Bias Analysis and Applicability of AIRS Brightness Temperature over Central Asia: Postprint

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Abstract

The Central Asian region is characterized by sparse conventional observation stations, necessitating the utilization of spaceborne hyperspectral AIRS data to determine the optimal initial conditions for numerical weather prediction in this area. Using AIRS radiance brightness temperature simulated from radiosonde input to CRTM as reference values, the bias in AIRS observed brightness temperature was analyzed, and the applicability of AIRS satellite data in the Central Asian numerical weather prediction operational system was evaluated. The results indicate: (1) The average of the maximum positive bias of brightness temperature over selected stations simulated by each channel is approximately 3.3 K, and the absolute value of the maximum negative bias is approximately 2.6 K. (2) The AIRS observed radiance brightness temperature averaged over multiple stations is overall slightly higher than the simulated brightness temperature, with its probability density distribution being closer to the normal distribution curve than that of individual stations. (3) Assimilation of AIRS improved the forecast performance of RMAPS-CA for upper-air elements such as geopotential height, temperature, and specific humidity, but did not improve the forecast of upper-air wind speed. For each element, the improvement from AIRS assimilation is greater in the lower levels than in the upper levels. After assimilation, the forecast RMSEs for geopotential height, temperature, specific humidity, and wind speed are less than 20 gpm, 2 K, 8$×$10-4 kg · kg-1, and 5 m · s-1, respectively.

Full Text

Bias Analysis and Applicability Evaluation of Atmospheric Infrared Sounder (AIRS) Radiance in Central Asia

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Abstract

Due to the scarcity of conventional observation stations in Central Asia, high-resolution satellite-borne atmospheric infrared sounder (AIRS) data are essential for analyzing optimal initial conditions for numerical weather prediction in this region. Using AIRS radiance simulated from radiosonde inputs in the Community Radiative Transfer Model (CRTM) as reference values, this study analyzes deviations in observed AIRS brightness temperature (BT) and evaluates the applicability of AIRS satellite data in the Central Asia numerical weather prediction operational system. The results indicate that: (1) The average maximum positive deviation of BT simulated over selected stations is approximately 3.3 K, while the absolute value of the maximum negative deviation is about 2.6 K. (2) The observed AIRS BT is slightly higher than the simulated BT overall, with its probability density distribution being closer to a normal distribution curve than that of individual stations. (3) Assimilation of AIRS data improves the forecast performance of the Rapid-Refresh Multiscale Analysis and Prediction System for Central Asia (RMAPS-CA) for upper-air elements including geopotential height, temperature, and specific humidity, but does not improve wind speed forecasts. For each element, the assimilation improvement is greater in the lower levels than in the upper levels. After assimilation, the root mean square errors of geopotential height, temperature, specific humidity, and wind speed are less than 20 gpm, 2 K, 8×10^{-4} $kg \cdot kg^{-1}$, and 5 $m \cdot s^{-1}$, respectively.

Keywords: AIRS; Central Asia; radiative brightness temperature; bias analysis; applicability

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1. Data and Methods

1.1 Data Sources The AIRS radiance data used in this study are Level 1 products obtained from the global data assimilation system, available as binary format files at 00 UTC, 06 UTC, 12 UTC, and 18 UTC cycles via ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/. Each file represents a mosaic of data from ±3 hours around the nominal observation time. In routine numerical weather prediction assimilation, 281 radiance channels are commonly used; therefore, this bias analysis and applicability evaluation focuses exclusively on these channels.

Radiosonde observations from July 2016 are utilized, with observations conducted twice daily at 07:15 and 19:15 Beijing Time. The global background field driving the regional numerical prediction model is the Global Forecast System (GFS).

1.2 Methodology The Community Radiative Transfer Model (CRTM), developed by the Joint Center for Satellite Data Assimilation (JCSDA), is employed for radiative transfer simulations. Specifically designed for satellite data assimilation, CRTM exhibits strong computational capability for simulating satellite observations under cloudy and rainy conditions. The model comprises four primary modules: a forward module, a tangent-linear module, an adjoint module, and a K-matrix module. Key functional components include surface emission and reflection models, aerosol absorption and reflection models, cloud absorption and scattering models, gas absorption models, and radiative transfer equation solvers.

In this study, CRTM is used to simulate BT for the research domain and period. Surface type and cloud fraction parameters required for the simulations are obtained from Weather Research and Forecasting (WRF) model forecasts. Radiosonde data are processed into 101-level profiles of temperature, pressure, and other elements in CRTM' s LOAD_{ATM}.in format and input into CRTM to simulate AIRS infrared BT, which serves as the reference "truth"for analyzing biases against observed BT.

The study domain corresponds to the mother grid coverage of RMAPS-CA (Regional Mesoscale Prediction System in Central Asia). The WRF model is configured with a single-layer grid scheme [Figure 1: see original paper], with numerical simulation schemes detailed in Table 1 . Since the GFS forecast field used as the background has already assimilated conventional observations, the control experiment (CTRL) is designed without any AIRS data assimilation, while the sensitivity experiment (AIRS) includes AIRS radiance assimilation.

2. AIRS Brightness Temperature Bias Analysis

To analyze AIRS BT biases in Central Asia, the spatial distribution of observations must first be characterized. AIRS radiance observations from 00 UTC, 06 UTC, 12 UTC, and 18 UTC cycles are stratified by pressure layers (Table 2). Most BT observations over China occur at pressures greater than 700 hPa. Lower-level BT observations are subject to significant deviations from simulated radiosonde BT due to influences from surface radiation and topography.

Within the $±$3-hour time windows, the majority of observations are concentrated in western Central Asia. The spatial distribution reveals that AIRS_{AQUA} observations are sparsely distributed in the western and northern regions of China, predominantly comprising high-level BT observations above 50 hPa. At 00 UTC $\pm$ 3 h, the western scanning band covers most of Xinjiang, Gansu, and the Tibetan Plateau, while the eastern band shifts eastward by approximately 20 degrees of longitude. At 06 UTC $\pm$ 3 h, the western scanning band passes over most of Xinjiang and Tibet, while the eastern band extends from Inner Mongolia and Gansu to central China [Figure 2: see original paper].

Based on this spatial distribution, sounding stations within scanning bands covering western China during the 00 UTC ± 3 h and 06 UTC ± 3 h windows are selected as representative sites (Table 3). Stations within $±$0.2° of the sounding sites are selected, based on the shortest distance and smallest observation time interval, for BT comparison and bias analysis. The analysis focuses on 137 channels commonly used in operational NWP assimilation modules.

Monthly mean BT biases for each of the 10 selected stations during July 2016 (the duration of the intensive observation experiment at Tazhong station) are presented in Figure 3 [Figure 3: see original paper]. The number of simulated BT profiles varies by station but is consistently less than expected. At Tacheng and Karamay stations, the observed AIRS BT is overall slightly higher than the CRTM-simulated BT, with probability density curves exhibiting good symmetry. The standard deviation of simulated AIRS BT bias probability density ranges from 0.03 to 0.33 K, with Minfeng and Aksu stations showing the smallest values.

The monthly mean positive bias is approximately 1.74 K. Stations at Yining, Kuqa, Hotan, and Tazhong exhibit bias probability densities closer to normal distribution, while Altay, Aksu, and Korla show the greatest deviation from normal distribution. Compared with individual stations, the average bias probability density across multiple sounding stations is more closely aligned with a normal distribution curve, with a baseline value y_0 3.44, peak value a 0.33, and mean value b 1.74, indicating that the multi-station average observed BT is slightly higher than simulated BT with a monthly mean positive bias of 1.74 K and standard deviation c 0.33 K [Figure 5: see original paper].

3. Applicability Evaluation

Based on the bias analysis results, although most channels show biases within $±$2 K with probability densities approaching normal distribution, some channels exhibit relatively large monthly mean biases. To further evaluate the applicability of AIRS radiance data in Central Asia, a set of AIRS radiance assimilation sensitivity experiments is designed. Building upon the control experiment (CTRL) without data assimilation, an AIRS infrared radiance assimilation experiment (AIRS) is conducted.

Given the spatial distribution characteristics of AIRS observations, the assimilation impact is evaluated by quantitatively analyzing forecast accuracy for upper-air elements (geopotential height, temperature, specific humidity) against sounding observations using bias and root mean square error (RMSE). Comparisons are made at the model integration initial time (00 UTC), 12-hour forecast (12 UTC), and 24-hour forecast (24 UTC) times.

3.1 Geopotential Height Forecast In the CTRL experiment, geopotential height forecasts are overall positive at 00 UTC, reaching maximum values in the lower troposphere below 850 hPa. The AIRS experiment significantly reduces these positive biases, particularly in the lower levels, with absolute reductions exceeding 120 gpm below 850 hPa. In the upper troposphere above 200 hPa, biases are negative and relatively constant with height. At 12 UTC, CTRL forecasts are negative throughout most levels, while the AIRS experiment reduces absolute bias values to within 20 gpm, except near 100 hPa where small positive biases remain. At 24 UTC, CTRL forecasts are again negative with minimal vertical variation, and AIRS assimilation yields neutral to slightly positive effects, with the most significant improvements in the mid-troposphere around 500 hPa [Figure 6: see original paper].

3.2 Temperature Forecast Temperature forecast biases in the CTRL experiment are positive at 00 UTC, with the AIRS experiment showing smaller biases at all levels. At 12 UTC, CTRL biases are negative, while AIRS assimilation warms the troposphere above 300 hPa and cools the lower levels, with maximum adjustment amplitude near 850 hPa. After assimilation, absolute temperature bias and RMSE are reduced across all levels, with the most significant improvements in the lower troposphere [Figure 7: see original paper].

3.3 Specific Humidity Forecast Specific humidity, defined as the ratio of water vapor mass to total air mass in a moist air parcel, shows consistent improvement across all forecast times after AIRS assimilation. Since the most significant forecast errors occur below 300 hPa, the analysis focuses on this layer. Compared with CTRL, the AIRS experiment exhibits smaller biases throughout the lower troposphere, indicating positive assimilation effects. Post-assimilation specific humidity RMSE is reduced to less than 8$\times10^{-4}$ kg · kg^{-1} at all levels, with the largest adjustments in the lower troposphere below 850 hPa.

3.4 Wind Speed Forecast In contrast to other variables, AIRS assimilation does not produce significant positive effects on upper-air wind speed forecasts across all forecast times. While the largest wind speed adjustments occur in the lower troposphere below 850 hPa, no substantial forecast improvement is observed.

4. Conclusions and Discussion

This study analyzes the bias distribution characteristics of AIRS satellite observations and evaluates assimilation effectiveness, yielding the following conclusions:

1. The average maximum positive deviation of simulated BT over selected sounding stations is approximately 3.3 K, with the absolute value of maximum negative deviation about 2.6 K. The observed AIRS BT is slightly

higher than simulated BT overall, with multi-station average bias probability density closely approximating a normal distribution (monthly mean positive bias 1.74 K, standard deviation 0.33 K).

2. AIRS assimilation improves RMAPS-CA forecast accuracy for geopotential height, temperature, and specific humidity, but does not improve upper-air wind speed forecasts. Improvement magnitude is greater in lower levels than upper levels, with post-assimilation RMSEs reduced to less than 20 gpm, 2 K, 8×10^{-4} kg·kg^{-1}, and 5 m·s^{-1} for geopotential height, temperature, specific humidity, and wind speed, respectively.

It should be noted that due to the limited duration of the intensive sounding experiment, this study only selected July 2016 as the research period for bias analysis. Given Central Asia' s sparse vegetation cover, surface radiation is substantial in summer but relatively small in winter over snow-free areas. Therefore, the bias analysis conclusions may not be applicable to other seasons. Additionally, considering operational implementation potential, this evaluation employed the RMAPS-CA system with three-dimensional variational data assimilation (3DVAR). Adoption of more advanced four-dimensional variational assimilation (4DVAR) methods may yield further improvements.

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Note: Figure translations are in progress. See original paper for figures.