altitude grid required by the Combined Atmospheric Radiative Transfer (CART) model (version CART2P1; developed by the team of Prof. Heli Wei, Hefei, Anhui, China) [22]. The vertical spacing of this grid is 1 km from 0 to 25 km, 2.5 km from 25 to 50 km, and 5 km from 50 to 120 km. The interpolated profiles were then input into CART, together with the satellite observation geometry parameters, to obtain the simulated spectral radiance

$L(\nu)$. Subsequently, the equivalent channel radiance L_{eq} at the satellite's entrance pupil is calculated by convolving with the HIRAS-II channel spectral response function. Finally, the equivalent brightness temperature is derived using Planck's law.

$$L_{eq} = \frac{\int_{\nu_1}^{\nu_2} L(\nu)S(\nu)d\nu}{\int_{\nu_1}^{\nu_2} S(\nu)d\nu} \quad (10)$$

In the formula, ν is the wavenumber and $S(\nu)$ is the channel spectral response function of the satellite.

The specific algorithm construction process of this paper is shown in Figure 1.

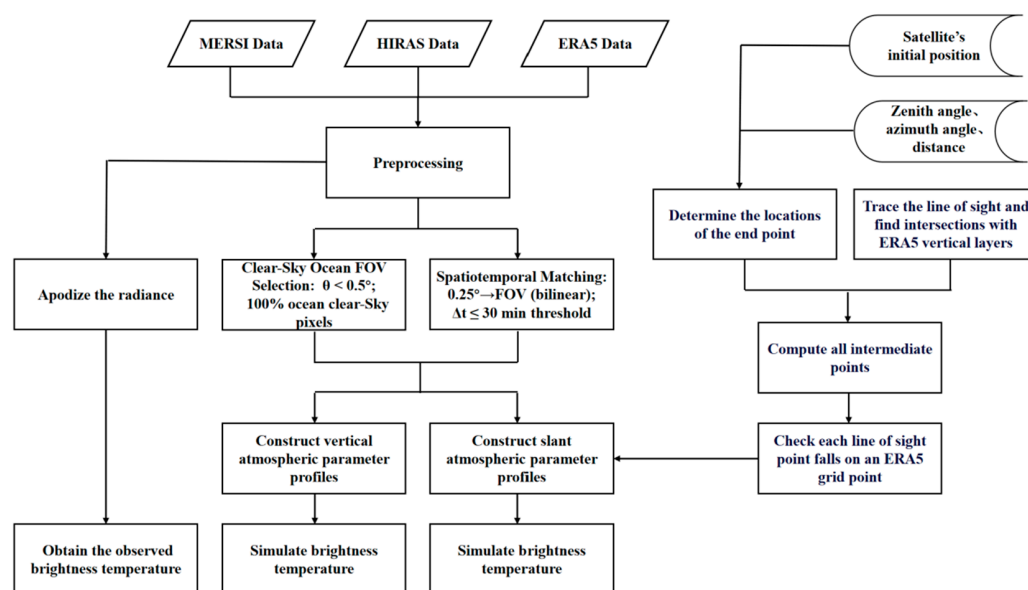


Figure 1. Flowchart of the method for constructing slant-path atmospheric parameter profiles along the satellite line-of-sight.

2.5. Bias Evaluation Method

This study used O-B bias (Bias) and standard deviation (Std) as accuracy evaluation metrics. The calculation methods for these two metrics are outlined as follows:

$$\text{Bias}_{j\text{mean}} = \frac{1}{N} \sum_{i=1}^N (O_{ij} - B_{ij}) \quad (11)$$

where N denotes the total number of samples, j denotes the channel, O_{ij} is the i th observed brightness temperature in channel j , B_{ij} is the corresponding simulated brightness temperature, $\text{Bias}_{j\text{mean}}$ represents the mean bias of the j th channel.

3. Results

3.1. Validation of the Method for Constructing Slant-Path Atmospheric Parameter Profiles Along the Satellite Line-of-Sight

Figures 2 and 3 display the distribution of mean bias in atmospheric temperature profiles (Figure 2) and atmospheric water vapor density profiles (Figure 3) along the satellite line-of-sight path versus the traditional vertical path, across different altitude layers, during the period from 19:20 to 19:50 UTC on 1 July 2023. The subplots, arranged from left to right and top to bottom, correspond to FOV1 to FOV9. The horizontal axis represents the position of dwell fields of view along each scan line (i.e., the scan angle FOR), with the nadir point located between FOR14 and FOR15. The vertical axis denotes altitude, and

the color scale indicates the average deviation value. These results are obtained by first calculating the difference between Exp.2 and Exp.1 for each FOR position of each FOV, and then averaging the results for the same observational geometry (i.e., the same FOV and FOR) across all scan lines during this time period.

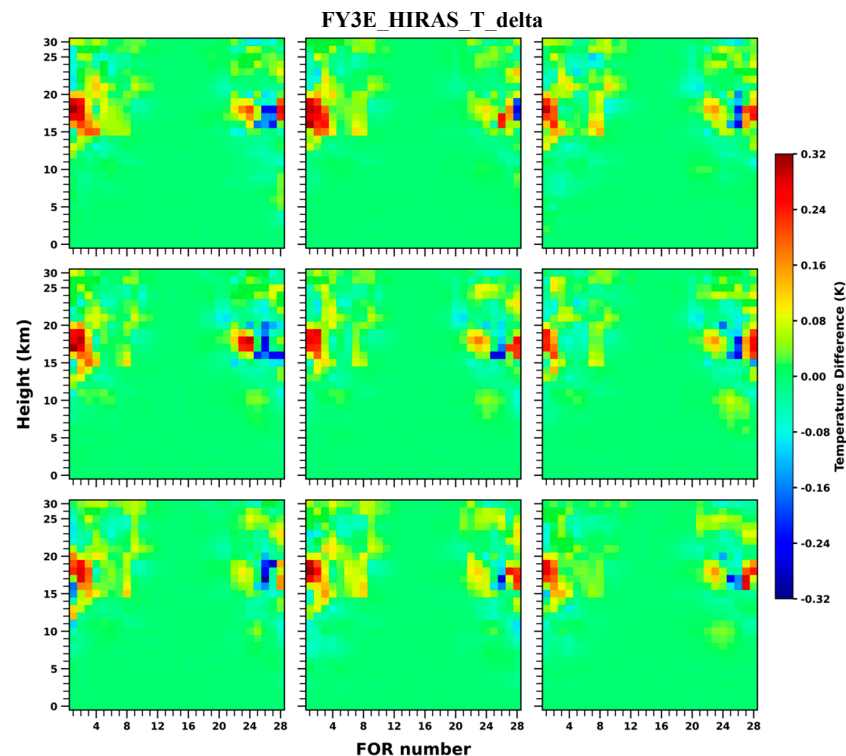


Figure 2. The distribution of mean bias in atmospheric temperature profiles at different altitude levels for each field of view (FOV) along the HIRAS-II observation path as a function of the scan angle.

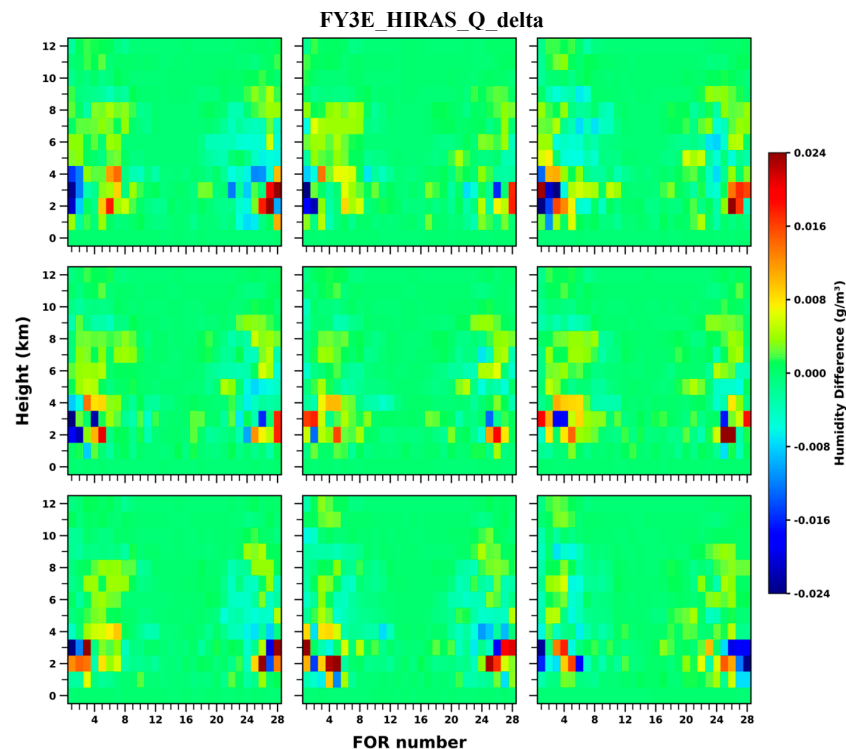


Figure 3. The distribution of mean bias in atmospheric water vapor density profiles at different altitude levels for each field of view (FOV) along the HIRAS-II observation path as a function of the scan angle.

As can be seen from Figure 2, the mean bias between the atmospheric temperature derived from the slant-path method proposed in this study and that from the vertical path ranges from -0.32 K to 0.32 K. The influence of the scan angle on the temperature and humidity biases becomes substantially larger as the satellite's line-of-sight transitions towards the edge of the scan line. Significant biases are observed above 15 km, where the maximum mean bias of 0.32 K occurs at the first scan angle near 17 km in the fourth FOV subplot. In contrast, Figure 3 reveals an opposite vertical distribution for humidity field bias, where the mean water vapor density bias varies between -0.024 g/m³ and 0.024 g/m³, predominantly concentrated below 5 km. The largest humidity bias is also found at the scan edge and diminishes gradually towards the nadir point. Overall, except for a few FORs near the nadir point exhibiting near-zero bias, both temperature and humidity deviations show noticeable asymmetry relative to the nadir in FOVs closer to the scan extremities.

Furthermore, to visually illustrate the differences between the two types of profiles for a specific observation sample and their impacts on radiative simulations, a case with a large satellite zenith angle at the scan edge is selected for analysis. This sample, acquired at 19:50 UTC on 1 July 2023, is located at 28.4° W, 85.34° N, with a satellite zenith angle of 57.66° and an azimuth angle of 272.24° . Figure 4 presents both the traditional vertical atmospheric profile and the slant-path atmospheric profile for this sample, showing variations in temperature and water vapor density with height. Additionally, it provides the mean brightness temperature simulation biases across different channels obtained by inputting these two profiles into the radiative transfer model.

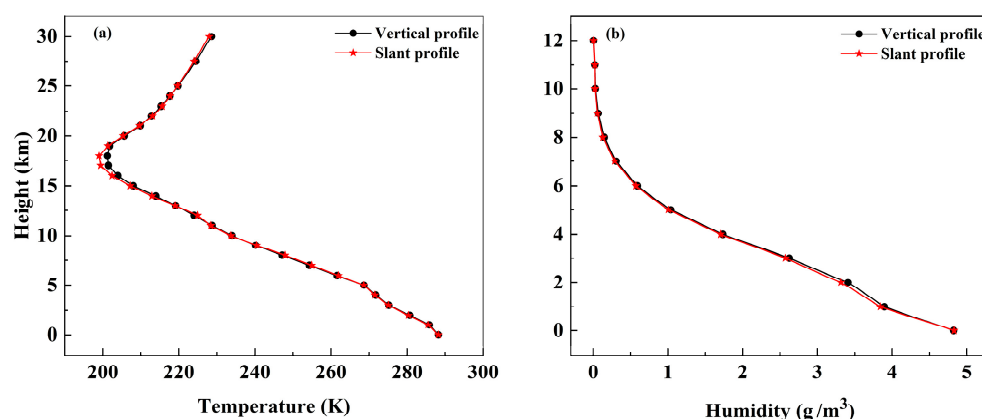


Figure 4. Comparison of atmospheric profiles at (28.4° W, 85.34° N): (a) atmospheric temperature; (b) water vapor density.

As summarized in Table 2, the discrepancies between the slant-path and vertical profiles from the near-surface to the mid-to-upper atmosphere primarily stem from the fact that the line-of-sight path traverses distinct horizontal atmospheric regions. When this path crosses areas characterized by significant temperature or water vapor gradients, considerable differences arise between the two profiles. These differences ultimately manifest in the simulated channel brightness temperatures. Notably, this effect is more pronounced in water vapor absorption channels than in CO₂ absorption channels.

Table 2. The mean absolute deviation in simulated brightness temperatures between the two atmospheric profiles across different channels.

Result	Brightness Temperature (K)									
	Ch35	Ch51	Ch67	Ch83	Ch99	Ch373	Ch453	Ch533	Ch613	Ch693
Δ BT (K)	0.31	0.33	0.25	0.21	0.16	0.42	0.47	0.56	0.51	0.58

3.2. Global Distribution Characteristics of FY-3E/HIRAS-II Bright Temperature Simulation Biases: An Intercomparison of Channels from the CO₂ and Water Vapor Absorption Bands

Figure 5 displays the brightness temperature differences simulated using profiles from Exp.1 and Exp.2 during the ascending orbit of the FY-3E satellite on 1 July 2023. On the left, the differences for five channels (channels 35, 51, 67, 83, 99) in the longwave CO₂ absorption band are presented, which fall within a relatively small range of -0.12 K to 0.12 K. In contrast, the five channels from the mid-wave water vapor absorption band on the right exhibit an expanded bias range of -0.3 K to 0.3 K, significantly larger than that of the CO₂ channels. Furthermore, among the CO₂ channels, the bias of channel 99 (centered at 710 cm^{-1}) is notably smaller than those of the other four channels. This may be attributed to its location near the edge of the strong CO₂ absorption band, where the absorption capability is comparatively weaker.

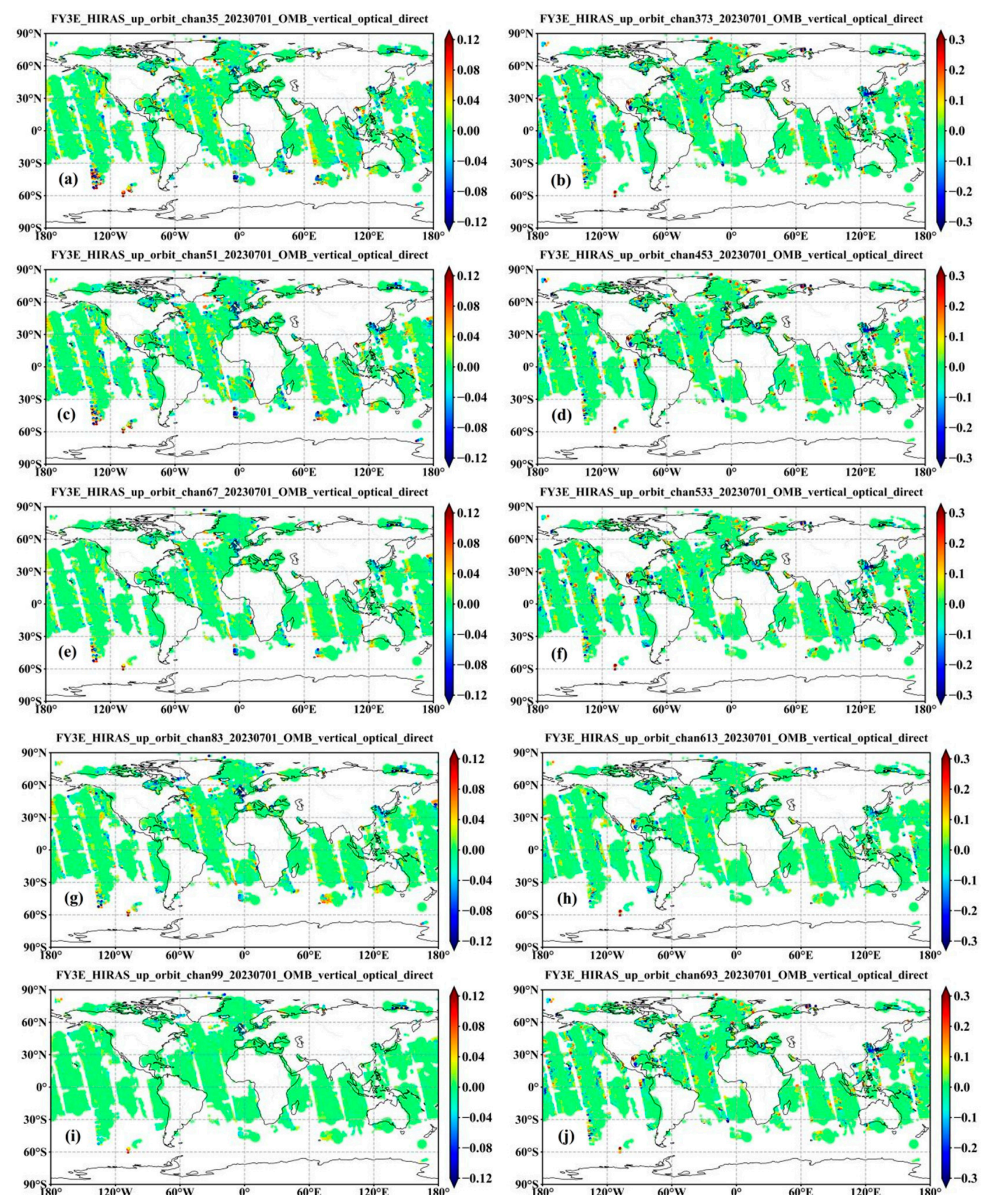


Figure 5. Brightness temperature differences measured with HIRAS-II long-wave channels 35 (a), 51 (c), 67 (e), 83 (g), and 99 (i) (left) and mid-wave channels 373 (b), 453 (d), 533 (f), 613 (h), and 693 (j) (right), simulated by Exp.1 and Exp.2, for an ascending FY-3E orbit on 1 July 2023 (the y -axis indicates the latitude, the x -axis indicates the longitude, and the colour scale represents the brightness temperature value).

For the CO₂ channels on the left, a pronounced concentration of differences is observed near 130 °W in the mid-latitudes of the Southern Hemisphere, where the deviations are significantly higher than in the surrounding areas, particularly evident in channels 35 and 51. For the water vapor channels on the right, a large bias concentration appears near 90 °W, 30 °N. Overall, the spatial distribution of differences is broadly similar for both the CO₂ and water vapor channels, with all significant deviations located at the edges of the scan line.

Figure 6 clearly illustrates the probability density distribution characteristics of brightness temperature biases for different infrared channels of HIRAS-II, simulated by the two methods. The upper subplot (a) reveals that within the CO₂ absorption band (channels 35, 51, 67, 83, and 99, corresponding to central wavenumbers of 670–710 cm^{−1}), the brightness temperature distribution of differences is highly concentrated, exhibiting a narrow range (−0.2 K to 0.4 K) and a peak density approaching 100. This indicates strong consistency between the two simulation methods in this band, attributable to the relatively stable concentration distribution of CO₂ as a well-mixed gas and the higher predictability of the temperature field. In contrast, the lower subplot (b) shows a significantly wider bias distribution (−1.0 K to 1.0 K) for the water vapor absorption band (channels 373, 453, 533, 613, and 693, corresponding to central wavenumbers of 1400–1600 cm^{−1}), with a peak density of only about 16 and evident tailing. This reflects the high spatial and temporal heterogeneity of water vapor and its substantial impact on simulation results.

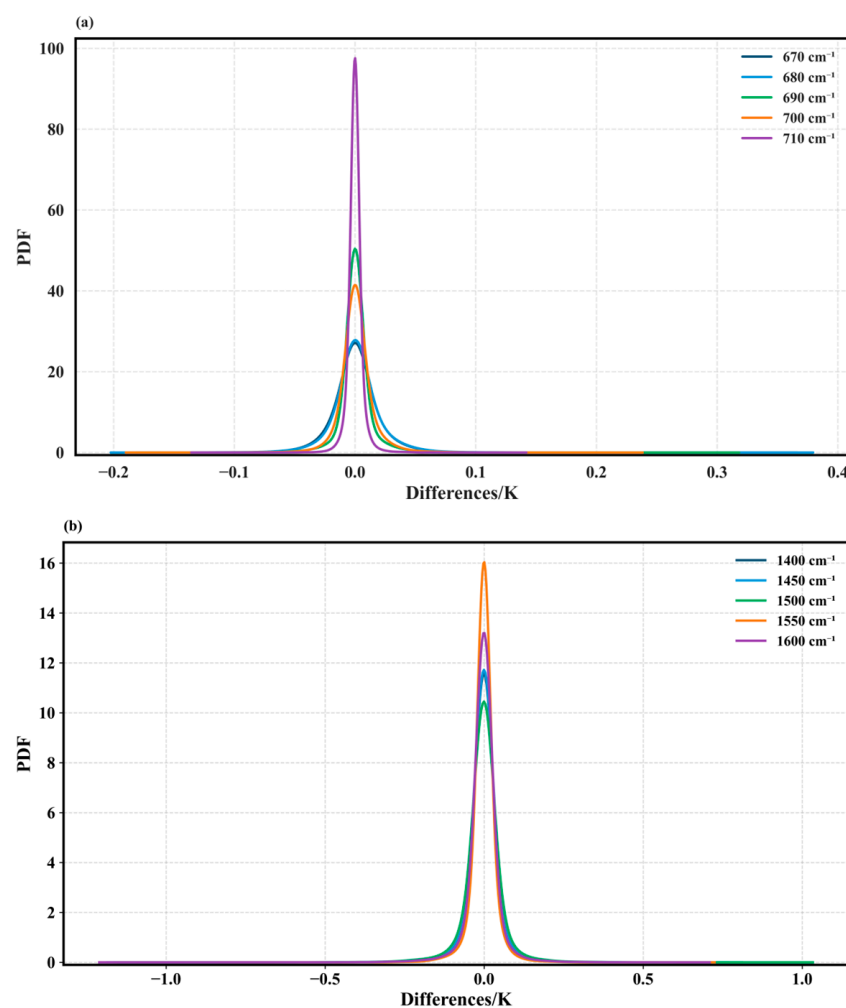


Figure 6. Probability density distributions of brightness temperature differences from the two simulation methods across channels (a) 35, 51, 67, 83, and 99; (b) 373, 453, 533, 613, and 693.

3.3. FY-3E/HIRAS-II Simulated Brightness Temperature Bias as a Function of Zenith Angle: A Channel Comparison Between CO₂ and Water Vapor Absorption Bands

Figure 7 presents a systematic comparison across ten HIRAS-II channels (five long-wave channels on the left; five medium-wave channels on the right). It clearly illustrates the variation in simulated brightness temperature bias as a function of satellite zenith angle across different spectral channels. These results are based on global clear-sky ocean samples collected from 1–31 July 2023. Following a series of quality control procedures and cloud filtering, the total effective sample size for a single channel amounts to approximately 981, 696. Overall, the bias distribution for all channels is centered around a zenith angle of 0°. When the zenith angle is less than 30°, the absolute bias values are predominantly small. However, when the zenith angle exceeds 30°, the absolute bias increases significantly. Notable differences in bias magnitude and distribution patterns are observed among the channels.

The long-wave CO₂ absorption channels (Figure 7a,c,e,g,i) exhibit excellent stability, with biases in all channels concentrated within ± 0.1 K. In particular, the bias in channel 99 further narrows to ± 0.05 K, which aligns with its location at the edge of the CO₂ absorption band and its lower sensitivity to variations in atmospheric parameters. In contrast, the medium-wave water vapor absorption channels (Figure 7b,d,f,h,j) show a stronger dependence on the satellite zenith angle, with the bias range expanding by tenfold to approximately ± 0.5 K. Notably, greater dispersion occurs at larger zenith angles, indicating that the medium-wave channels are more sensitive to slant paths, and the simulation results are more significantly influenced by the observation geometry.

This difference primarily stems from the distinct radiative characteristics of long-wave and medium-wave channels in different atmospheric layers. Long-wave channels are primarily sensitive to thermal radiation from the middle and lower atmosphere, where the atmospheric path is relatively homogeneous. Consequently, the difference in simulation results between vertical and slant paths is minimal. In contrast, mid-wave channels are typically more sensitive to constituents in the middle and upper atmosphere, such as water vapor and ozone. The longer atmospheric column traversed by the slant path amplifies the impact of horizontal inhomogeneity in atmospheric parameters. This leads to a more pronounced accumulation of errors from absorption and emission processes, resulting in a significant increase in bias with larger zenith angles.

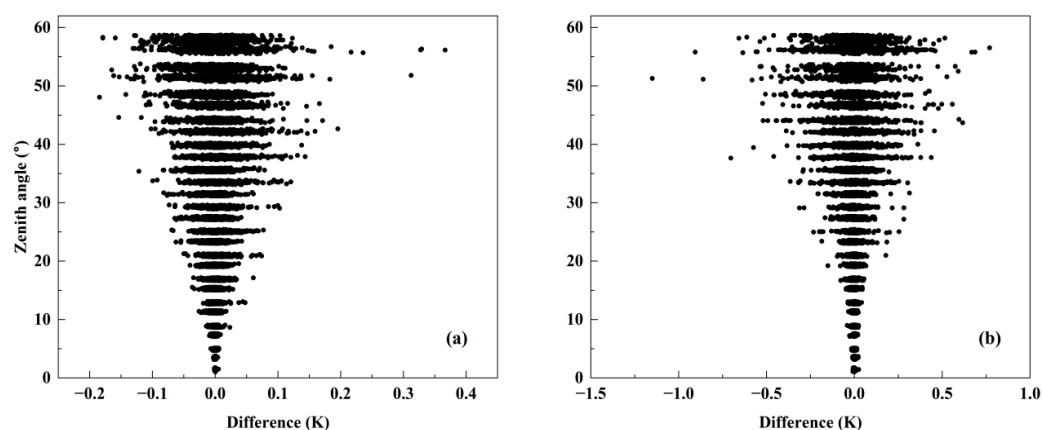


Figure 7. Cont.

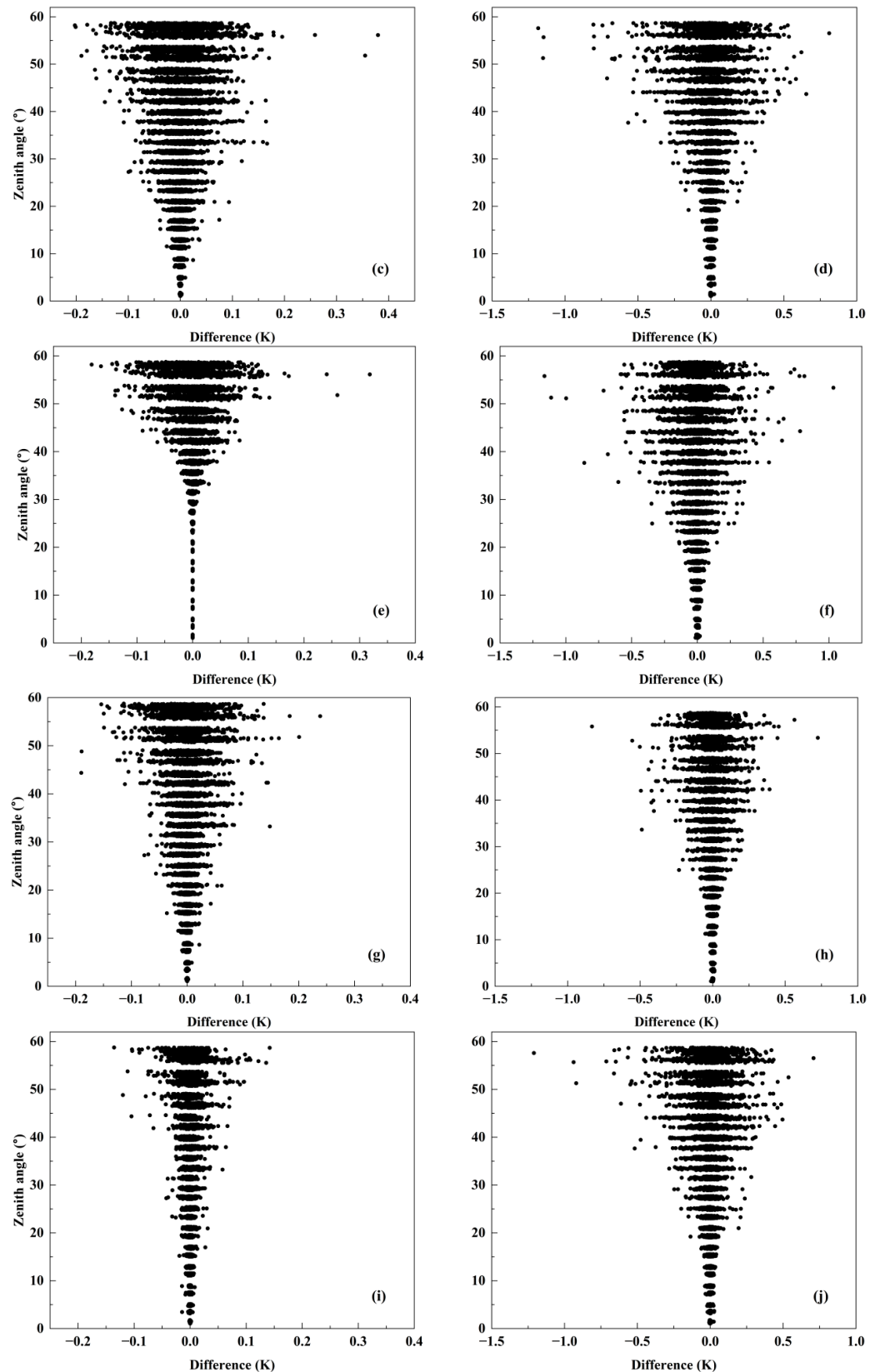


Figure 7. The distribution of simulated brightness temperature differences with respect to satellite zenith angle, derived from HIRAS-II long-wave (a) channel 35, (c) channel 51, (e) channel 67, (g) channel 83, and (i) channel 99, as well as medium-wave (b) channel 373, (d) channel 453, (f) channel 533, (h) channel 613, and (j) channel 693, based on simulations from Exp. 1 and Exp. 2.

3.4. A Comparison of Simulation Performance Between Slant and Vertical Paths: Latitudinal Dependence and Limb Effects of CO₂ and Water Vapor Absorption Bands

Figure 8 displays the latitudinal variation characteristics of the simulated brightness temperature bias derived from methods Exp.1 and Exp.2 during the period from 1 July to 31 July 2023. In each Field of View (FOV) subplot, the x -axis represents the FOR (Field of Regard) position along the scan line, while the y -axis represents the brightness temperature difference between Exp.1 and Exp.2. The analysis reveals that for the five channels within the CO₂ absorption band, the average bias for profiles near the nadir is significantly smaller than that at the swath edges. The minimum bias, approximately 0 K, occurs at the nadir point. The maximum bias occurs at the left edge of the scan line in FOV8 of Figure 8a, reaching 0.18 K. Furthermore, the bias distribution is asymmetric about the nadir point. This asymmetry is likely attributable to the orbital inclination of the polar-orbiting satellite not being exactly 90°, resulting in a latitudinal discrepancy between the two sides of the scan line and thus inconsistent FOV latitudes. Additionally, the fluctuation amplitude of the bias varies with the observation angle but is not significantly affected by the channel wavenumber. The bias values gradually decrease from high latitudes toward low latitudes.

A similar experiment is conducted for five water vapor absorption channels of HIRAS-II, with the results shown in Figure 9. The distribution pattern in Figure 9 is similar to that in Figure 8. Along the scan line, the bias at the nadir point is smaller than that at the edges. The maximum deviation also occurs at the left edge of the scan line in FOV8 of Figure 9a, reaching 0.38 K. The variation in bias across the nine detector elements within the same latitudinal zone with respect to the scan angle is not very pronounced. Furthermore, the bias variation exhibits a non-monotonic, aperiodic oscillation, and the bias distribution differs among the various channels. Overall, the simulation bias between methods Exp.1 and Exp.2 is greater for the water vapor absorption channels than for the CO₂ absorption channels. This is primarily attributed to the strong horizontal inhomogeneity of water vapor, which leads to significant differences in the atmospheric conditions sensed by the slant-path observations at the swath edges compared to the vertical-path observations, thereby resulting in larger brightness temperature simulation biases.

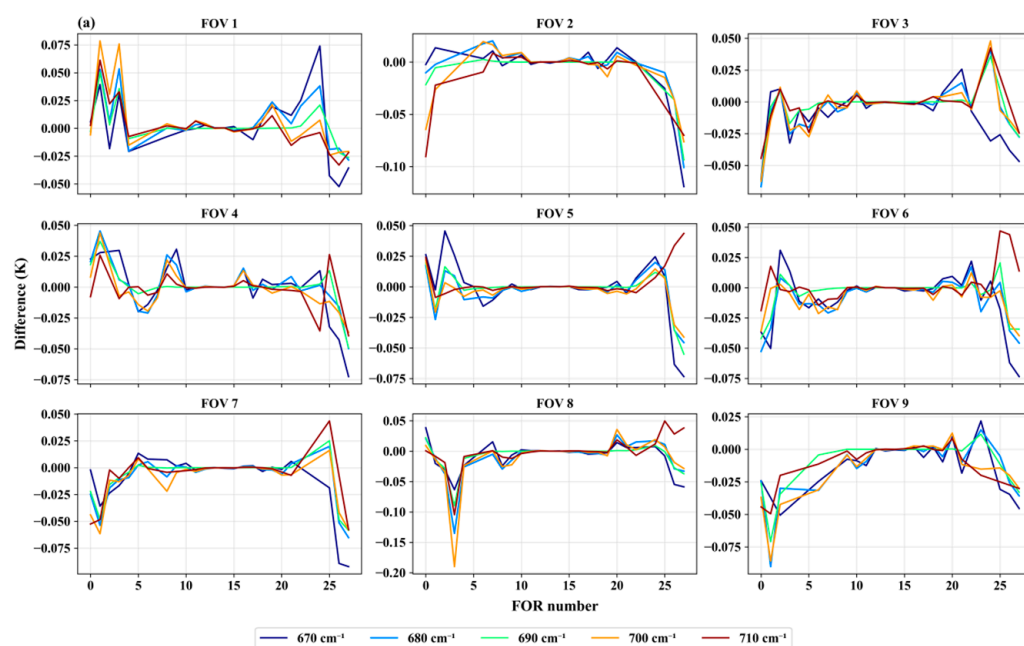


Figure 8. Cont.

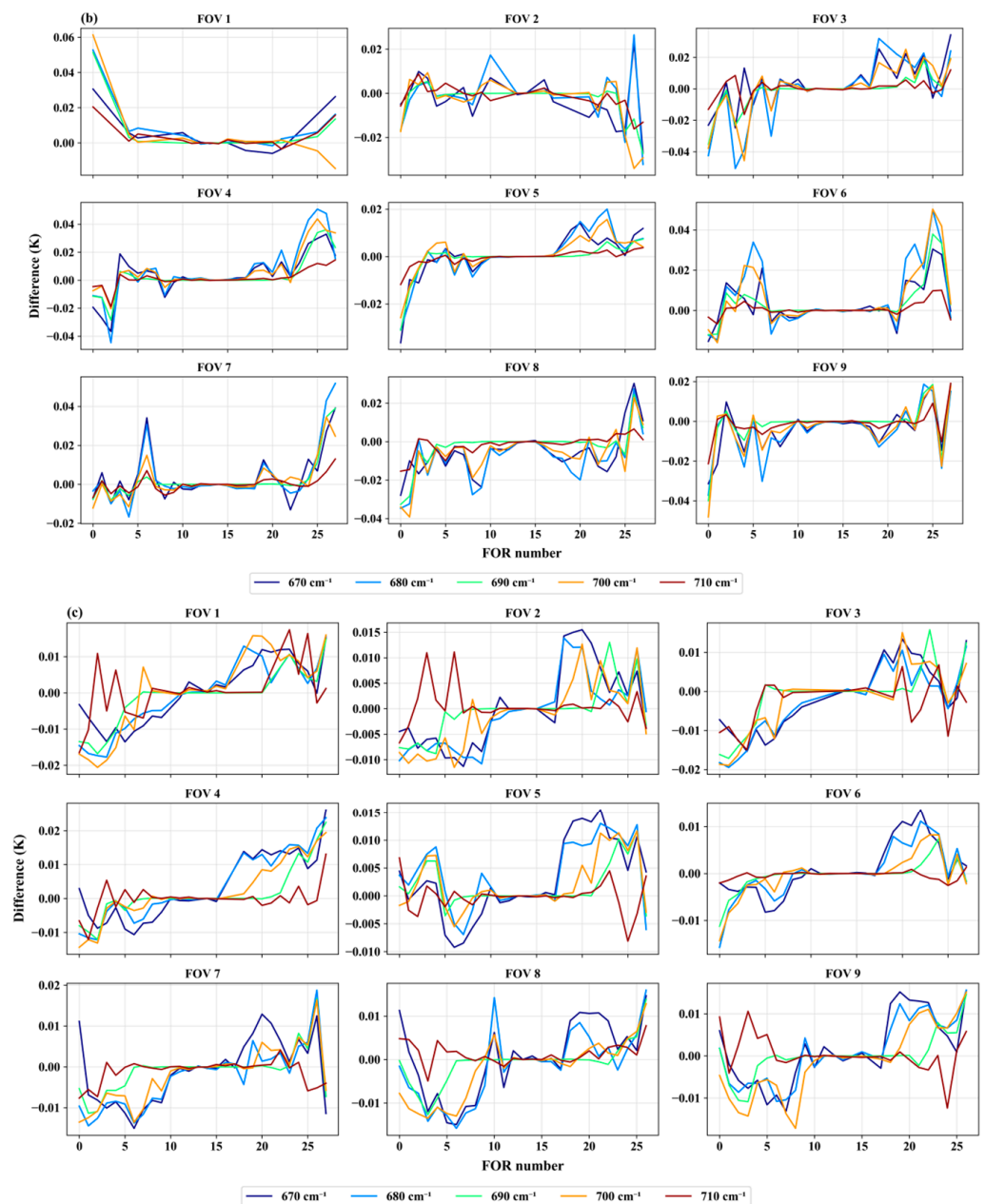


Figure 8. Distribution of the brightness temperature differences for individual FOVs, simulated by Methods Exp.1 and Exp.2, across the five FY-3E/HIRAS-II CO₂ absorption channels as a function of scan angle, for three latitude zones: (a) 80~70°, (b) 50~40°, and (c) 20~10°.

Furthermore, building upon our initial analysis of ascending-mode samples from 1–31 July 2023, we supplement the dataset with descending-mode FY-3E/HIRAS-II observations acquired between 1 and 5 July 2023. We conduct an independent statistical assessment of the latitudinal dependence of brightness temperature simulation biases in water vapor absorption channels. The results demonstrate that the discrepancies in brightness temperatures between Exp.1 and Exp.2 are similarly concentrated at the scan edges in the descending samples, intensifying with increasing latitude. This confirms that the simulation biases induced by slant-path geometry are not exclusive to ascending orbits. Additionally, the descending samples exhibit distinct asymmetries across the scan swath compared to their ascending counterparts. Since the primary experiments in this study are based on ascending samples, the descending results serve solely as supplementary validation and are not discussed in detail in the main text.

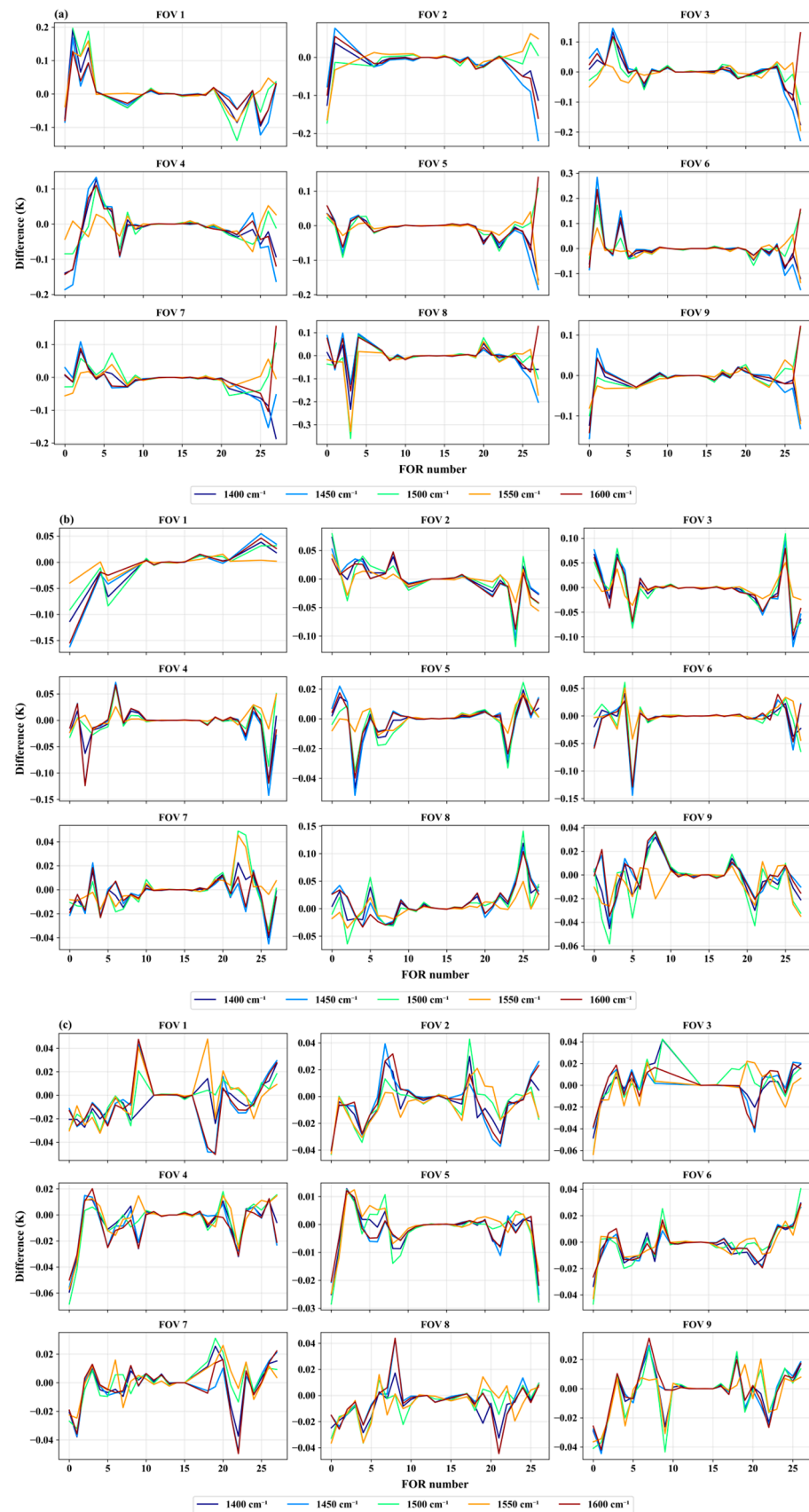


Figure 9. Distribution of the brightness temperature differences for individual FOVs, simulated by Methods Exp.1 and Exp.2, across the five FY-3E/HIRAS-II water vapor absorption channels as a function of scan angle, for three latitude zones: (a) 80~70°, (b) 50~40°, and (c) 20~10°.

3.5. Comparison Between Simulations of the Two Schemes and Satellite Observations

The aforementioned chapter mainly revealed the significant differences between the results obtained from the two simulation methods. This section will compare the simulation results of the two methods with the actual satellite-observed brightness temperatures. It is important to note that the satellite-observed brightness temperatures used here are all calculated based on the FY-3E/HIRAS-II Level-1 radiance data described in Section 2.1, after applying quality control and apodization processing. Using representative channel 51 in the CO₂ absorption band (Figure 10a) and channel 613 in the water vapor absorption band (Figure 10b), we analyze the O–B bias variations with FOR position for Exp. 1 and Exp. 2 across different FOVs, referenced against actual observed brightness temperatures.

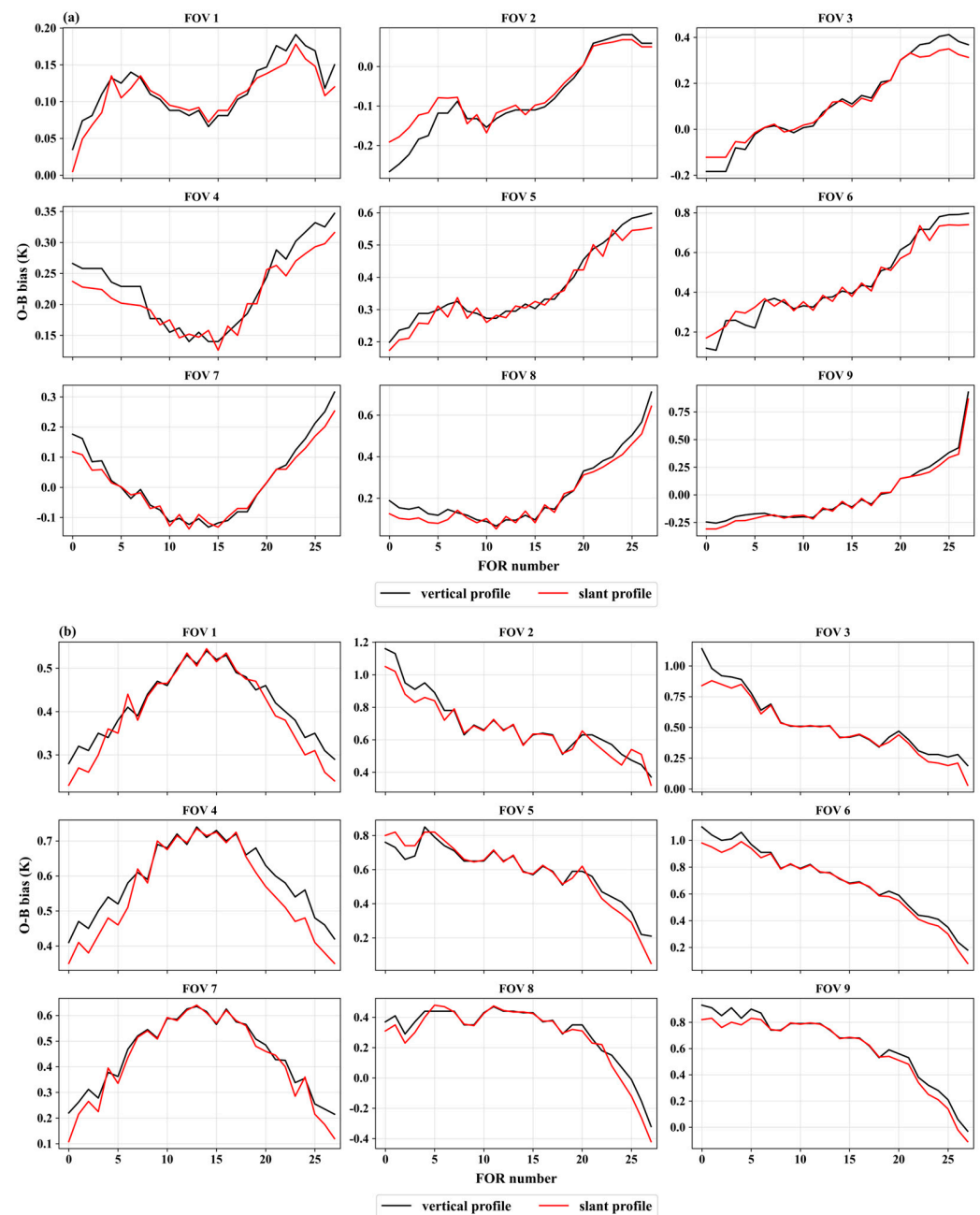


Figure 10. Distribution of O–B mean biases as a function of scan angle for nine FOVs of HIRAS-II across different channels: (a) Channel 51; (b) Channel 613.

Results indicate that the differences between the two experiments are negligible near the nadir. However, at the scan edges, Exp. 2 generally exhibits smaller O–B biases, suggesting an improvement in simulating off-nadir fields of view (FOVs). Furthermore, the O–B mean biases demonstrate a degree of symmetry in FOVs 1, 4, and 7, whereas a pronounced asymmetric distribution is observed in most other FOVs, particularly in FOVs 3, 6, and 9. For the CO₂ absorption channel 51, the maximum O–B difference between the two experiments occurs at the leftmost end of the FOV5 scan line, reaching approximately 0.07 K. Similarly, for the water vapor absorption channel 613, the maximum discrepancy is about 0.16 K.

Table 3 presents the statistical results of the average maximum deviations between two simulation schemes and actual satellite-observed brightness temperatures across ten representative channels in the scanning edge region. These results were obtained by aggregating and averaging the corresponding deviations from nine FOVs within the scanning edge area. From Table 3, it can be observed that channel 51 exhibits the largest mean bias in the CO₂ absorption band, while channel 613 shows the largest mean bias in the water vapor absorption band. Furthermore, we found that the Exp.2 scheme demonstrates superior simulation performance across all channels compared to Exp.1. These results fully demonstrate that the Exp.2 scheme is not only applicable to sounding channels with different characteristics, but also exhibits particularly significant improvements in the water vapor channel, as it more effectively captures the error characteristics induced by the spatial inhomogeneity of atmospheric parameters along complex paths.

Table 3. Statistical results of the maximum mean bias between the two simulation schemes and satellite-observed brightness temperatures across channels in the scan-edge region.

Experiment	Brightness Temperature (K)									
	Ch35	Ch51	Ch67	Ch83	Ch99	Ch373	Ch453	Ch533	Ch613	Ch693
Exp.1	0.38	0.33	0.33	0.32	0.28	0.77	0.82	0.78	0.7	0.73
Exp.2	0.36	0.3	0.31	0.31	0.27	0.7	0.76	0.73	0.6	0.65

4. Discussion

Fengyun-3E (FY-3E) is the world's first early-morning polar-orbiting meteorological satellite. Its onboard Hyperspectral Infrared Atmospheric Sounder-II (HIRAS-II) is a critical tool for atmospheric remote sensing, and the accurate processing of its observational data is essential for improving numerical weather prediction and climate research. This paper compares two simulation schemes with actual observed brightness temperatures and demonstrates that the Exp.2 scheme exhibits smaller simulation biases across all tested channels and zenith angle intervals. This represents a reasonable experimental design and yields a positive improvement. However, the present study has certain limitations that require further investigation in future work:

In this experiment, clear-sky samples over the global ocean were selected to investigate the effect of observation geometry by controlling for homogeneous surface conditions and excluding cloud effects. While this approach isolates key variables, it restricts the validation scenarios. In real operational applications, complex land surfaces and non-clear-sky conditions are involved, and atmospheric parameters exhibit greater horizontal inhomogeneity.

Furthermore, it is important to note that the maximum improvement in simulation bias observed in this experiment is approximately 0.1 K. While its absolute value is slightly lower than the calibration accuracy of the HIRAS-II instrument (about 0.3 K–0.5 K), this improvement holds clear significance in the context of radiative transfer applications. Under actual low-elevation-angle observation conditions, the atmospheric path length increases significantly, amplifying the uncertainties inherent in radiative transfer simulations.

Consequently, under such observation geometries, the simulation bias itself can reach or even exceed the instrument's noise level, becoming a key factor affecting data quality and application performance. From this perspective, even systematic improvements on the order of 0.1 K are noteworthy and essential for practical radiative transfer measurements and applications.

Future research efforts will primarily focus on the following directions: first, quantitatively assessing the relative importance of the “slant-path effect” over different underlying surfaces; second, developing a slant-path radiative transfer simulation scheme capable of coupling cloud scattering, aerosols, and complex land-surface radiative processes; and third, building upon this foundation to construct an “end-to-end” atmospheric correction and assimilation model applicable to all fields of view and all-weather conditions. This will fully unlock the application potential of FY-3E/HIRAS-II hyperspectral data in severe convection monitoring, regional climate analysis, and high-precision environmental parameter retrieval.

5. Conclusions

This paper addresses the issue of radiance simulation bias under large scan angles for the FY-3E/HIRAS-II instrument caused by horizontal inhomogeneity of atmospheric parameters. A novel oblique-path atmospheric parameter profile construction method (Exp.2) is proposed and implemented. This method accurately calculates the intersection points of the satellite line-of-sight with various height layers of the ERA5 reanalysis data and employs a hybrid interpolation algorithm combining inverse distance weighting and spline interpolation to obtain continuous atmospheric parameter distributions along the oblique path. To evaluate its effectiveness, a comparative experiment against the traditional vertically homogeneous profile approach (Exp.1) was designed and systematically validated using global oceanic clear-sky samples from July 2023.

The main conclusions of the study are as follows: First, the oblique-path atmospheric temperature and water vapor density profiles constructed using the new method show significant differences from the traditional vertical profiles, with the differences most pronounced at the edge of the scan line. Second, in terms of brightness temperature simulation, the differences between Exp.2 and Exp.1 exhibit strong spectral and zenith angle dependencies. In the CO₂ absorption band, the differences are mainly concentrated between −0.1 K and 0.1 K, while in the water vapor absorption band, the difference range expands to −0.5 K to 0.5 K. The simulation differences for all channels increase significantly when the satellite zenith angle exceeds 30°. Most importantly, comparison with actual satellite-observed brightness temperatures demonstrates that the Exp.2 method effectively reduces simulation biases in the edge scan regions. The average bias in water vapor absorption channels is reduced by up to approximately 0.1 K, outperforming the 0.03 K improvement observed in CO₂ absorption channels. Overall, the new method developed in this study, while maintaining the computational efficiency of the one-dimensional radiative transfer model framework, significantly enhances the accuracy and reliability of hyperspectral infrared radiative transfer forward simulations under complex observation geometries by inputting oblique-path atmospheric information that better aligns with three-dimensional physical reality. This improvement holds positive significance for enhancing the atmospheric correction of remote sensing data at large scan angles and the subsequent accuracy of atmospheric parameter retrieval, providing technical support for more effective utilization of edge-scan data.

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