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An Integrated Direct Broadcast Satellite Data Platform for Real-Time Management, Visualization, and Applications of CSPP-Derived Products

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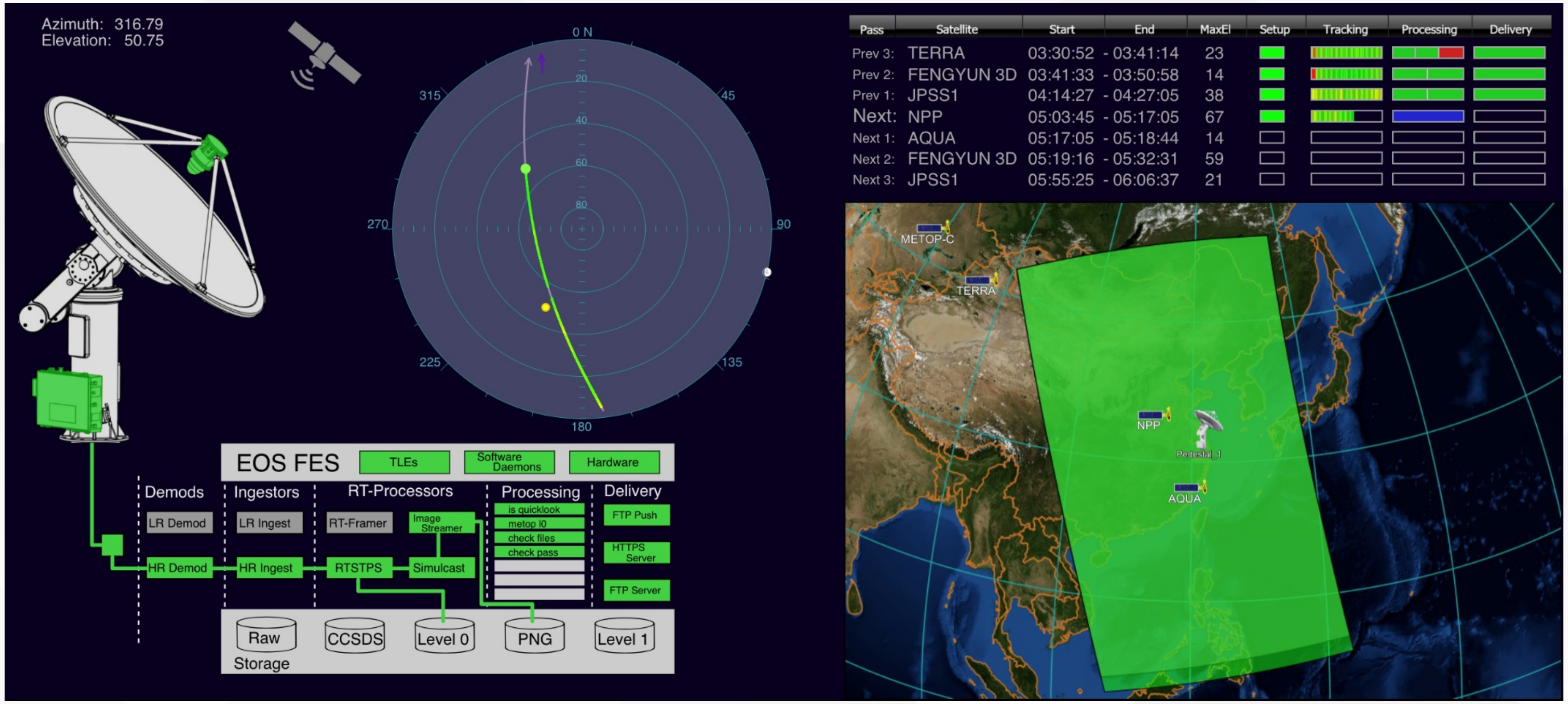
Outline

PART 1

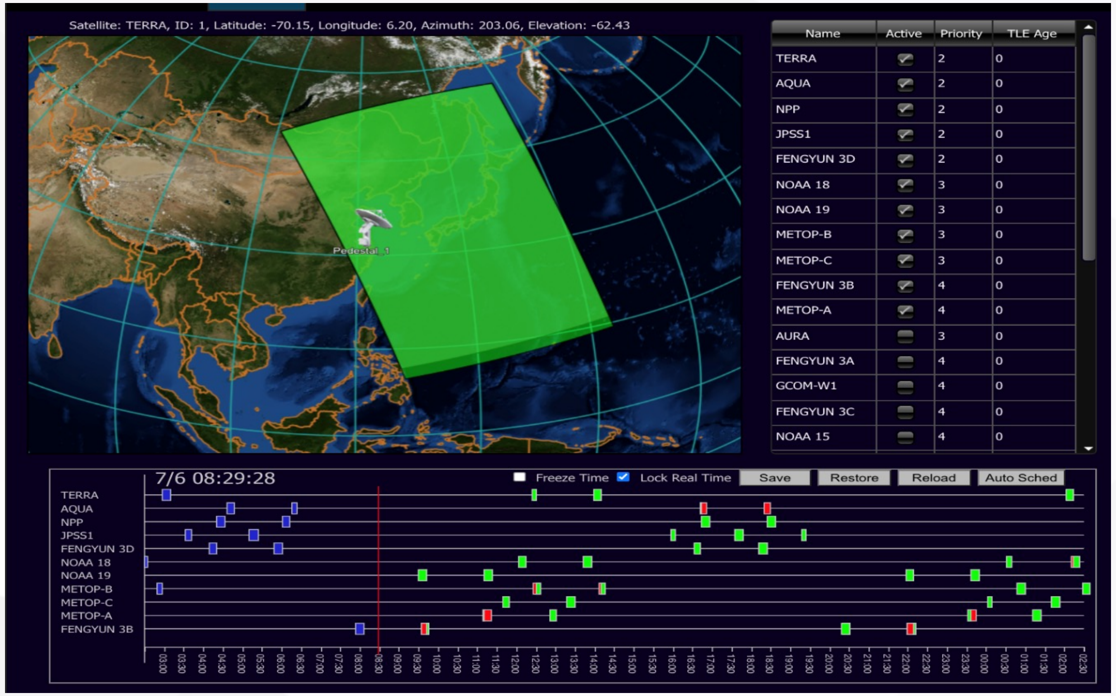
Direct Broadcast & CSPP Real-Time Processing System

Real-Time Direct Broadcast Satellite Observation System



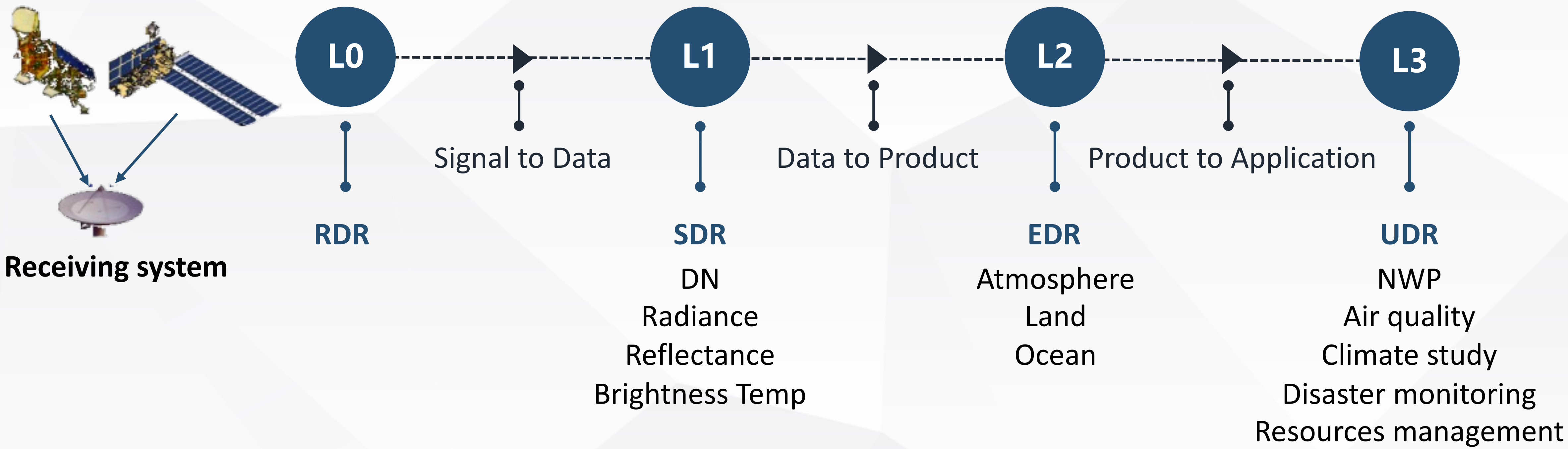
- An X/L-band direct broadcast reception system jointly established by ECNU and UW-Madison in 2010
- Supports near-real-time reception of multiple polar-orbiting satellite systems, including the JPSS series from NOAA, the Metop satellites from EUMETSAT, and China's FY-series satellites
- Provides continuous multi-sensor observations over East Asia and the Western Pacific

Automated Satellite Tracking and Reception Scheduling



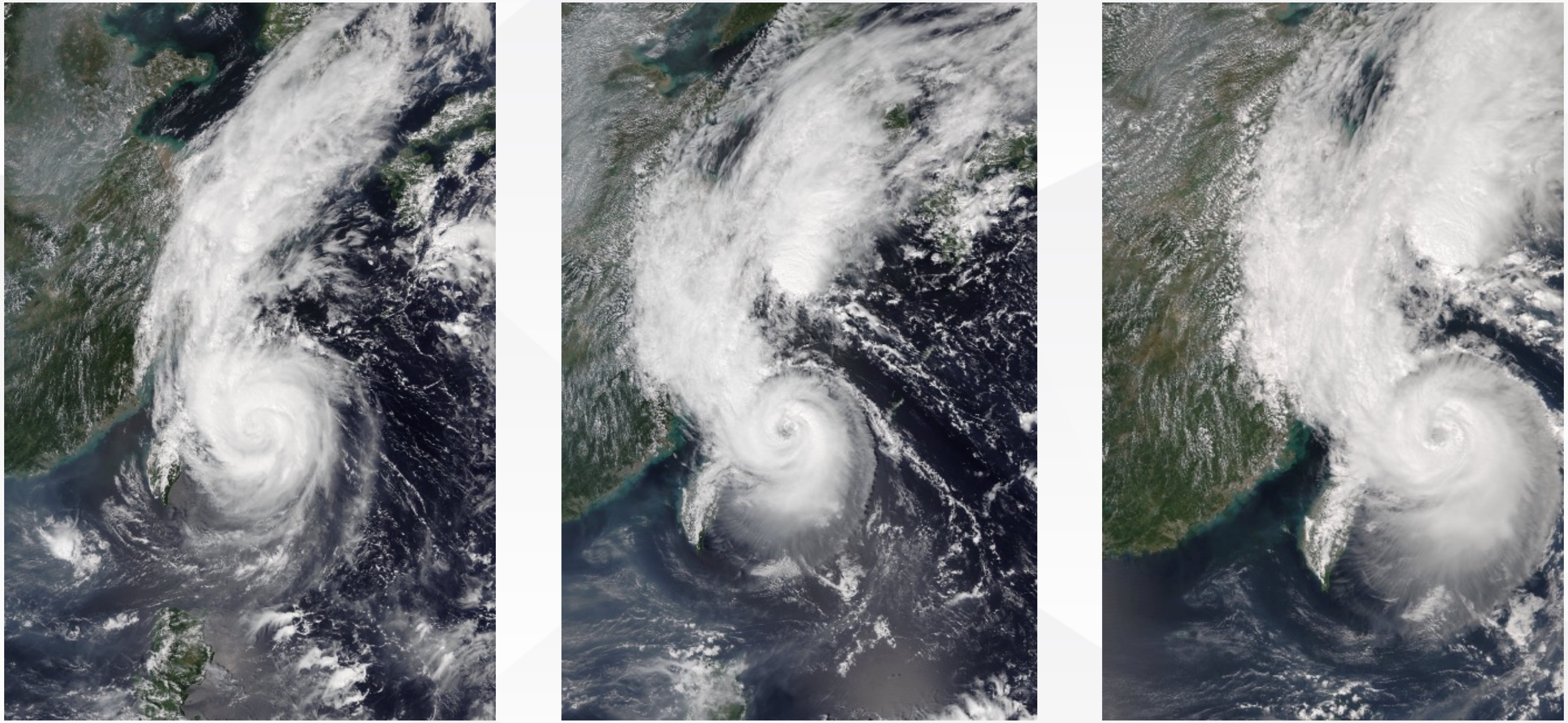
- To support operational applications, the system includes an automated satellite tracking and scheduling framework.
- During simultaneous satellite overpasses, the system performs priority-based reception control to optimize antenna usage and data acquisition efficiency.
- The platform also provides real-time visualization of orbital tracks, overpass timing, and spatial coverage, enabling continuous monitoring of the reception status.

End-to-End Processing Framework for CSPP-Derived Products



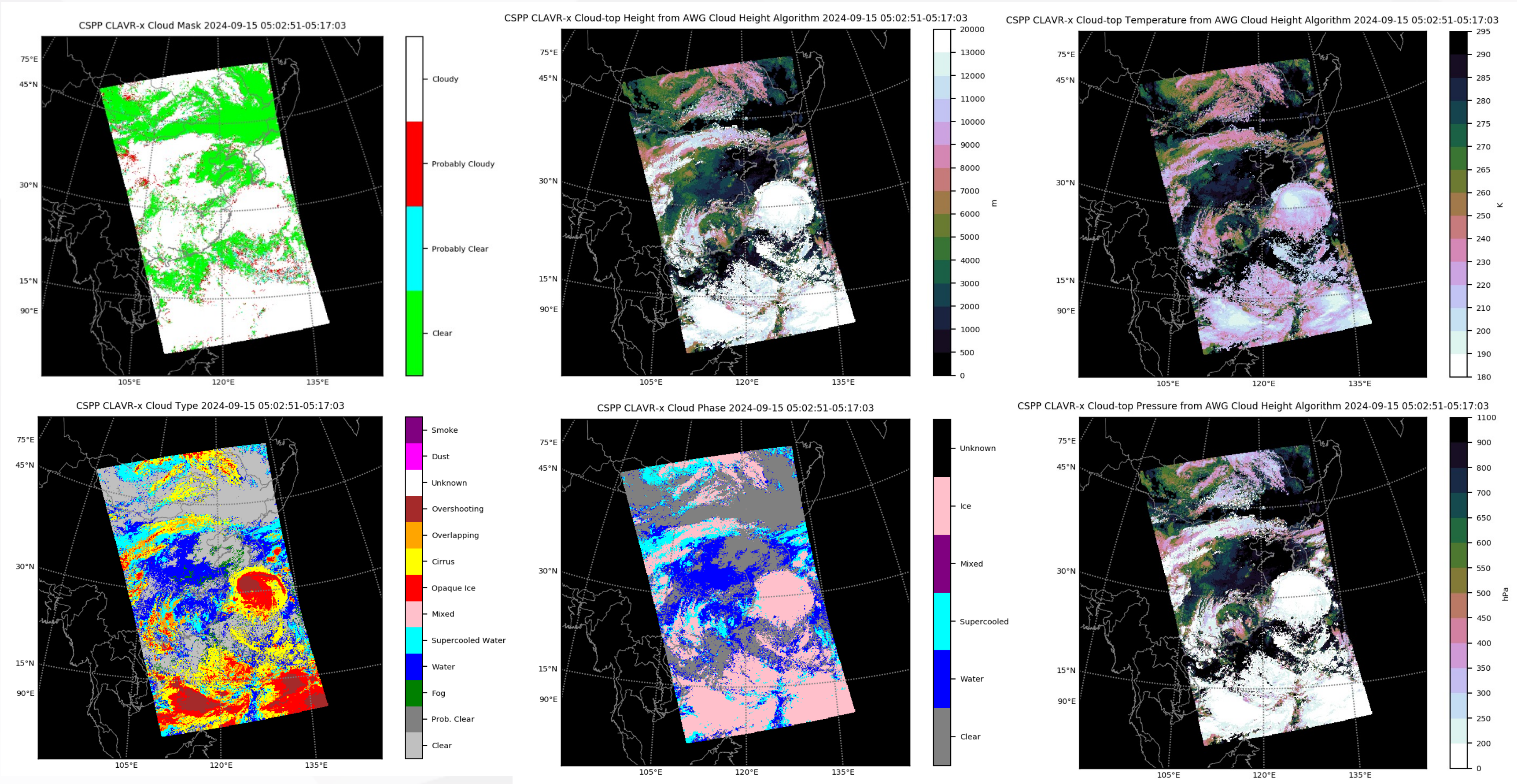
- After satellite reception, the raw direct broadcast signals are processed through the CSPP pipeline to generate multiple levels of satellite products.
- The workflow starts from RDR, which are converted into SDR, including calibrated radiance, reflectance, and brightness temperature observations. These SDRs are then further processed into EDR, including atmospheric, land surface, and oceanic retrieval products.
- Finally, these products support downstream applications such as NWP, air quality forecasting, …

High-Resolution True-Color Satellite Imagery



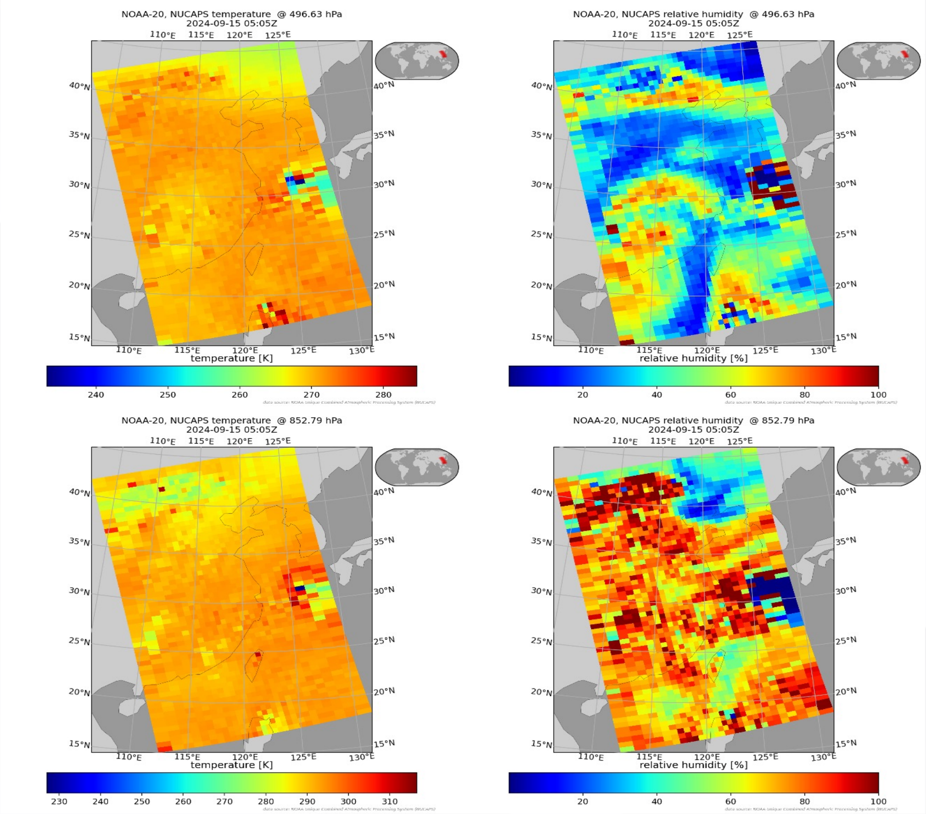
- Near-real-time true-color imagery from VIIRS observations
- Intuitive visualization of typhoon structure, cloud organization, and environmental conditions
- Supports rapid situational awareness and disaster response

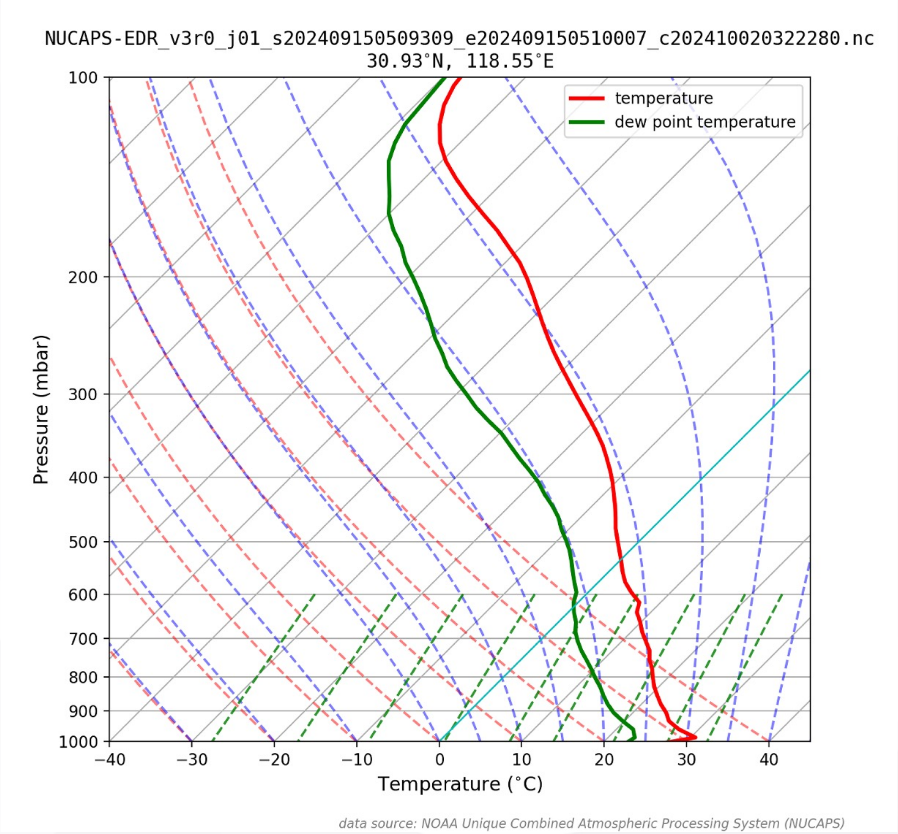
Cloud Property Retrieval Products from CSPP CLAVR-x



- Cloud mask, cloud-top height/temperature, cloud phase, and cloud type products
- Supports cloud classification and cloud microphysical analysis
- Important for severe weather monitoring and radiative studies

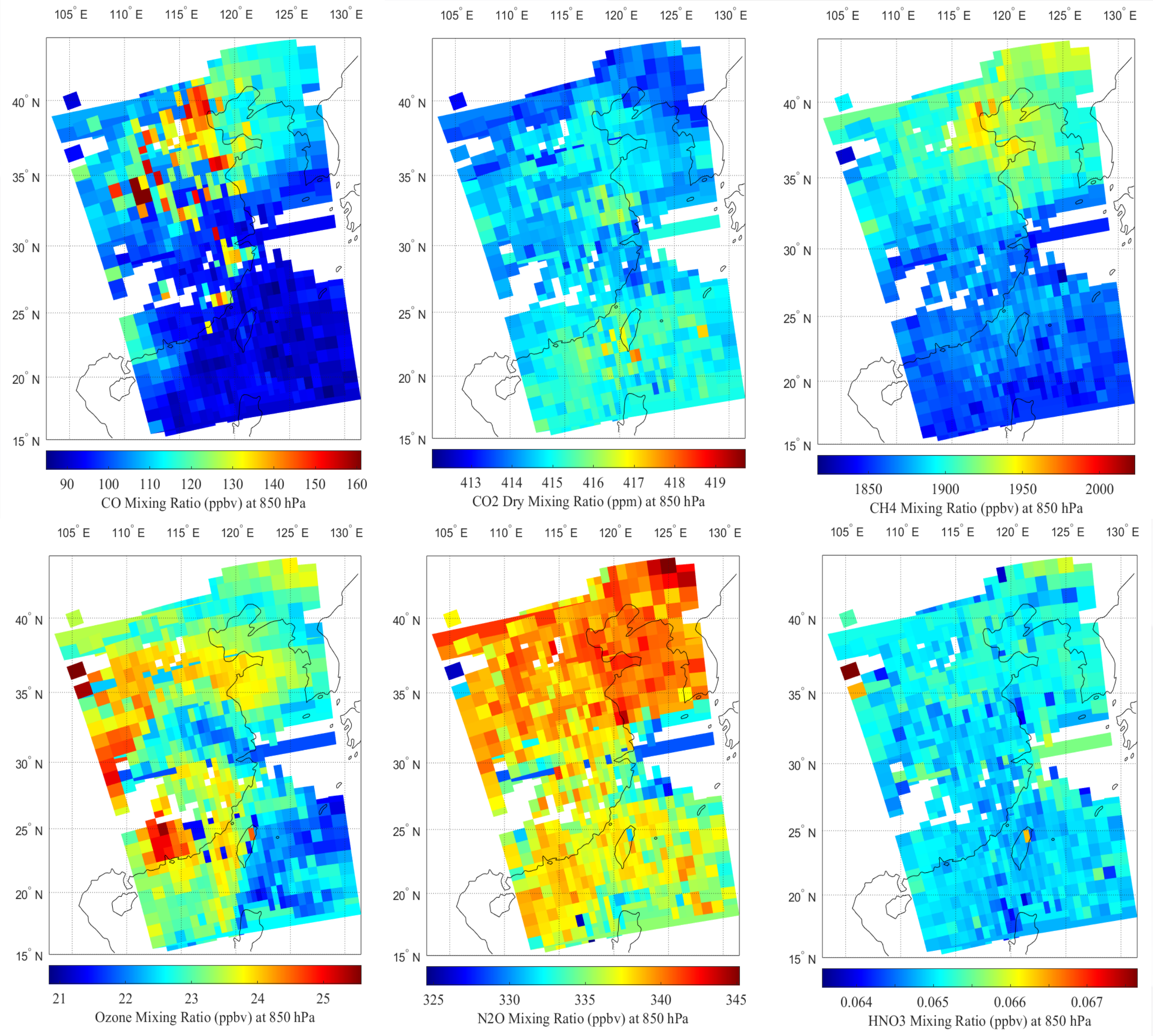
Atmospheric Thermodynamic Profile Retrievals from NUCAPS





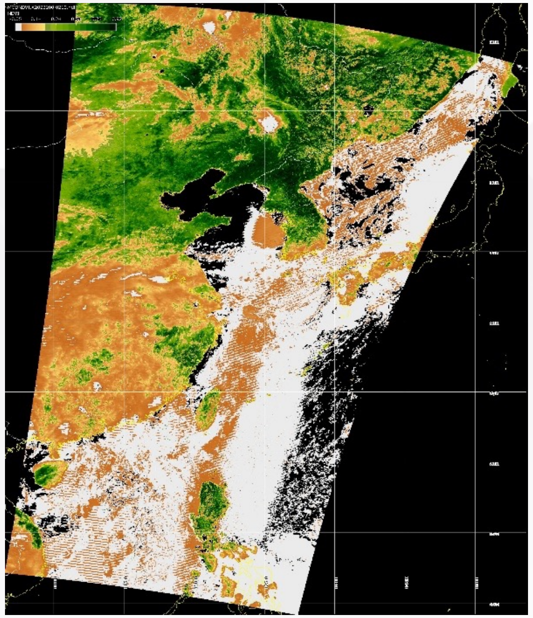
- In addition to 2D satellite products, the platform also supports visualization of atmospheric profile retrievals from NUCAPS.
- These products are generated from combined CrIS and ATMS observations and include temperature and moisture profiles throughout the troposphere.
- The platform supports both horizontal distribution analysis and vertical sounding visualization, enabling rapid assessment of atmospheric thermodynamic structure and stability conditions.

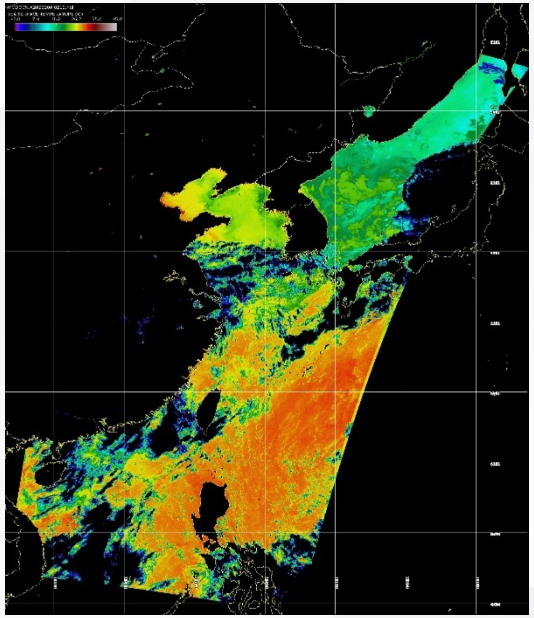
Atmospheric Trace Gas Retrieval Products

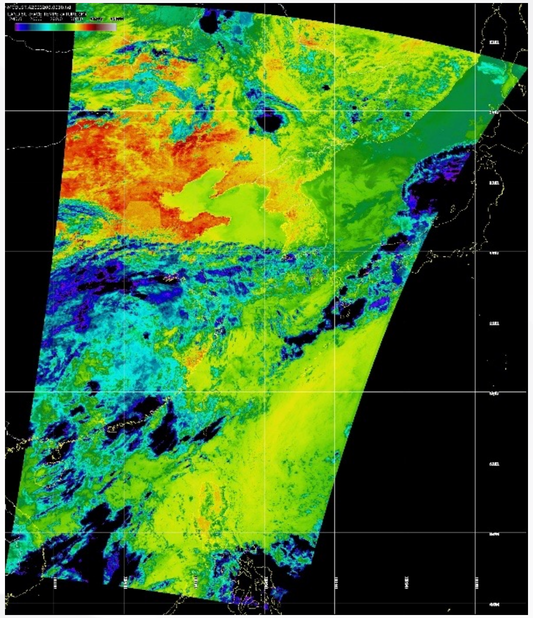


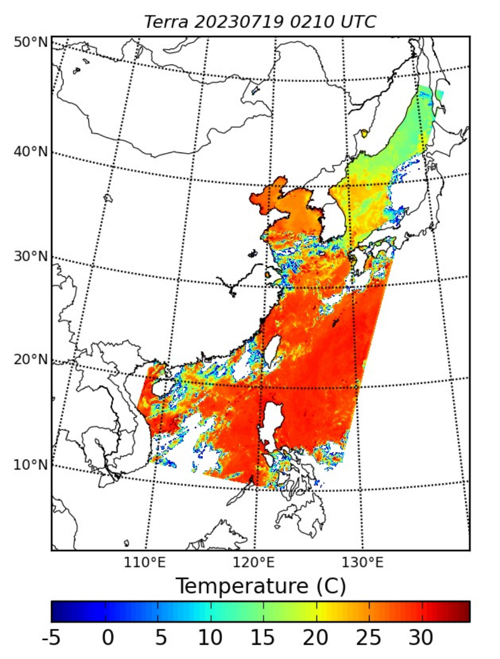
- Supports atmospheric trace gas retrieval products, including carbon monoxide, carbon dioxide, methane, ozone, and several other atmospheric constituents.
- Provides important information for air quality monitoring, atmospheric chemistry studies, and greenhouse gas applications.

Land and Ocean Environmental Products



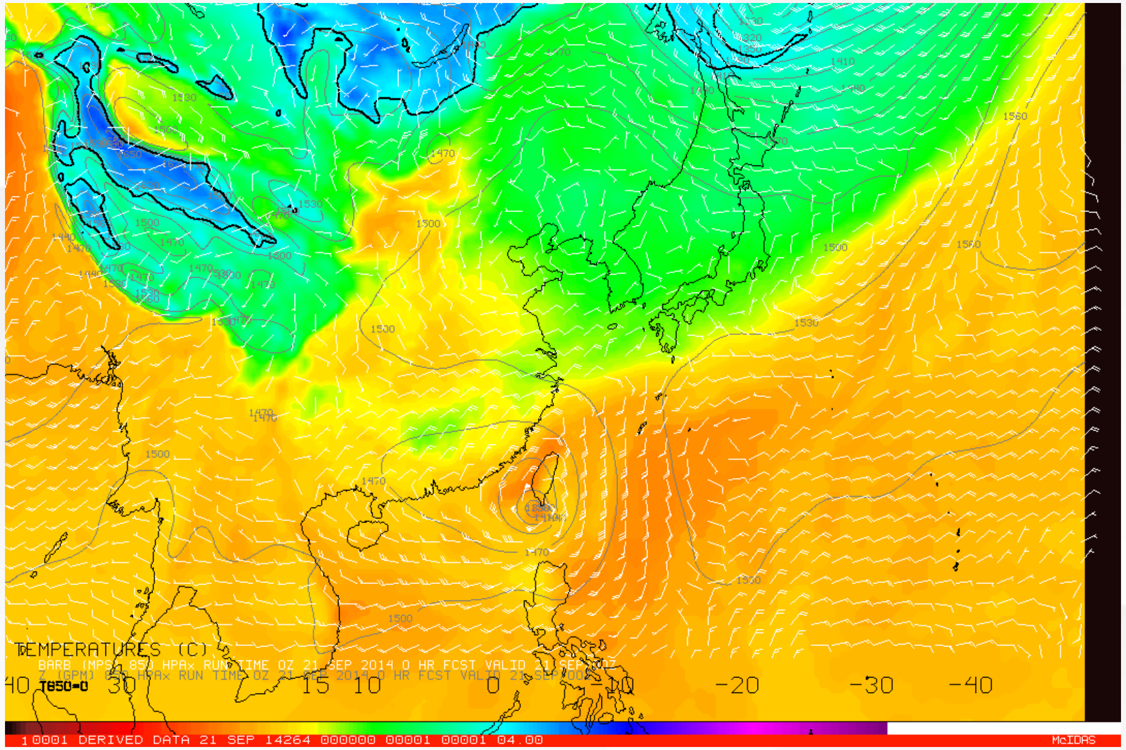


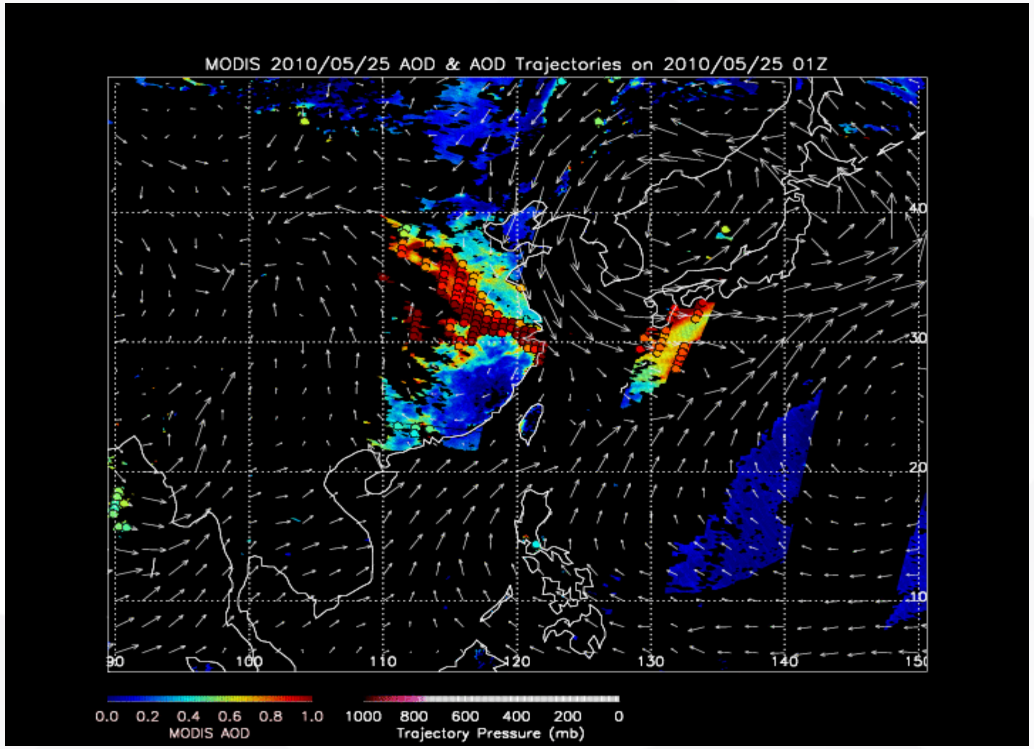




- Beyond atmospheric applications, the platform also supports land and ocean environmental products.
- These include vegetation indices, land surface temperature, and sea surface temperature products derived from satellite observations.
- Such datasets are widely used in ecosystem monitoring, agricultural applications, urban studies, and marine environmental analysis.

Applications in Numerical Prediction and Air Quality Forecasting





- Finally, these satellite products are further integrated into downstream environmental applications
- Satellite products assimilated into regional numerical prediction systems
- Aerosol products combined with trajectory analysis for air quality forecasting
- Support severe weather and environmental monitoring applications

PART 2

Satellite Product Management & Visualization Platform

Challenges in Real-Time Satellite Product Utilization

Rapid Growth of Satellite Products

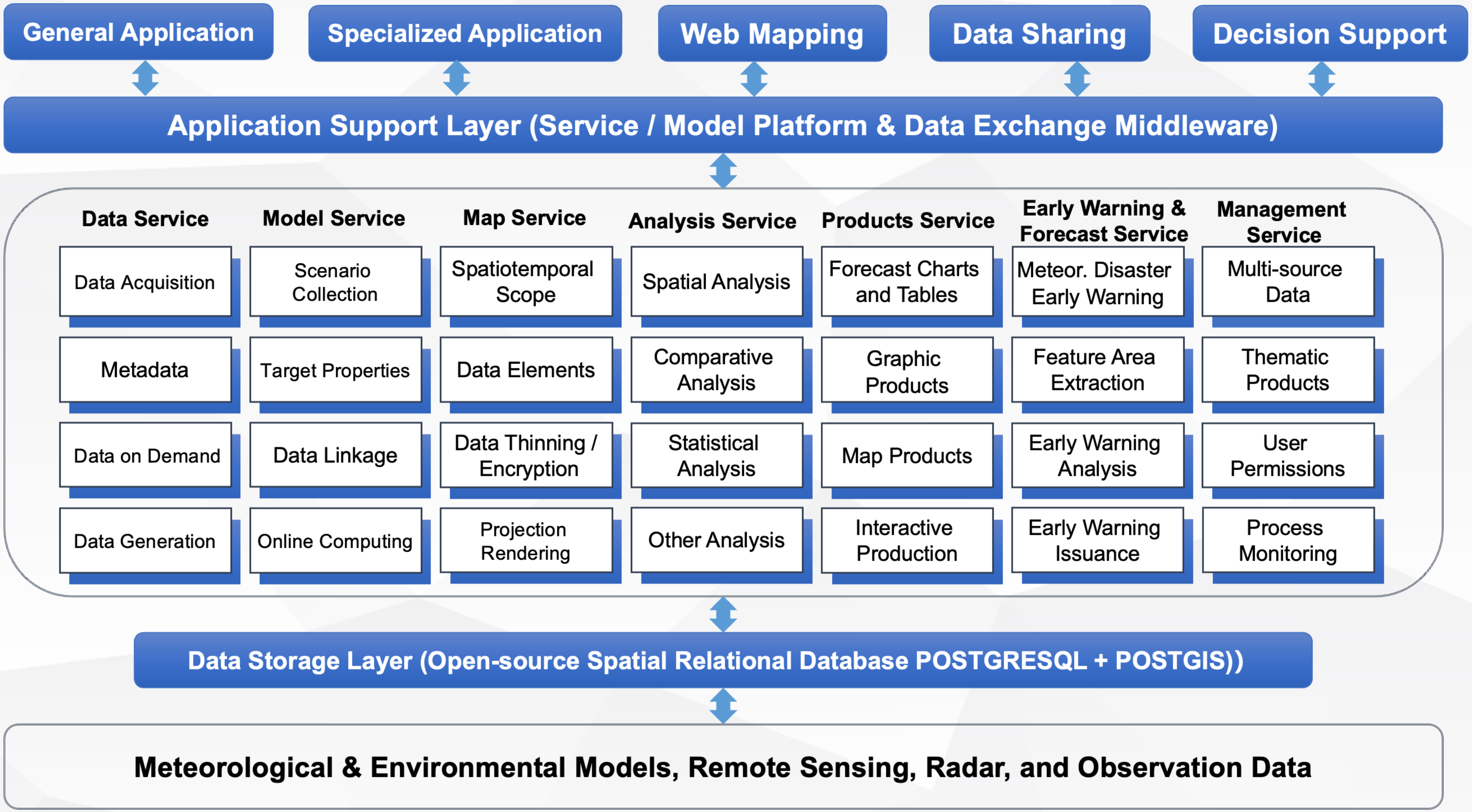
- Increasing volume of SDR/EDR products
- Multi-sensor and multi-source observations
- High-frequency real-time updates

Challenges

- Massive data storage and management
- Efficient visualization and rapid access
- Interactive analysis of 2D and 3D products
- Real-time operational applications

A unified satellite intelligence platform is required for real-time management, visualization, and applications of CSPP-derived products.

Overall Architecture of the Satellite Products Intelligence Service Platform



Core Technologies of the Satellite Intelligence Platform

Core Key Technologies

01

High-Performance Distributed Architecture

Built on an open-source database system with robust spatial processing capabilities. Features independent, interactive user/resource management and flexible multi-region deployment to seamlessly scale and meet diverse client needs.

02

Massive Atmospheric Data Visualization & Mining

Enables direct raw data ingestion with real-time, second-level rendering. Supports multi-projection map overlay, seamless zooming/panning, rapid querying, and advanced professional charting

03

Cross-Platform Big Data Sharing

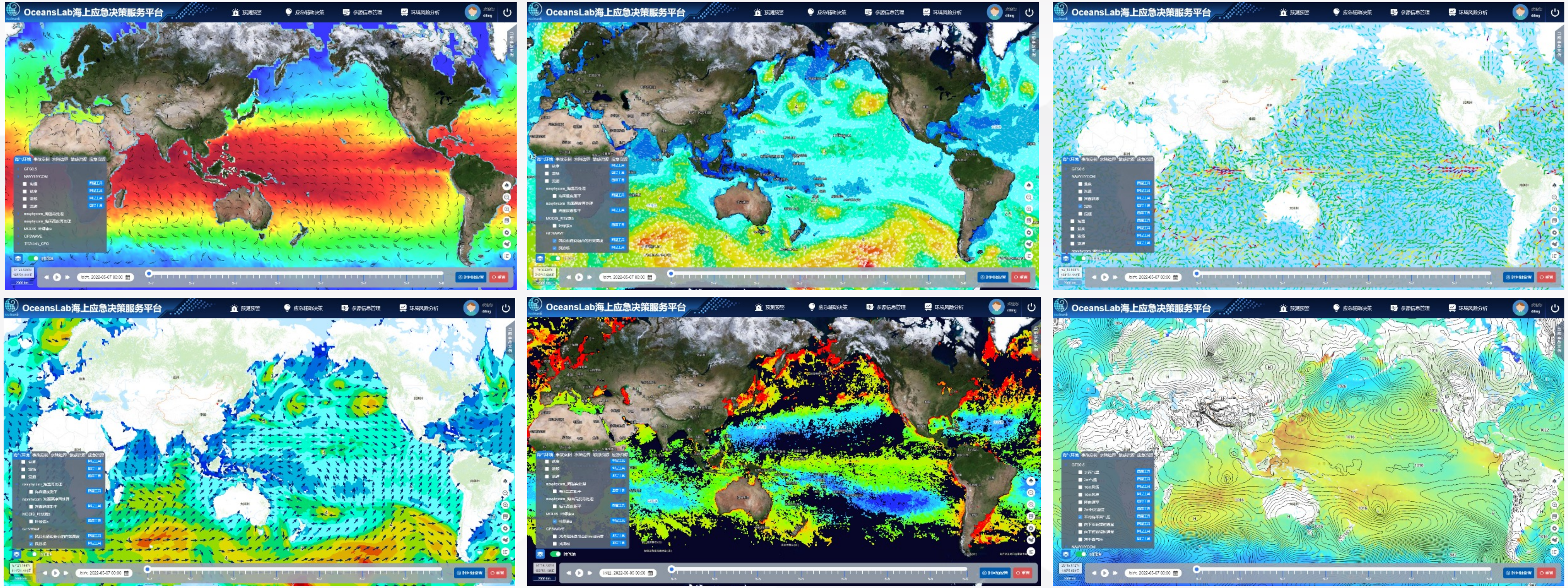
Seamlessly connects multi-source atmospheric spatio-temporal data with numerical models. Standardizes GIS maps, data publishing, and cross-model invocation for plug-and-play interoperability and data product sharing.

04

Online-Driven Atmospheric Numerical Models

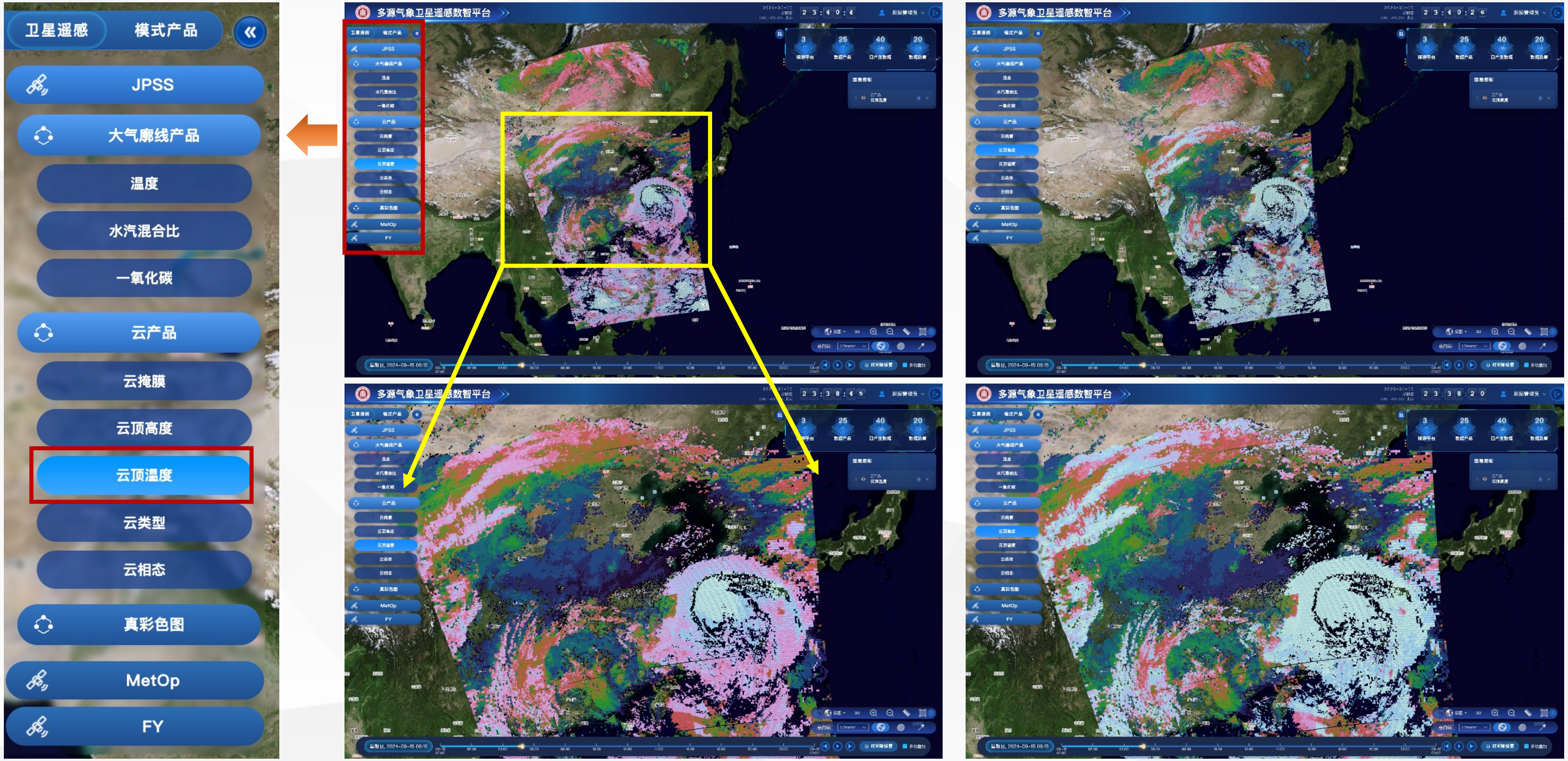
Integrates multi-model engines into a single platform, supporting high concurrency online driving and execution of professional atmospheric environmental numerical models.

Interactive Visualization of Meteorological and Environmental Data



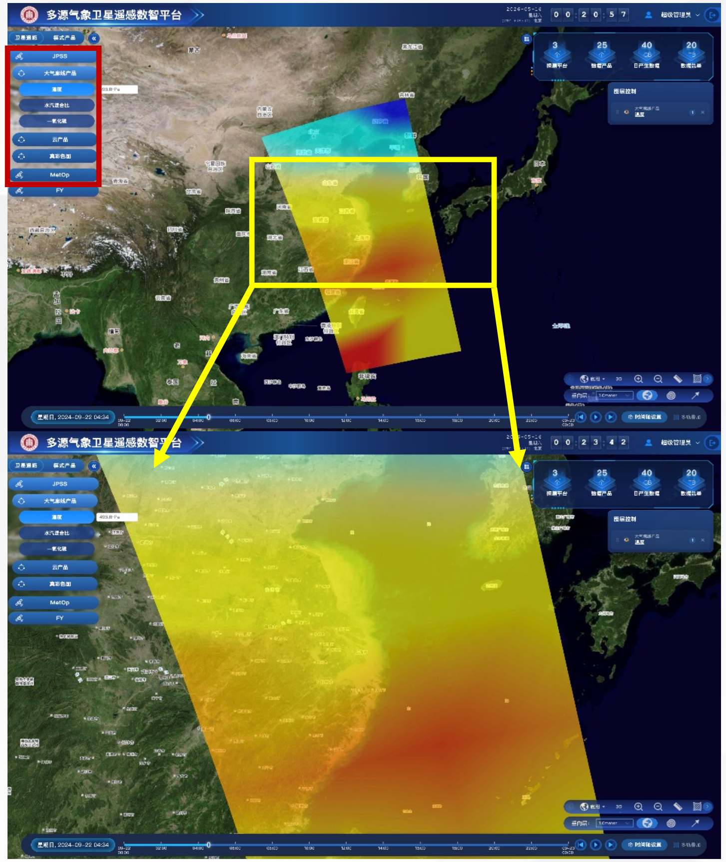
- One key capability of the platform is Interactive visualization of meteorological and environmental datasets.
- It supports both scalar fields and vector fields, including contour maps, wind vectors, and environmental overlays.
- Users can perform interactive zooming, temporal animation playback, and multi-layer analysis directly within the web interface.

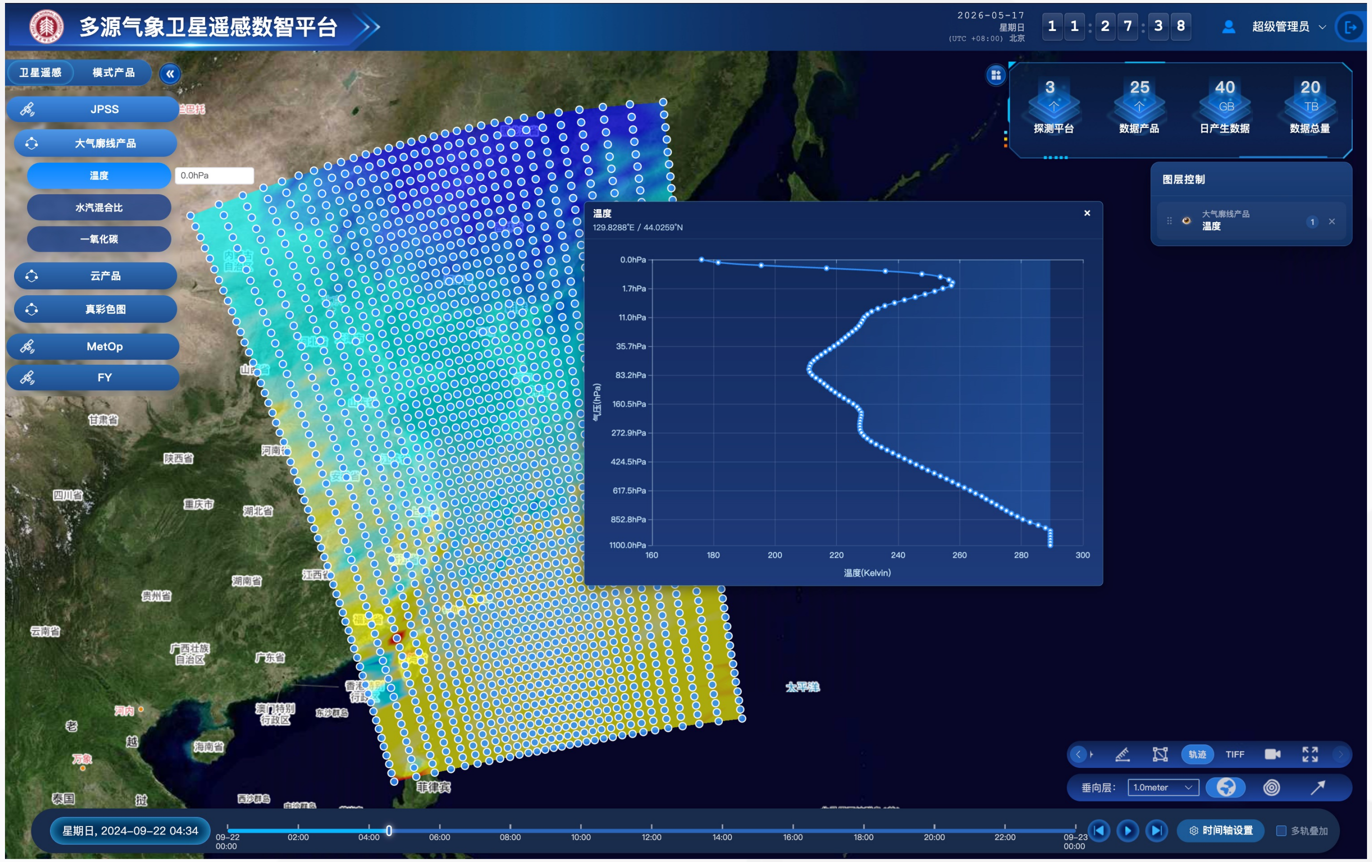
Interactive Visualization of CSPP Cloud Products



- This example demonstrates the interactive visualization capability for CSPP cloud products.
- The platform supports seamless zooming and regional analysis for operational weather monitoring applications.

Interactive Analysis of NUCAPS Thermodynamic Profiles





- Beyond 2D products, the platform also supports interactive analysis of atmospheric profile retrievals from NUCAPS.
- Visualize thermodynamic fields horizontally and select any individual pixel to display the corresponding vertical profile.
- This capability enables rapid analysis of atmospheric thermodynamic structure and stability conditions in real time.

Flexible Data Management for Multi-Source Environmental Products

- Supports automatic ingestion and indexing of multiple data formats, including NetCDF and HDF products.
- Automatically extracts spatiotemporal metadata and supports different grid structures, enabling efficient integration of newly generated CSPP products.

PART 3
Low-Latency AI Retrieval and Future Applications

Toward Low-Latency AI-Enhanced Satellite Retrieval

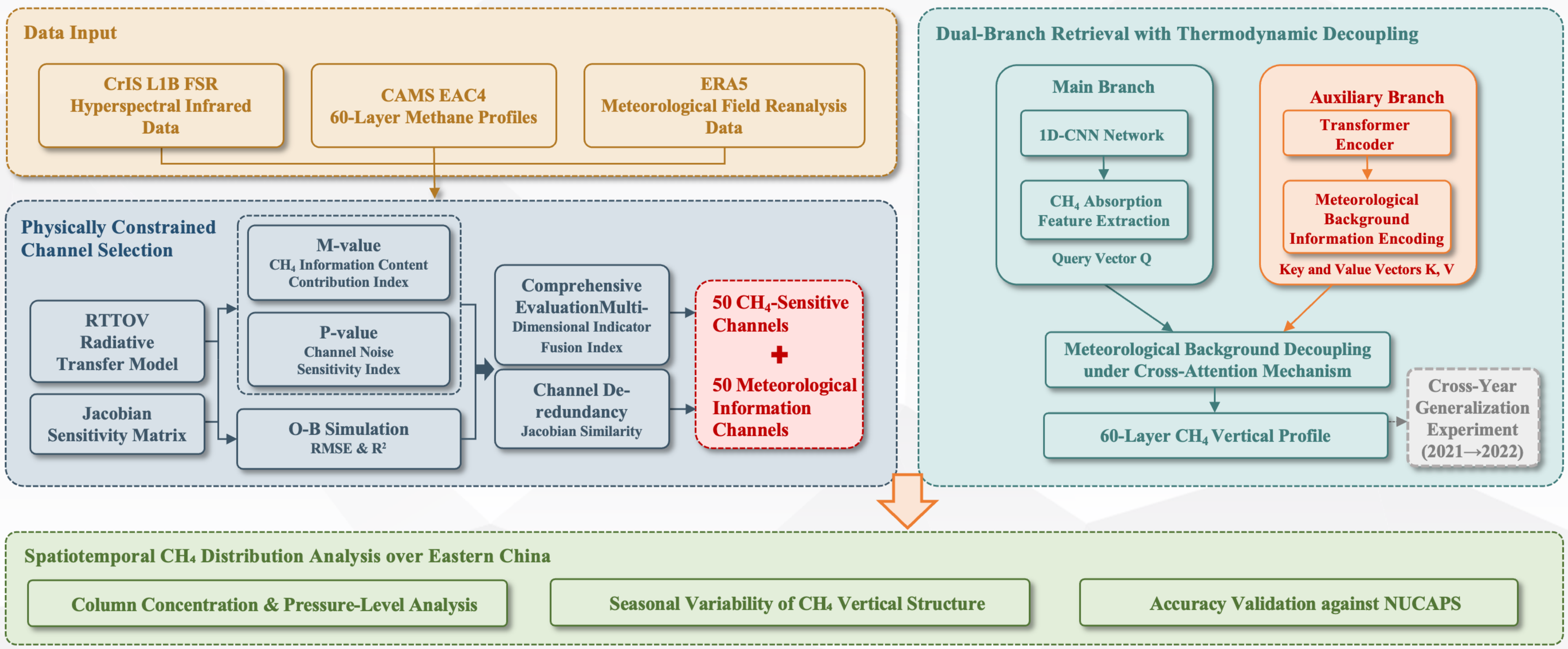
- Although modern satellite systems can provide large amounts of environmental products in near real time, some advanced physical retrieval algorithms still remain computationally expensive and time consuming.
- This limitation becomes increasingly important for large-scale operational applications and rapid-response environmental monitoring.

AI retrieval frameworks provide a promising pathway for next-generation low-latency satellite applications.

Motivation for AI-Based CH_4 Vertical Profile Retrieval

- Most existing methane satellite retrievals from shortwave infrared sensors mainly provide column concentrations, with limited vertical profile information.
- In contrast, thermal infrared hyperspectral sounders such as CrIS provide valuable sensitivity to the vertical structure of methane throughout the troposphere.
- However, traditional optimal estimation retrievals are computationally expensive, while many existing machine learning approaches lack physical constraints and thermodynamic decoupling mechanisms.
- Therefore, our goal is to develop a physics-constrained AI framework for rapid methane vertical profile retrieval from CrIS observations.

Overall Framework of AI-Based CH_4 Profile Retrieval



- The framework integrates CrIS hyperspectral observations, CAMS methane profiles, and ERA5 meteorological fields.
- We perform physically constrained channel selection based on Jacobian sensitivity analysis, observational consistency, and redundancy reduction.
- A dual-branch deep learning framework is developed to separately characterize methane spectral information and meteorological background information.

Multi-Dimensional Composite Channel Selection Strategy

- Based on RTTOV Jacobian analysis, identify methane-sensitive channels by *M* and *P* metric, and provide a physically interpretable basis for channel selection;

M

Methane Sensitivity

$$S_{x,i} = \left|\sum_{l=1}^{N_{lev}} K_{x,i,l} \cdot \Delta x_l\right| \Rightarrow M_i = \frac{S_{CH_4,i}}{NE\Delta T_i}$$

Quantifies the net channel response to CH_4 absorption based on the RTTOV Jacobian matrix.

P

Methane Purity

$$P_i = \frac{S_{CH4,i}}{S_{H_2O,i} + S_{Temp,i} + S_{CO_2,i} + S_{O_3,i} + S_{CO,i} + S_{N_2O,i}}$$

Quantifies the fractional contribution of the CH_4 Jacobian relative to interfering species such as water vapor and temperature.

- Based on observation-minus-background matched datasets, RMSE and R^2 identify stable and reliable channels under real observation conditions.

RMSE

O-B Root Mean Square Error

$$RMSE_i = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(y_{O,i,k} - y_{B,i,k}\right)^2}$$

Reflects the overall radiometric error of each channel.

R²

O-B Coefficient of Determination

$$R^2 = 1 - \frac{\sum_{k=1}^{N}\left(y_{O,i,k} - y_{B,i,k}\right)^2}{\sum_{k=1}^{N}\left(y_{O,i,k} - y_{O,i}\right)^2}$$

Reflects the ability of each channel to capture brightness temperature variability.

- Develop a composite channel selection index to integrates physical sensitivity and observational consistency

$$\textit{Composite index} = M_{\text{norm}} \cdot P_{\text{norm}} \cdot \left[0.5 \cdot R^2_{\text{norm}} + 0.5 \cdot \left(1 - RMSE_{\text{norm}}\right)\right]$$

Comparison of Different Channel Selection Strategies

Fig. (a): Spectral distribution of composite index. Figs. (b) & (c): Per-channel distributions of physical sensitivity (M, P) and observational consistency (RMSE, R^2) metrics; filled circles mark top-50 positions. Color bars show spectral locations and overlap rates with the composite scheme across all five approaches.

M & P

Both show strong physical consistency in characterizing target gas response, but fail to identify channels heavily affected by instrument noise or model error.

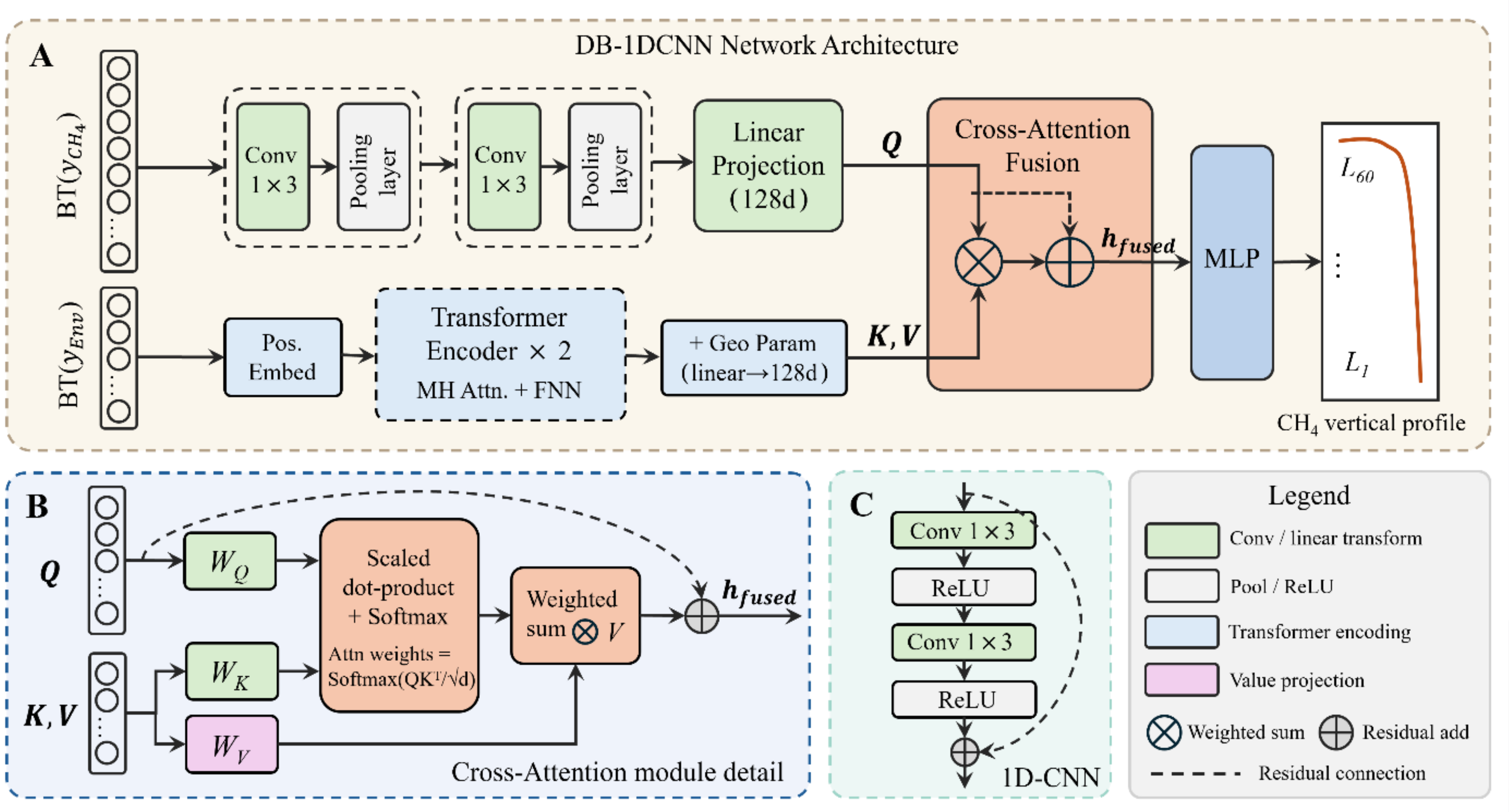
RMSE & R^2

Top-50 by RMSE are relatively scattered with lower information content; top-50 by R^2 are overly concentrated in localized regions, risking redundancy from structurally similar channels.

Composite Index

Jointly incorporating physical sensitivity and observational consistency achieves unified multi-dimensional constraints, reducing high-noise and low-information channels while balancing effectiveness and stability.

Dual-Branch Deep Learning Architecture with Thermodynamic Decoupling



Primary Branch

Uses a 1D-CNN to extract CH_4 spectral features

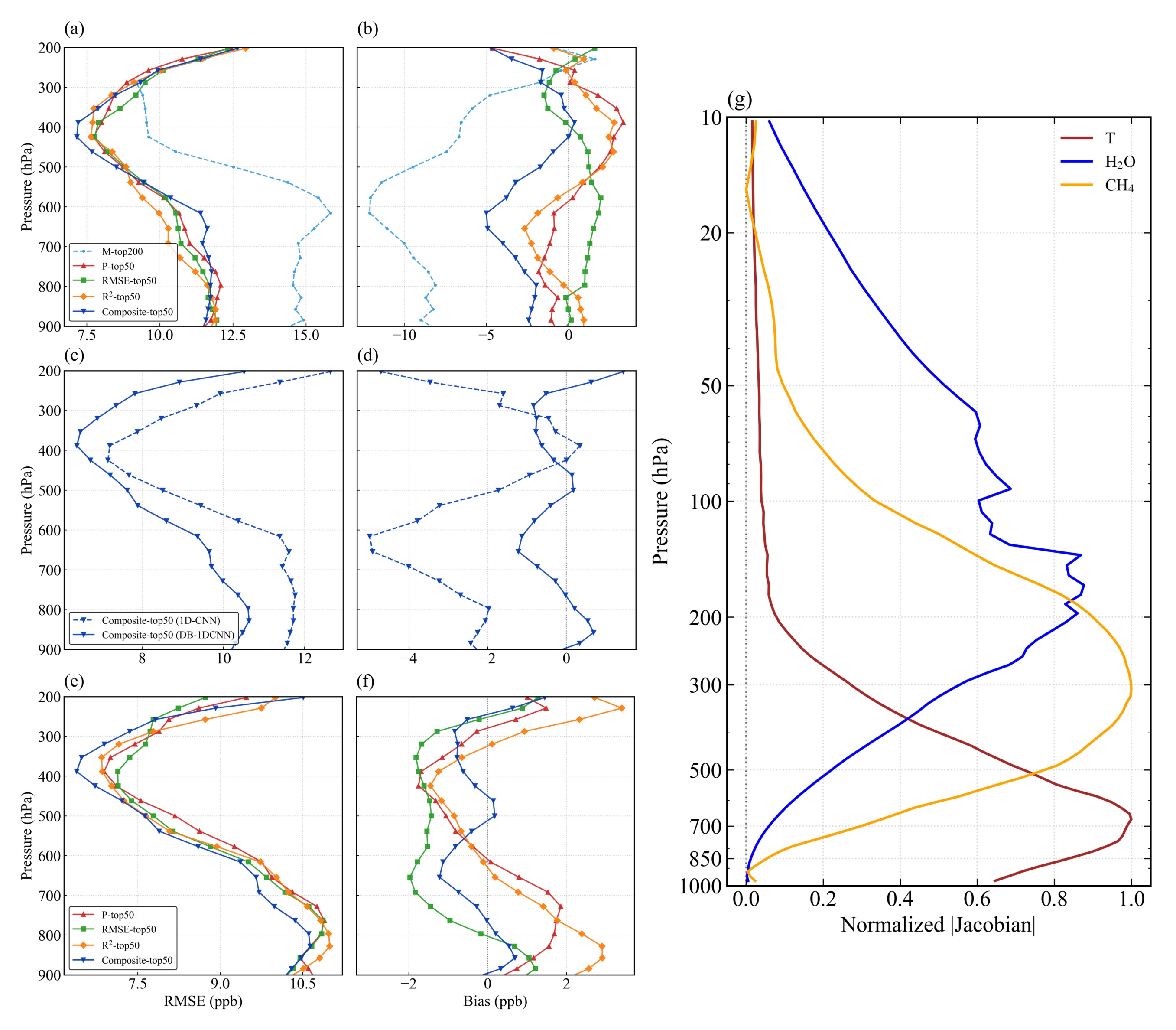
Auxiliary Branch

Uses a transformer encoder to characterize meteorological background information

Cross-Attention Fusion

Cross-attention fuses features from both branches and decouples meteorological background interference and improve methane retrieval

Retrieval Performance Improvement with the Dual-Branch Framework



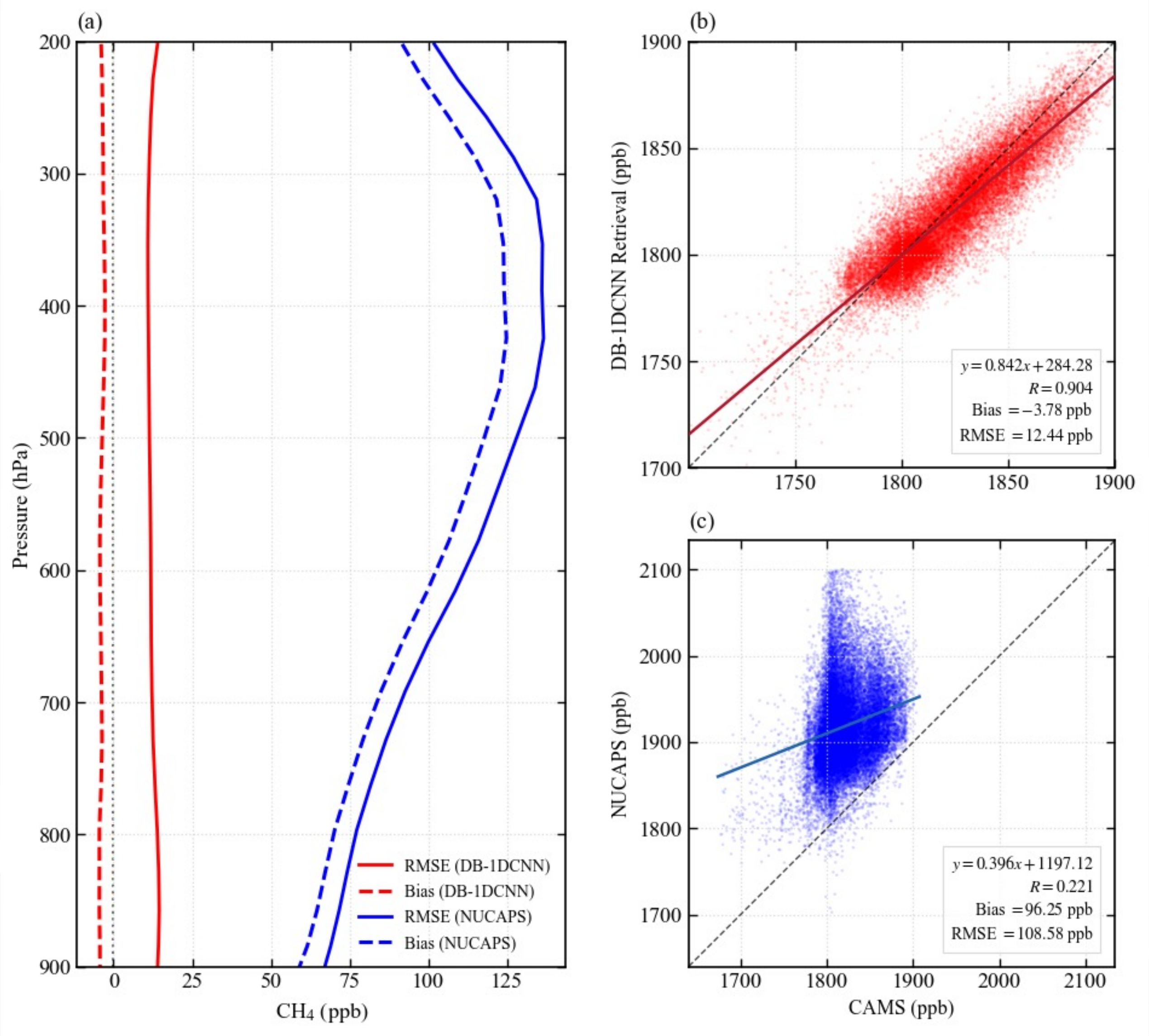
Channel Selection

- The physically constrained channel selection improves the quality of methane-sensitive spectral inputs and reduces thermodynamic contamination.

Dual-Branch Framework

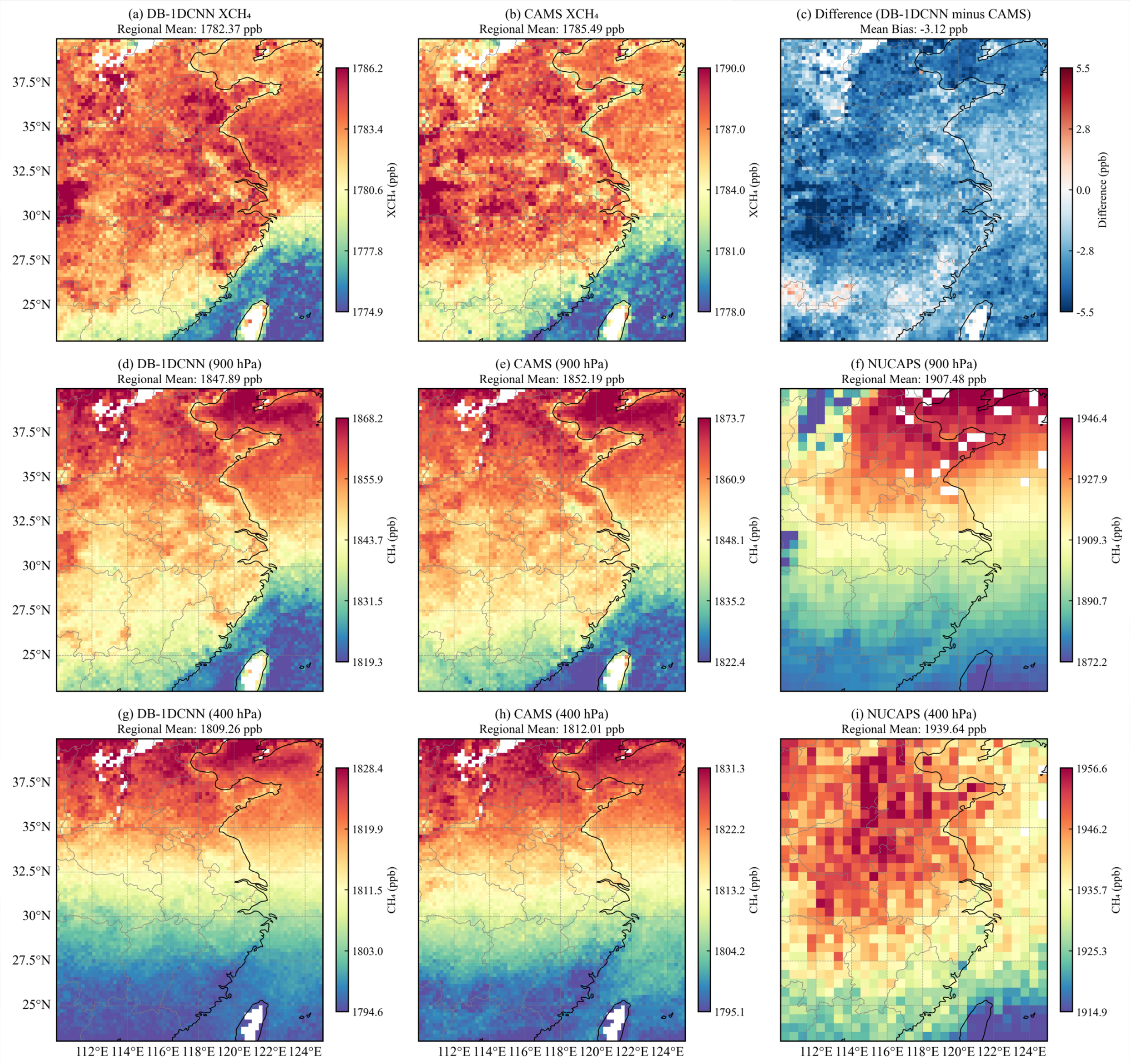
- The dual-branch framework further improves retrieval performance, significantly reducing RMSE and bias throughout the troposphere.
- The largest improvement occurs in the 600–800 hPa layer, where temperature interference is strongest.

Comparison with operational NUCAPS products



- To evaluate model robustness, we conducted an independent cross-year validation experiment.
- The model was trained using 2021 data and evaluated using an independent 2022 dataset.
- Compared with the operational NUCAPS product, the proposed framework shows substantially improved consistency with atmospheric reanalysis (CAMS), with lower RMSE and more stable retrieval performance across the troposphere.

Spatial Structure of Retrieved CH_4 Profiles



- The retrieved methane fields successfully reproduce the large-scale spatial distribution patterns over eastern China.
- Compared with NUCAPS, the proposed framework better preserves fine-scale spatial variability, particularly in the lower troposphere and near the surface.
- These results demonstrate the potential of AI-enhanced thermal infrared retrievals for future high-resolution atmospheric composition applications.

Conclusions and Future Perspectives

- In summary, we developed an end-to-end framework for real-time direct broadcast satellite processing, visualization, and AI-enhanced retrieval applications.
- The system supports automated CSPP processing, interactive environmental visualization, and physics-constrained AI retrievals for atmospheric composition monitoring.
- Future work will focus on integrating AI-based retrieval algorithms directly into operational direct broadcast processing systems for next-generation low-latency satellite applications.

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Thanks for your attention!

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