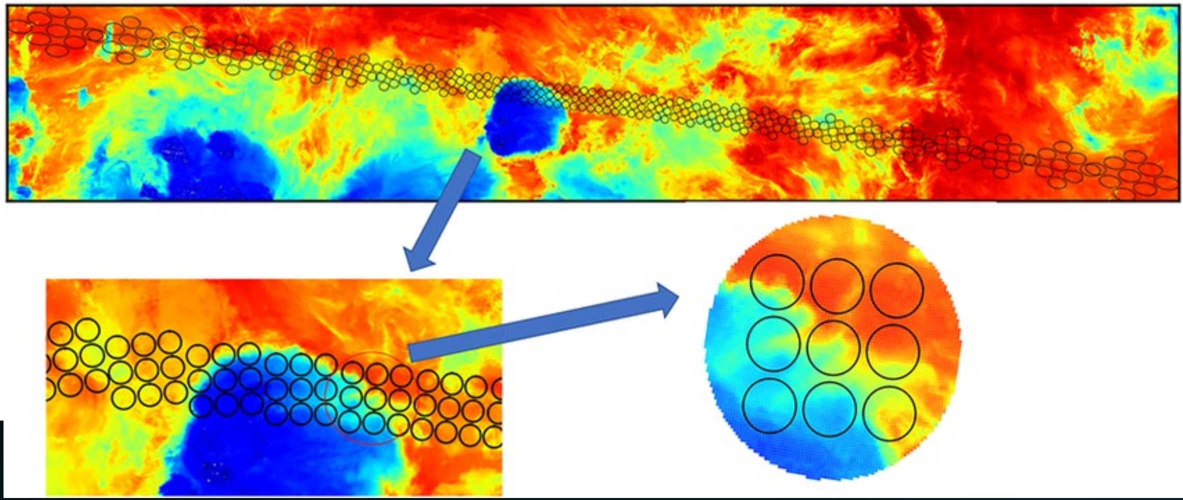
SPIE. SENSORS+ IMAGING

Enhancing Single Field-of-View IR Sounder Retrievals through AI-Driven Integration of Cloud Information from Multispectral Imagers



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Key Facts

- IR sounders provide detailed spectral information but lack the spatial resolution and spectral diversity needed to robustly characterize heterogeneous clouds.

- High-resolution visible/IR imager measurements provide complementary spatial and cloud-property information.

- The single field-of-view retrieval algorithm can benefit a lot from a sounder-matched, high-quality cloud information generated from imager measurements.

Solutions

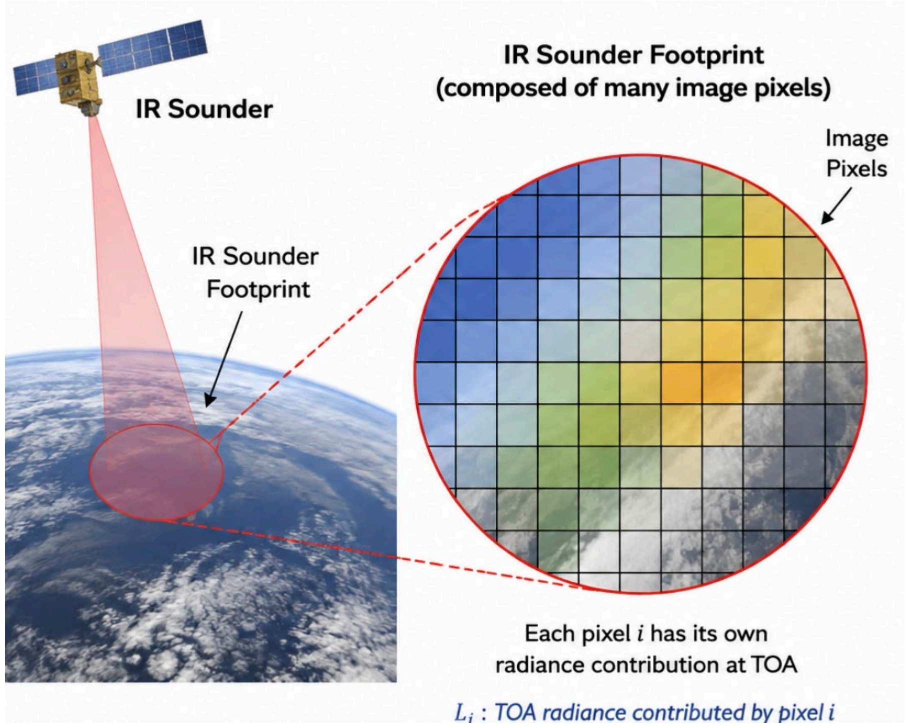
- A physically consistent framework is needed to aggregate or statistically represent imager-based high spatial resolution cloud information within the coarser IR sounder footprint.

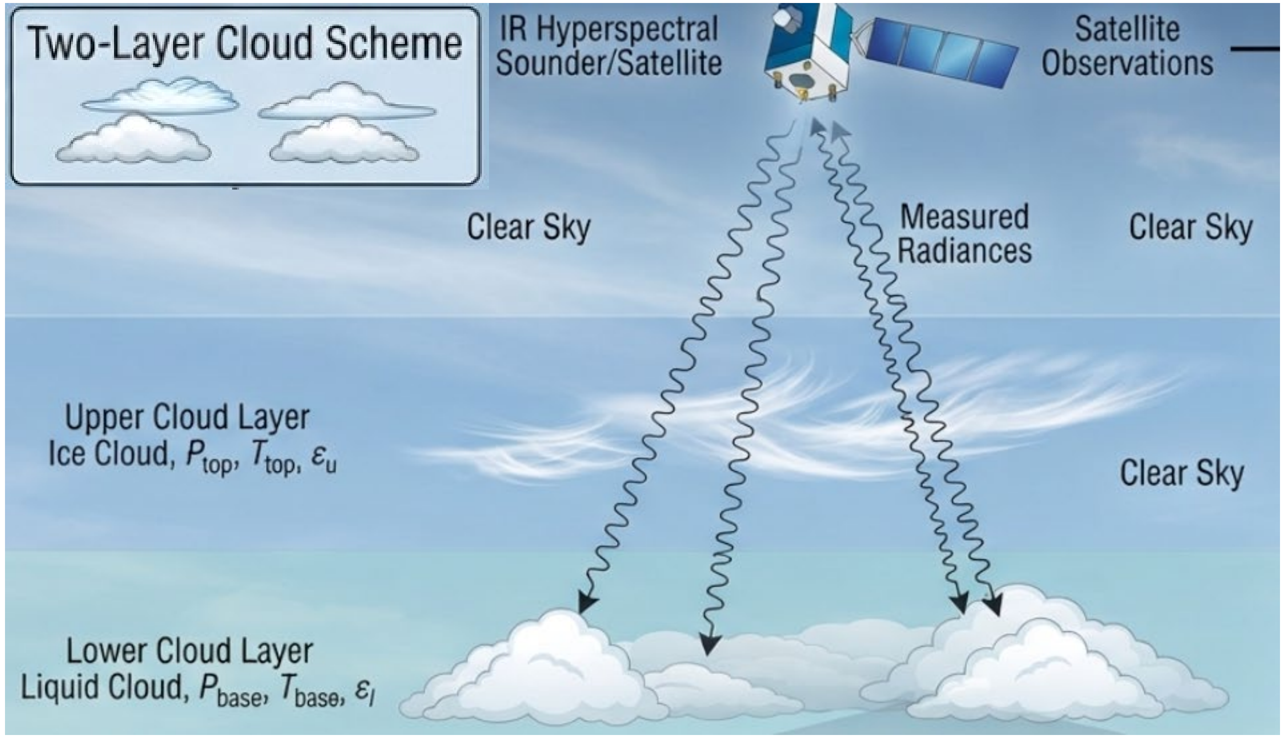
- The need for an efficient AI approach to learn relationships between IR radiances and physically consistent cloud parameters established from existing high-quality imager–sounder datasets.

  - Imager based reflected solar measurements, critical to the retrieval of cloud microphysical properties, are not available during night.

  - Near real time applications also prevent the use of Level-2 cloud products retrieved from imager measurements.

Two-Layer Cloud Parameterization Scheme Bridging Imager Data with IR Sounder Measurements





The total TOA radiance measured by an IR sounder for a footprint is the sum of the radiance contributions from all image pixels within that footprint.

The two-layer cloud scheme strikes an optimal balance between computational efficiency and physical realism in "all-sky" retrieval

Some Formulae

Estimation for TOA radiance of IR sounder footprint

From IR sounder retrieval scheme

$$R(\nu) = \epsilon_{ice}(\nu)B\left(\widehat{T_{ice}},\nu\right) + (1-\epsilon_{ice}(\nu))\epsilon_{wat}(\nu)B\left(\widehat{T_{wat}},\nu\right) + (1-\epsilon_{ice}(\nu))(1-\epsilon_{wat}(\nu))\overline{\epsilon_s}(\nu)B\left(\widehat{T_s},\nu\right)$$

- $\widehat{T_{ice}}$, ϵ_{ice} ice cloud temperature and effective emissivity
- $\widehat{T_{wat}}$, ϵ_{wat} water cloud temperature and effective emissivity
- $\widehat{T_s}$, ϵ_s surface temperature and emissivity

The relationship holds in window regions where gas absorption is negligible

In the imager pixel domain

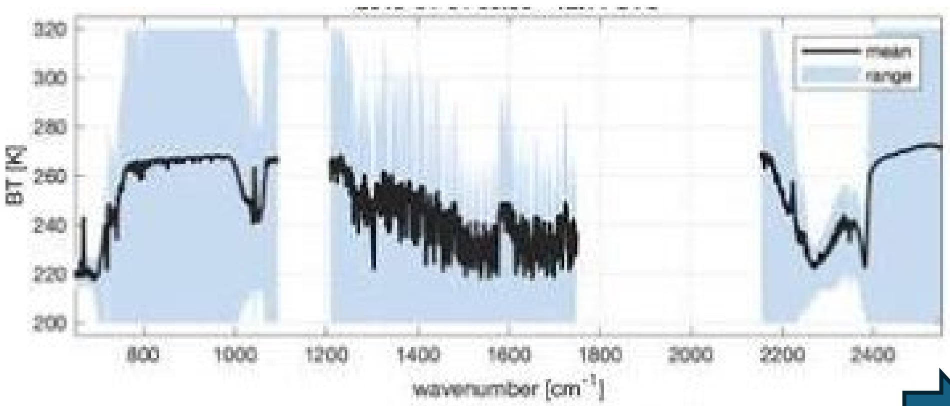
$$R(\nu) = R^{cld}(\nu) + R^{surf}(\nu)$$

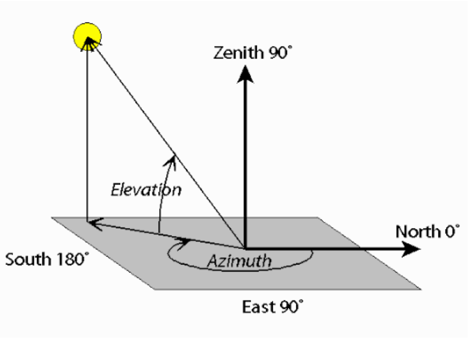
$$R^{cld}(\nu) = \frac{1}{N_{ice}+N_{wat}+N_{clr}}\left[\sum_{i=1}^{N_{ice}} \epsilon_i^{ice}(\nu)B\left(T_i^{ice},\nu\right) + \sum_{i=1}^{N_{wat}} \epsilon_i^{wat}(\nu)B\left(T_i^{wat},\nu\right)\right]$$

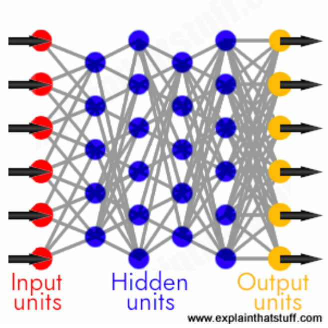
$$R^{surf}(\nu) = \frac{1}{N_{ice}+N_{wat}+N_{clr}}\left[\sum_{i=1}^{N_{ice}}(1-\epsilon_i^{ice})\epsilon_i^{s}(\nu)B(T_i^{s},\nu) + \sum_{i=1}^{N_{wat}}\left(1-\epsilon_i^{wat}\right)\epsilon_i^{s}(\nu)B(T_i^{s},\nu) + \sum_{i=1}^{N_{clr}}\epsilon_i^{s}(\nu)B(T_i^{s},\nu)\right]$$

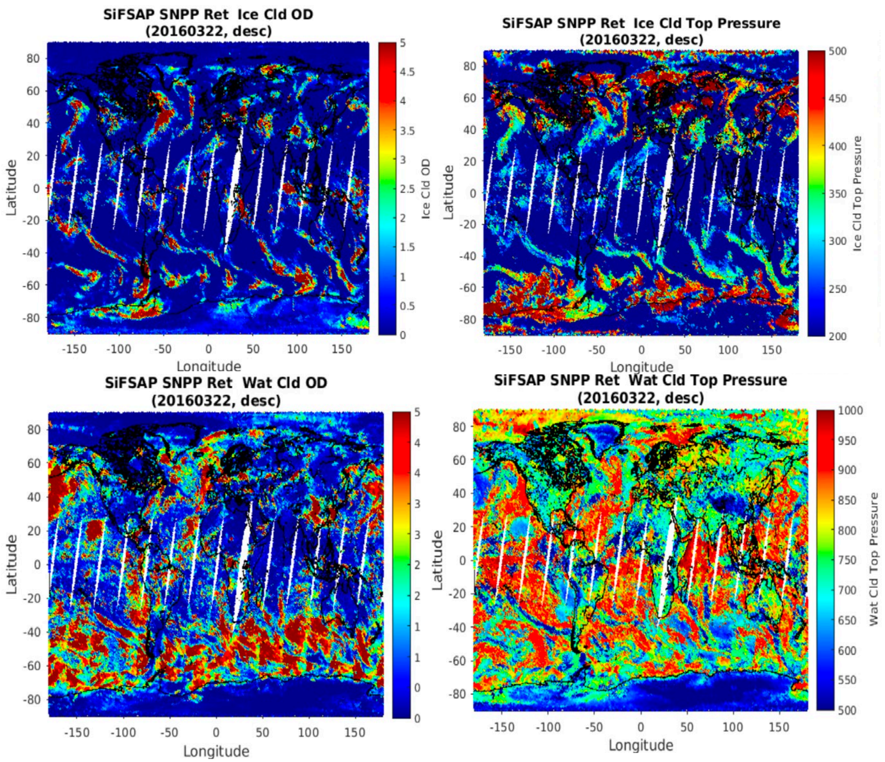
$N_{ice}, N_{wat}, N_{clr}$ --- number of ice cloud, water cloud, and clear sky pixels within a sounder footprint

AI based Cloud Properties Retrieval Using IR Sounder Spectral Radiances

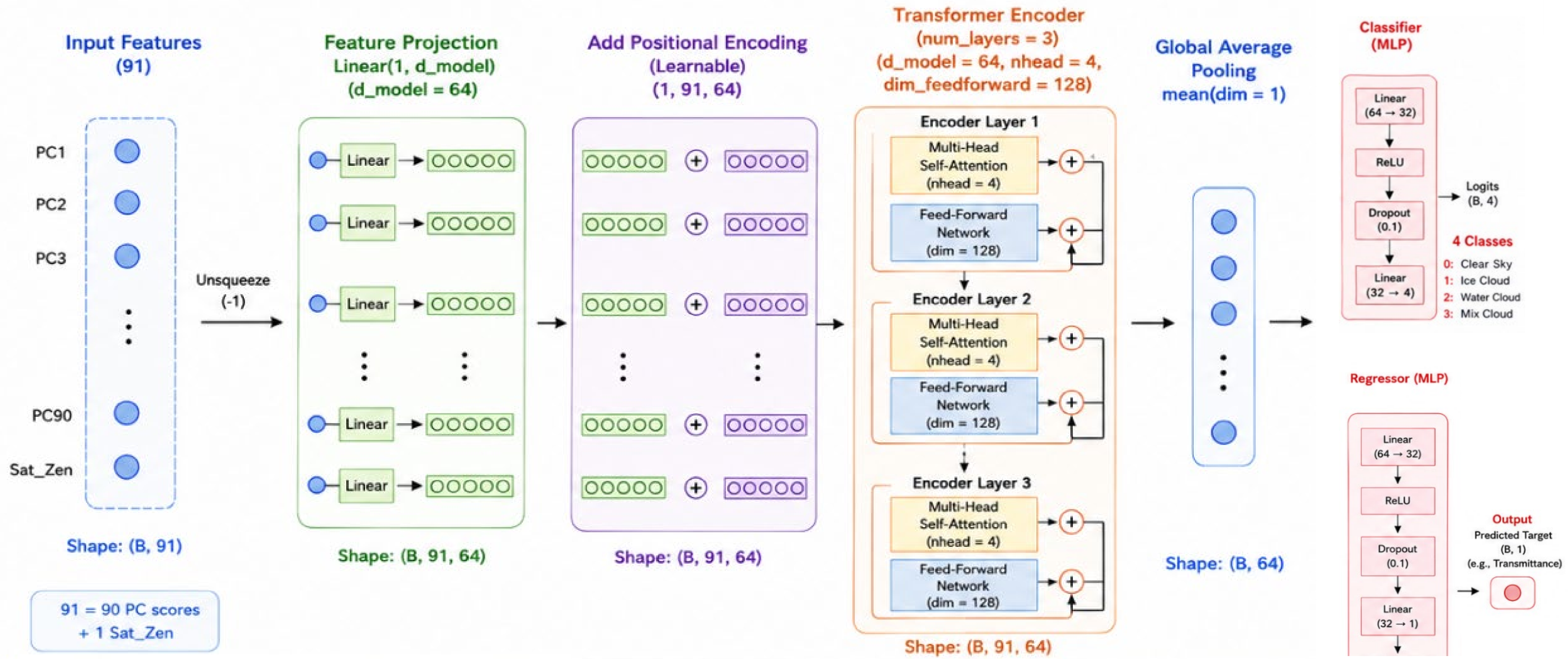








Transformer based AI Structure



- **Input:** 91 input features (e.g., radiance PC scores + Sat_Zen)
  Shape: (B, 91) where B is the batch size.
- **Feature Projection:** Each scalar feature is linearly projected to a d_model-dimensional embedding.
- **Add Positional Encoding:** Learnable positional embeddings (one per feature) are added to provide feature identity.
- **Transformer Encoder:** 3 stacked encoder layers.
  - Multi-head self-attention (nhead = 4)
  - Feed-forward network with residual connections & LayerNorm

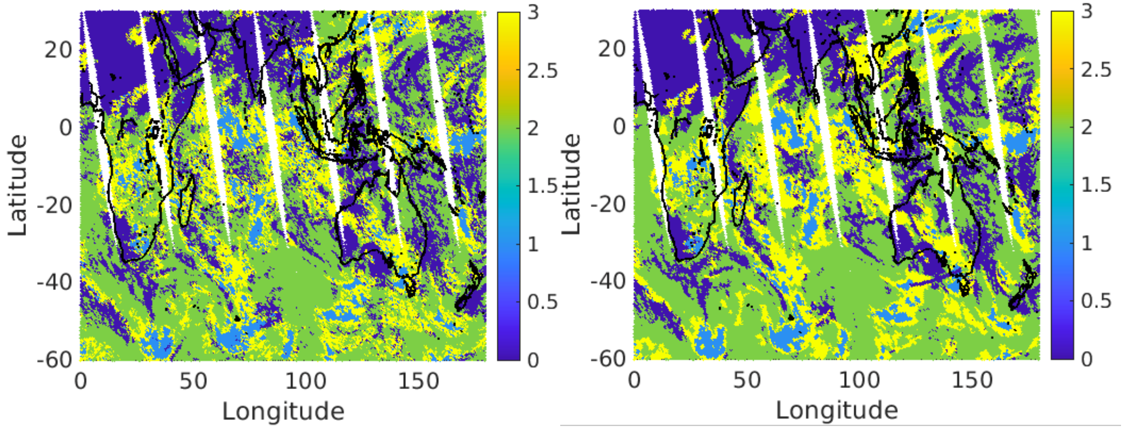
- **Global Average Pooling:** Average over the feature dimension (91) to obtain a fixed-size representation.

Forward Pass Summary

Input (B,91) → Project (B,91,64) → + PosEnc (B,91,64) → Transformer Encoder (B,91,64) → Mean Pool (B,64) → MLP

Results and Validation

Cloud Phase

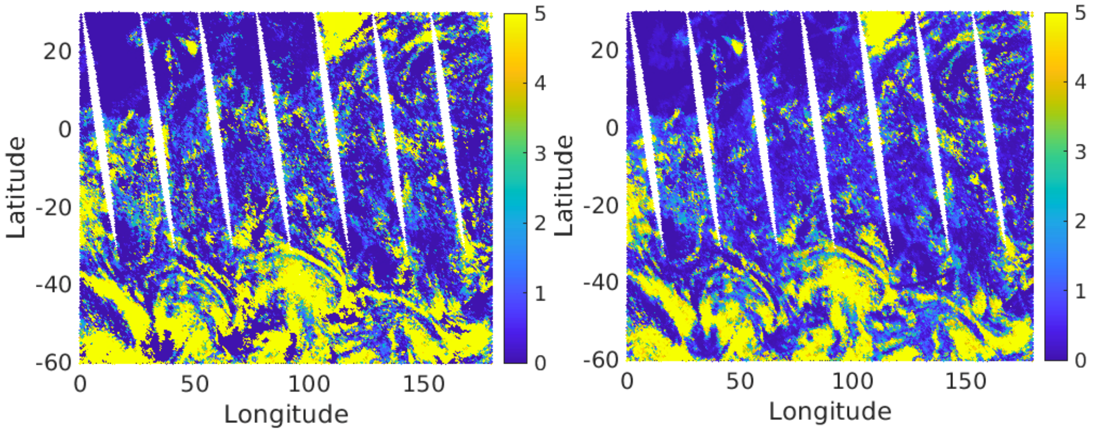


ice clouds detection success rate 95%

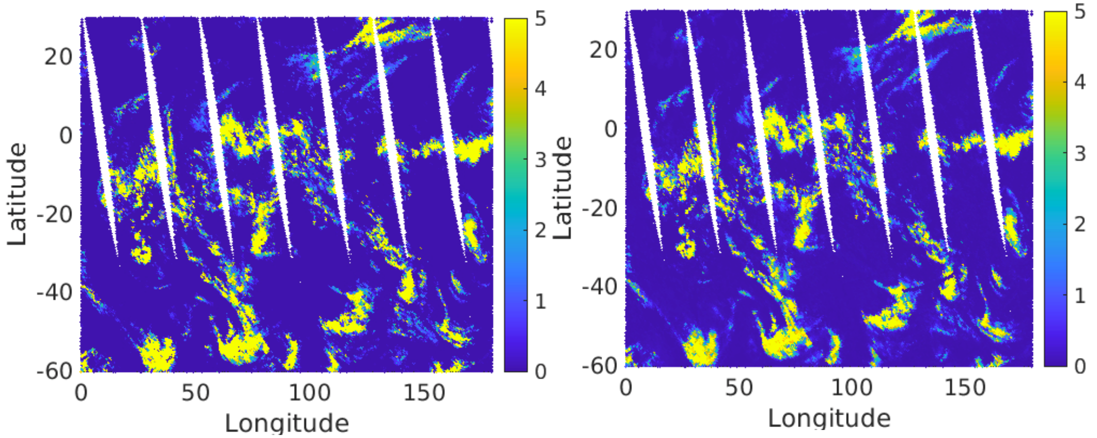
water clouds detection success rate 93%

Challenge:
~19% ice cloud and ~6% water cloud footprints are classified as mixed phase

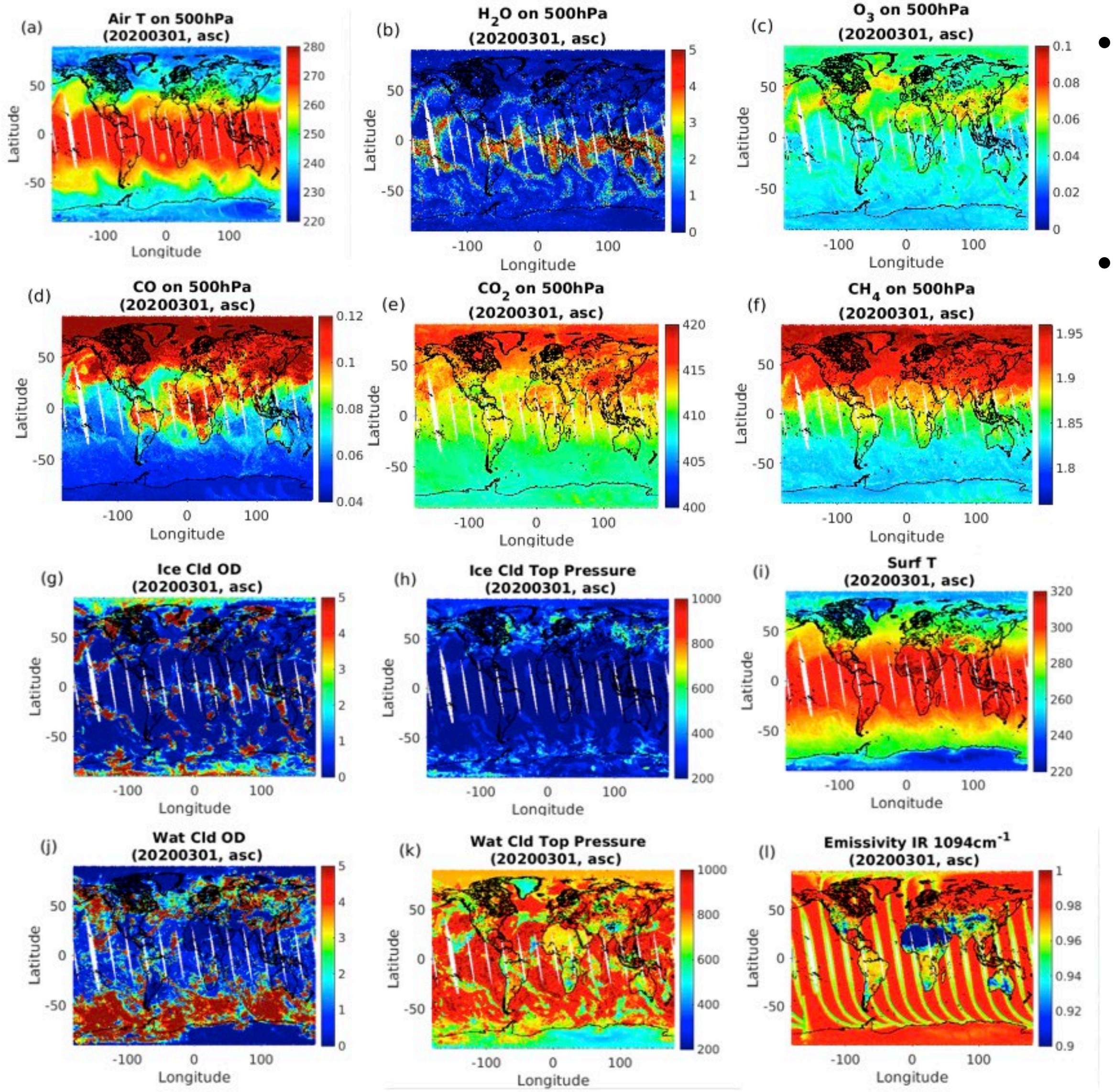
Water Cloud Optical Depth



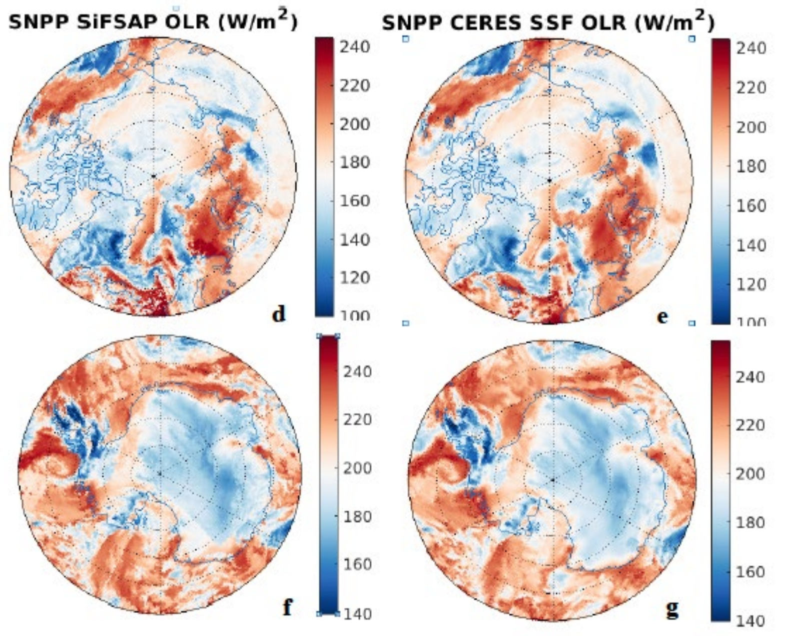
Ice Cloud Optical Depth



Single Field-of-view Atmospheric Sounder Product (SiFSAP) System



- The Principal Component Radiative Transfer Model (PCRTM) based physical retrieval system suitable for fast all-sky application on IR sounder data of individual footprints
- Production of a complete suite of geophysical properties (including clouds) to enable the radiometric consistency to observations



Contribution to the Single Field-of-view Retrieval

- Enabled the simultaneous retrieval of ice and water cloud properties along with the other atmospheric variables including T, Q, surface emissivity, trace gases

  - ➢ Improve the cloud retrieval accuracy by leveraging the *a prior* information for the imagers
  - ➢ Reduce the uncertainty in atmospheric variables due to the crosstalk with cloud
  - ➢ Greatly reduce the non-linearity issue in the optimal estimation method based iterative process
  - ➢ Improve the spectral radiance fitting

Application Potentials

- Real-time/Near Real-time retrieval using sounder observations
- Data fusion between imagers and sounder products
- All sky data assimilation
- Improve the radiation budget estimation using a comprehensive cloud scheme which enables ‘radiation closure.’
- …