Applicability Study of FY-4A Satellite for Short-duration Heavy Precipitation in Ningxia (Postprint)

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Abstract

By collecting cases of short-duration heavy rainfall in Ningxia from 2018 to 2020 and their corresponding FY-4A satellite data, five FY-4A satellite products were selected for usability analysis: cloud type CLT, cloud phase CLP, cloud top height CTH, tropopause folding deepest depth TFTP_Z_{depth}, and quantitative precipitation estimation QPE. The results show that: (1) The data reception rate and physical preservation status of FY-4A are sufficient to support real-time monitoring and early warning operations; (2) The five products exhibit different performances in short-duration heavy rainfall cases in Ningxia, among which CLT and CLP demonstrate good usability and can effectively determine cloud categories; whereas both CTH and QPE have significant errors with a systematic underestimation trend, requiring correction through other means; CTT and TFTP_Z_{depth} show relatively clear correspondence with short-duration heavy rainfall, while high CTH values are conducive to heavy rainfall occurrence, they are not a necessary condition for it. Overall, FY-4A satellite data possess certain usability and reference value for short-duration heavy rainfall events in Ningxia, and can provide good data support for convective weather identification and weather modification operations.

Full Text

Applicability Study of FY-4A Satellite in Short-term Heavy Precipitation Events in Ningxia

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Abstract

By collecting short-term heavy precipitation cases in Ningxia from 2018 to 2020 and their corresponding FY-4A satellite data, this study examines the applicability of five satellite products: Cloud Type (CLT), Cloud Phase (CLP), Cloud Top Height (CTH), Quantitative Precipitation Estimation (QPE), and Tropopause Folding Depth (TFTP_Z_{depth}). The results demonstrate that: (1) The data reception rate and physical preservation status of FY-4A products are sufficient to support real-time monitoring and early warning operations; (2) CLT and CLP exhibit good availability and can effectively determine cloud categories; (3) Both CTH and QPE show significant errors with systematic underestimation trends, requiring correction through additional methods; (4) CTT and TFTP_Z_{depth} demonstrate clear correspondence with short-term heavy precipitation, where high values are conducive to but not necessary for heavy rainfall occurrence. Overall, FY-4A satellite products possess certain usability and reference value for convective weather identification and weather modification operations in Ningxia.

Keywords: FY-4A satellite; short-term heavy precipitation; applicability analysis; statistical analysis; Ningxia

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1. Data and Methodology

1.1 Data Sources

1.1.1 FY-4A Satellite Data The FY-4A satellite, launched on December 11, 2016, is the first satellite of China's second-generation geostationary quantitative remote sensing meteorological satellite series and represents one of the world' s most advanced new-generation stationary meteorological satellites. Equipped with a multi-channel scanning imaging radiometer, lightning imager, interferometric atmospheric vertical sounder, and space weather monitor, FY-4A provides 14 classes of quantitative products. This study focuses on applicability analysis of products derived from multi-channel scanning imaging radiometer observations, including Cloud Type (CLT), Cloud Phase (CLP), Cloud Top Height (CTH), Quantitative Precipitation Estimation (QPE), and Tropopause Folding Depth (TFTP_Z_{depth}). The data format is MICAPS, with a temporal coverage from 00:00 to 23:00 during 2018–2020.

1.1.2 Comparative Data Cloud characteristic observations: Artificial cloud observation data and sounding data from Yinchuan National Reference Climatological Station were selected. Artificial cloud observations are reported every three hours, while sounding data are available at 08:00 and 20:00 daily.

Automatic weather station data: Hourly rainfall data from automatic stations were used to calculate cumulative precipitation corresponding to satellite product periods. Cases with hourly precipitation $ 10$mm \cdot h^{-1}$ were selected for analysis. The 1-minute data were accumulated to obtain 15-minute and hourly precipitation amounts for error analysis.

Data window setting: To facilitate more efficient data processing, redundant data elimination, and analysis, two types of data windows were established: an impact area (95°–115°E, 30°–50°N) covering the central-eastern Northwest China region, and a key area (102°–110°E, 33°–40°N) encompassing Ningxia and its upstream/downstream regions [Figure 1: see original paper].

1.2 Data Reception Rate

FY-4A data products are primarily acquired through three channels: the National Comprehensive Meteorological Information Sharing System (CIMISS), the China Meteorological Administration satellite data broadcast system, and ground receiving stations. The first two channels provide "post-processed" gridded data (retained for six months) or HDF format data (retained for six months), while ground stations receive MICAPS format data (retained for three months), satisfying requirements for real-time warning monitoring and short-term retrospective analysis.

Statistical analysis of multi-channel scanning imaging radiometer channel data reception rates shows that the average reception rate for 10 channels is 94%–99%, with a minimum of 84%–93%. For the five selected products, the average reception rate is 83%–95%, with a minimum of 64%–80% [Figure 2: see original paper]. These transmission rates fully meet the operational needs for monitoring and early warning of severe convective weather in Ningxia.

1.3 Product Selection Principles

The following principles guided product selection:

1. **Relevance to heavy precipitation:** Products directly describing cloud characteristics were prioritized, including cloud type, cloud base height, cloud thickness, cloud top height, cloud category, cloud top temperature (brightness temperature), and cloud structure parameters.
2. **Observational availability:** Products with directly accessible artificial observation data or computable parameters were selected, such as cloud type, cloud top height, and precipitation estimation. Yinchuan Station is one of the few stations in China that maintains artificial cloud observations, enabling comparative analysis.

3. **Temporal coincidence:** Cases where short-term heavy precipitation occurrence/duration overlapped with Yinchuan sounding observation periods were selected for CTH validation, ensuring at least partial coverage of balloon sounding time.

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2. Applicability Analysis

2.1 Cloud Type (CLT) and Cloud Phase (CLP)

Analysis of short-term heavy precipitation events in Yinchuan from 2018–2020 reveals that CLT data primarily indicate warm-cold mixed clouds (54.6% of observations), warm water clouds (24.46%), and supercooled water clouds (14.11%), with other cloud types showing lower proportions . Corresponding CLP analysis shows that mixed-phase and liquid-phase clouds account for 86.02% and 6.96% of cases, respectively, while ice-phase clouds represent only 7.99%. Notably, 11.09% of cases were classified as cloud-free, likely attributable to interpolation methods and temporal discrepancies.

These results demonstrate that CLT and CLP products exhibit good availability for cloud category determination. Short-term heavy precipitation in Ningxia is primarily associated with liquid-phase clouds (warm-cold mixed clouds, warm water clouds, and supercooled water clouds), with minimal ice-phase cloud presence.

2.2 Cloud Top Height (CTH)

CTH validation employed an empirical approach combining artificial observation of cloud base height ranges with relative humidity and dew-point methods for cloud thickness estimation. The formula for estimated cloud top height is:

$$H_{top} = H_b + H_t$$

where H_b represents cloud base height and H_t represents cloud thickness.

2.2.1 Cloud Base Height Ranges from Artificial Observations In Ningxia, low and middle clouds typically have base heights of 600–2000 m, while high clouds range from 2500–4500 m. Precipitation-producing clouds mainly include cumulonimbus, stratocumulus, nimbostratus, and altostratus, with base heights varying from approximately 600 m (cumulonimbus, stratocumulus, nimbostratus) to 2500 m (altostratus) .

2.2.2 Cloud Height Estimation and Comparison Using Yinchuan sounding data and the relative humidity-dew point method, cloud thickness was estimated through the formula:

$$RH = \frac{e}{e_s} \times 100\%$$

where RH is relative humidity, e is actual vapor pressure, and e_s is saturation vapor pressure. Simplified thresholds indicate that $RH \geq 87\%$ generally identifies cloud regions.

Comparison between CTH observations and sounding estimates for 2018–2020 short-term heavy precipitation events shows that observed minimum, maximum, and mean values average 2355 m, 8905 m, and 6894 m, respectively. Relative errors compared to sounding estimates are -6834 m, -284 m, and -3183 m, with absolute errors of 665 m, 3224 m, and 665 m . Given the top-down observation characteristic of satellite remote sensing, maximum values are most relevant for comparison. The results indicate that FY-4A CTH observations tend to underestimate cloud height (relative error < 0), with an average error of 665 m. However, the error range spans 665–6894 m, indicating relatively low stability.

Analysis of absolute error statistics shows that for observed minimum values, errors exceeding 3000 m account for 53.45%, while mean absolute errors exceed 2000 m. In contrast, errors relative to maximum observed values are more reasonable: 75.86% of cases show errors <1000 m, with 22.41% and 24.14% in the 500–1000 m and 1000–2000 m ranges, respectively . For convective clouds reaching tens of thousands of meters, errors within 1000 m are considered acceptable. Therefore, using maximum values for CTH validation is more appropriate. FY-4A CTH products demonstrate certain usability and reference value for short-term heavy precipitation in Ningxia but require correction through additional methods in operational applications.

2.3 Quantitative Precipitation Estimation (QPE)

Error comparison between 15-minute QPE products and automatic station observations for 106 short-term heavy precipitation events in 2020 reveals that QPE shows systematic underestimation. The maximum relative deviation is 2.45 mm, minimum is -76.2 mm, and average is -25.27 mm, corresponding to relative errors of 99.28%, 98.77%, and 30.19%, respectively . Absolute errors range from 0.11 mm to 16.79 mm, with a mean of 0.88 mm. Using the criterion of absolute error \$ \$4.12 mm, only 7.55% of products meet the usability standard, while 11.32% meet the \$ \$15 mm standard. Overall, FY-4A QPE products are significantly smaller than observations, though this systematic bias may be addressed through statistical correction methods.

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3. Continuity Characteristics Analysis

To analyze correlation and continuity features, Cloud Top Temperature (CTT), Cloud Top Height (CTH), and Tropopause Folding Depth (TFTP_Z_{depth}) were compared with corresponding precipitation amounts from short-term heavy precipitation cases.

3.1 Cloud Top Temperature (CTT)

From a total sample of 106 cases, 87 qualified samples were selected after standardization. According to cloud physics, ice crystal clouds or mixed-phase clouds with large optical thickness have effective emission temperatures approximating actual cloud top temperature, while warm water clouds show greater differences. Cloud top temperature typically ranges from -80°C to 30°C, with Northwest China convective clouds generally $ $10°C.

Analysis reveals a significant negative correlation between CTT and precipitation (correlation coefficient = -0.64). The standardized sequence interval is -0.64 to 0.88 (original range: 162.13–285.15 K), with minimum temperatures reaching -111.02°C [Figure 3: see original paper]. This indicates that lower CTT values favor heavy precipitation occurrence.

3.2 Cloud Top Height (CTH)

From 106 total samples, 87 qualified samples were analyzed. Nimbostratus clouds typically have bases at 600–2000 m and tops at 600–4500 m, with thickness generally exceeding 300 m. Therefore, 1000 m was set as the minimum CTH threshold.

The original CTH sequence spans 1000.6–15656.6 m, with extreme values exceeding 14600 m. After standardization, the range remains large at -0.1 to 1.0, showing weak correlation with precipitation (correlation coefficient <0.1) [Figure 4: see original paper]. This demonstrates that CTH has no direct correlation with precipitation intensity; while high cloud tops facilitate heavy precipitation, they are not a sufficient condition.

3.3 Tropopause Folding Depth (TFTP_Z_{depth})

TFTP_Z_{depth}, a physical quantity characterizing tropopause folding depth rarely used in operational practice, shows clear positive correlation with precipitation (correlation coefficient = 0.38). The original sequence ranges from 0.01–14.38 km, with standardized values of -0.51 to 0.49 and relatively small intersample differences [Figure 5: see original paper]. The consistent trend between TFTP_Z_{depth} and precipitation curves indicates good applicability of this product in Ningxia.

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4. Conclusions

1. **Data availability:** FY-4A satellite data reception and physical preservation status are adequate to support real-time monitoring and early warning

operations for short-term heavy precipitation in Ningxia.

2. **Product performance:** Among the five analyzed products, CLT and CLP demonstrate good availability for cloud category determination. Short-term heavy precipitation in Ningxia is primarily associated with liquid-phase clouds (warm-cold mixed clouds, warm water clouds, and supercooled water clouds), with minimal ice-phase cloud presence.

3. **Error characteristics:** Both CTH and QPE exhibit significant systematic underestimation errors. CTH shows an average bias of approximately 665 m compared to sounding estimates and artificial observations, with error spans exceeding 6000 m and relatively low stability. QPE is substantially lower than observations, with only about 7.55% of products meeting usability standards, though statistical correction methods may improve applicability.

4. **Correlation analysis:** CTT and TFTP_Z_{depth} show clear relationships with short-term heavy precipitation, exhibiting significant negative and positive correlations, respectively. CTH demonstrates no direct correlation with precipitation intensity; high cloud tops favor but do not guarantee heavy precipitation.

Overall, FY-4A satellite products possess certain usability and reference value for convective weather identification and weather modification operations in Ningxia, providing valuable data support for operational meteorological services.

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