Observation of Deep Convective Cloud-Top Height and Vertical Temperature Structure of Hurricane Using Hyperspectral Infrared Sounder and its Single-Field-View Retrieval Products

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Outline

- **Purpose:** To develop a new method to estimate CTH utilizing hyperspectral infrared sounders
  - Hurricanes, tropical cyclones (TC), or typhoons are major natural disasters. It was found that TC intensity changes are closely linked to deep convective clouds, with stronger TCs associated with higher cloud top heights (CTH) → Observation of CTH is important for monitoring TC development and TC dynamics study

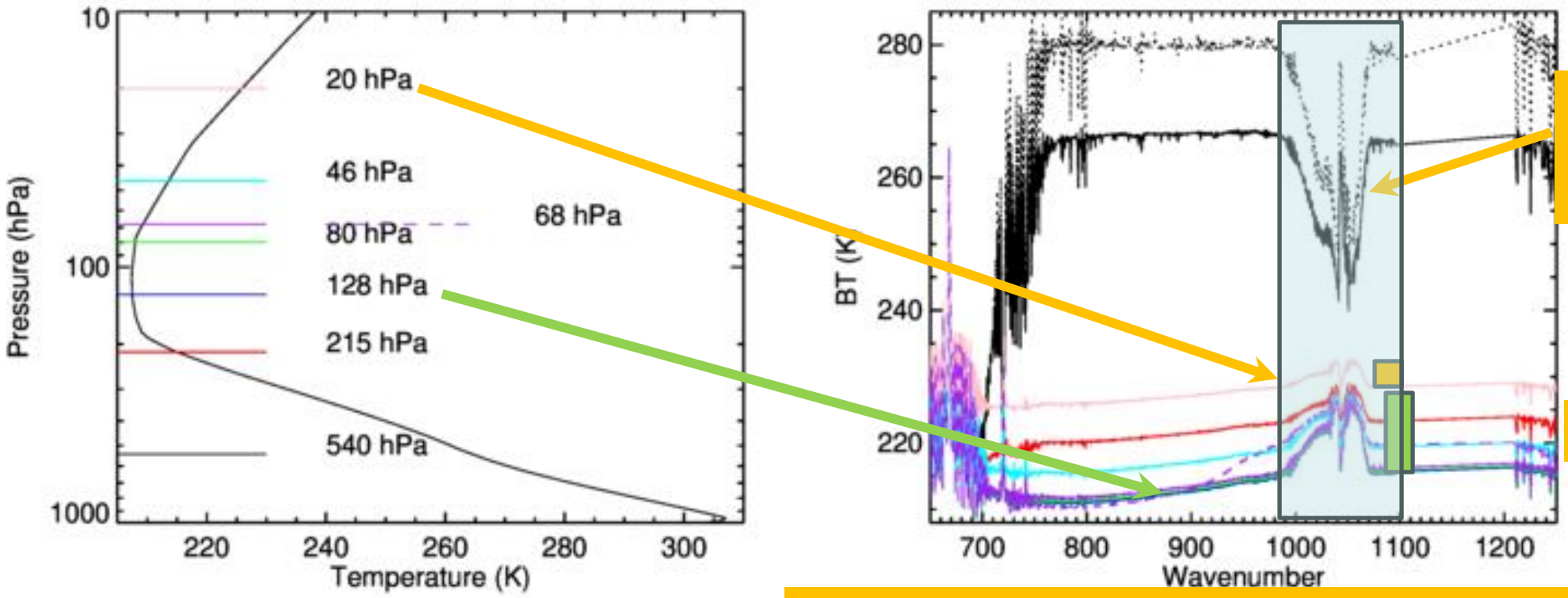
- **Method: using the Inverted-V Spectra near 9.6 μm O_3 band**
  - PCRTM model simulation and CrIS-measured spectra for Hurricane Ian (September 28, 2022);
  - Good correlation between the inverted-V Spectra height (H_index) and CTH determined using BT11 to fit CrIS collocated temperature profiles from ERA-5;

- **Applications:** – CTH from hurricane Dorian (201909) and recent hurricane Helene (202409) and Milton (202410)

- **Observation of Hurricane using Single-Field-View (SFOV) sounding retrieval product, SiFSAP**
  - Observation of Hurricane "Ian" clouds, ozone and thermodynamic structure using SiFSAP

- **Summary**

Simulated Inverted V-shape Spectrum at O3 band from PCRTM Simulations and Its use for Cloud-top Height Detection



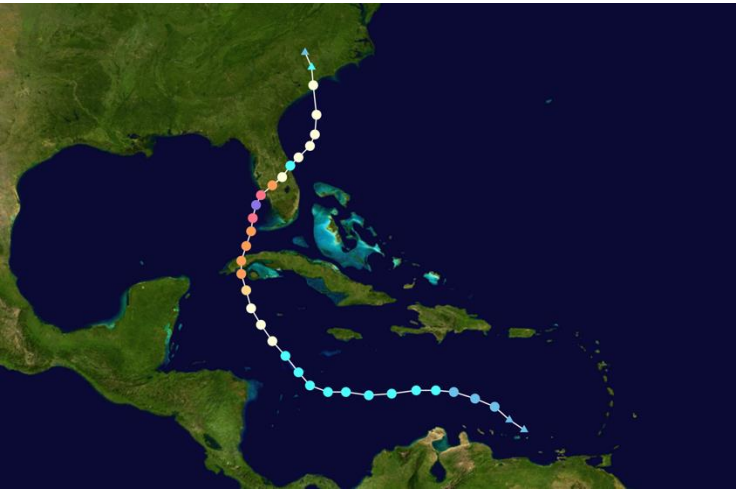
For clear sky and low clouds

high clouds

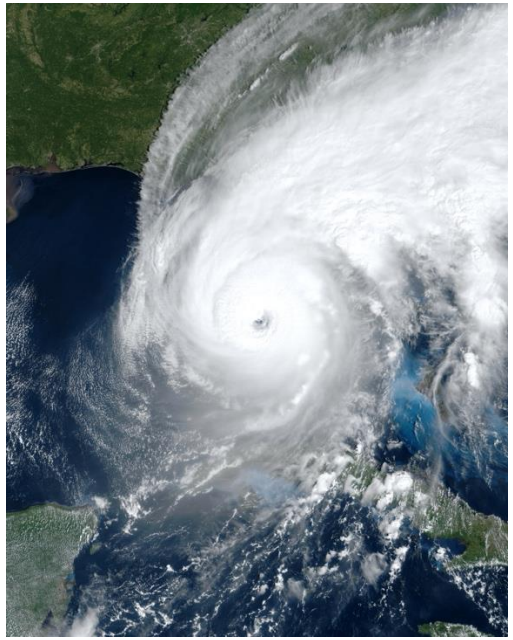
- ✓ Inverted-V shape near 9.6 μm for high clouds ;
- ✓ The depth of inverted V will be used for height detection;
- ✓ Inverted-V is shallower for clouds at stratosphere than at tropopause;

Temperature profile from ERA5 (left) and the PCRTM-simulated spectra (right). Different colors for the spectra correspond to the clouds with different top heights with the same color lines in the left panel. Dash dark line in the right is for clear sky, and pink dash line is for ice cloud with De=30 μm.

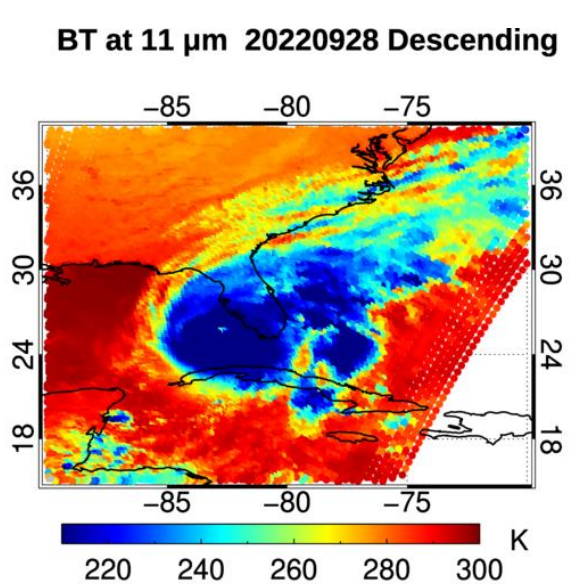
Hurricane Ian

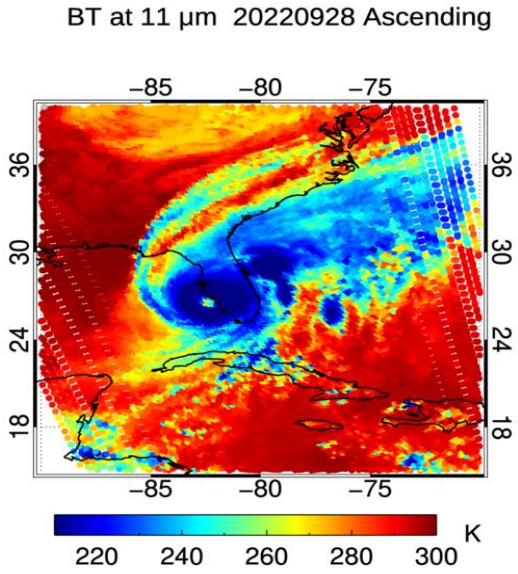


- Hurricane “Ian” is the third-costliest weather disaster on record of USA, and the deadliest hurricane to strike the state of Florida since the 1935.
- Ian was formed as Tropical Storm on 24 September 2022, developed to Category 2 on September 26;
- Then moved to Florida Keys and reached Category 4 intensity on the morning of September 28.
- It proceeded across Central Florida and moved into the Atlantic Ocean at 15:00 UTC on September 29 as a strong tropical storm;



28 Sept 2022





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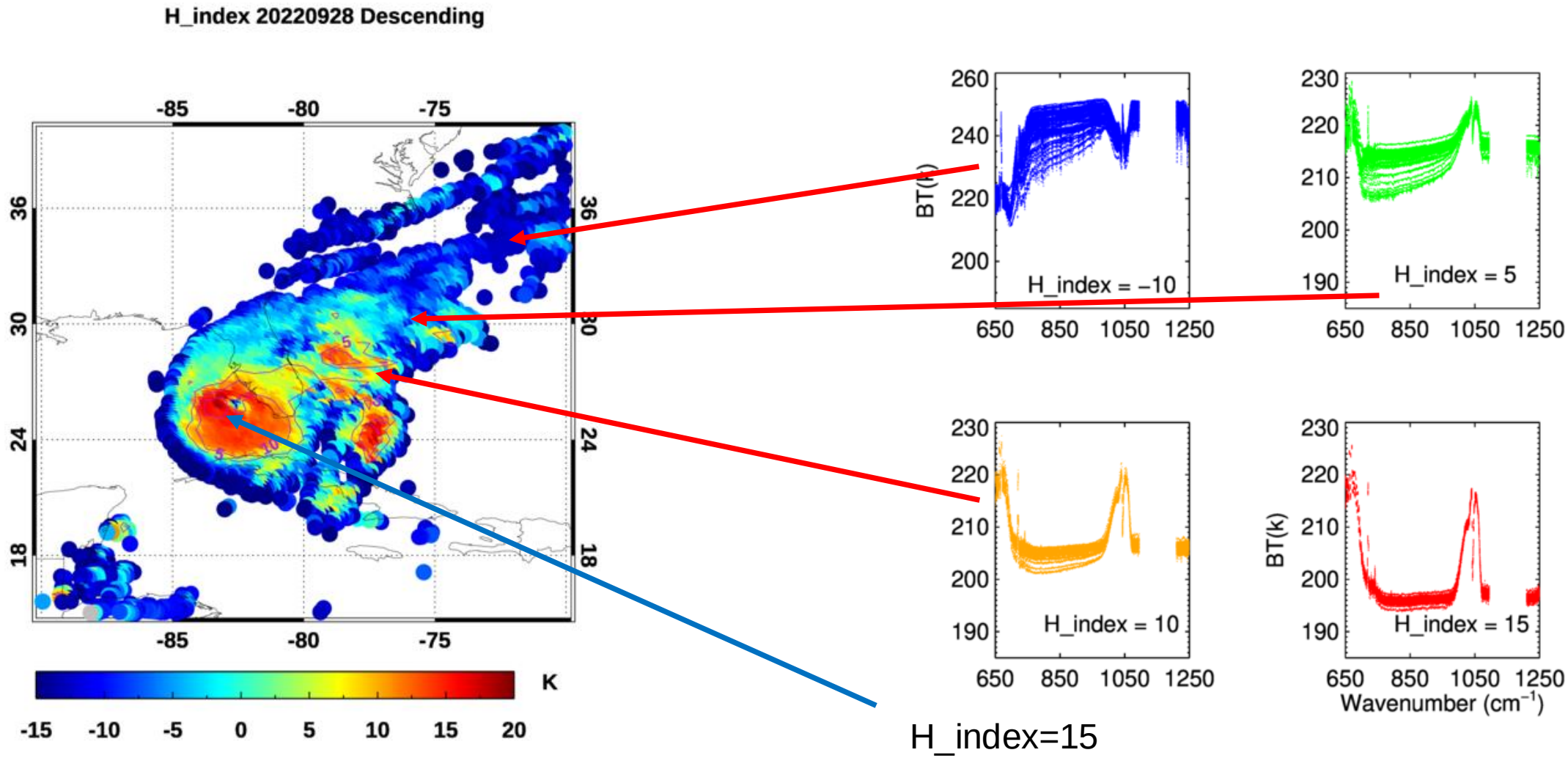
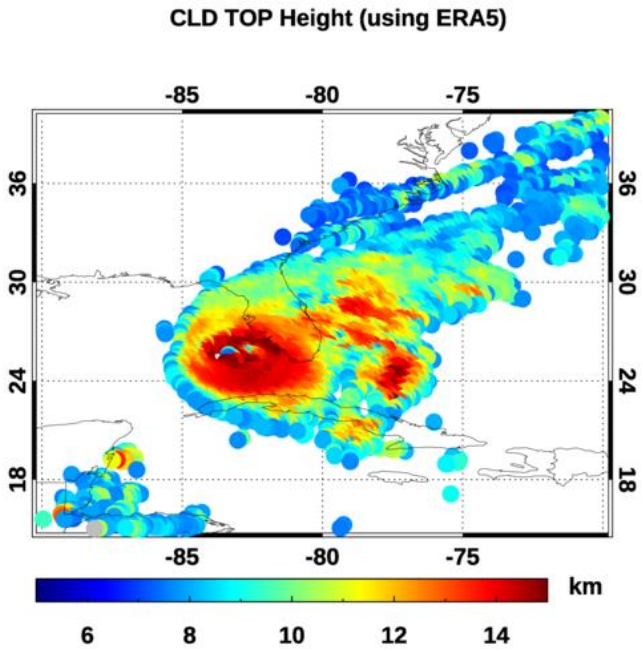
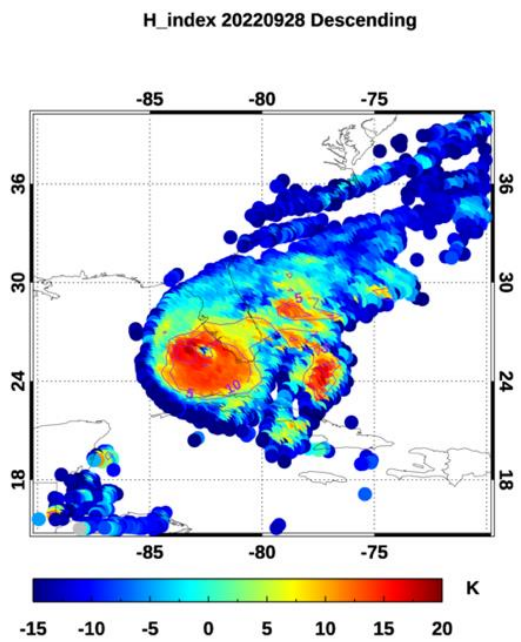
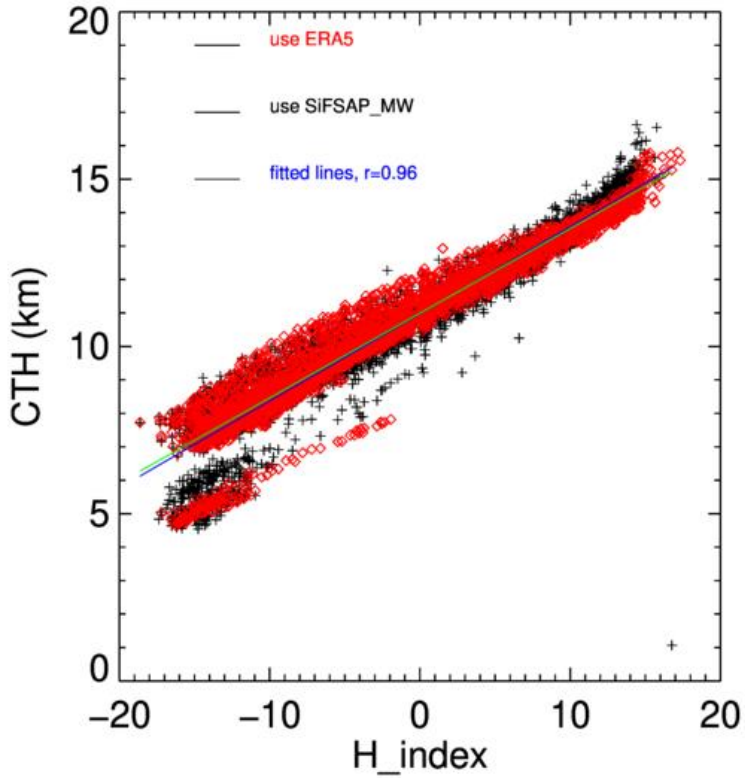
CrIS Measured Spectra for Hurricane Ian



Correlation of H_index with Cloud Top Height (CTH)

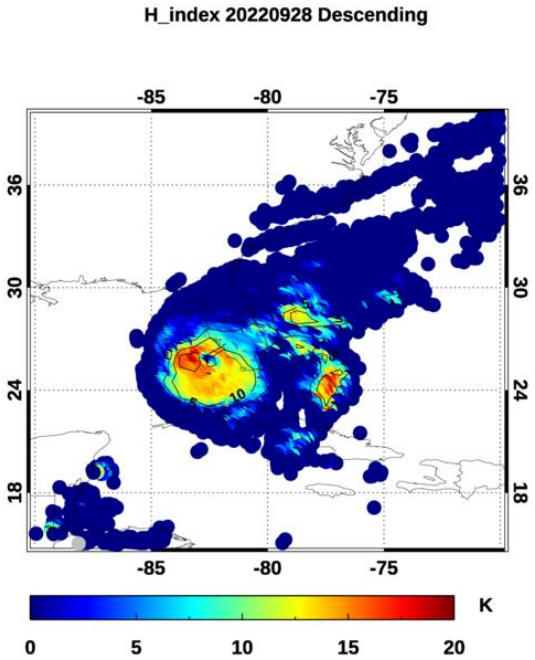




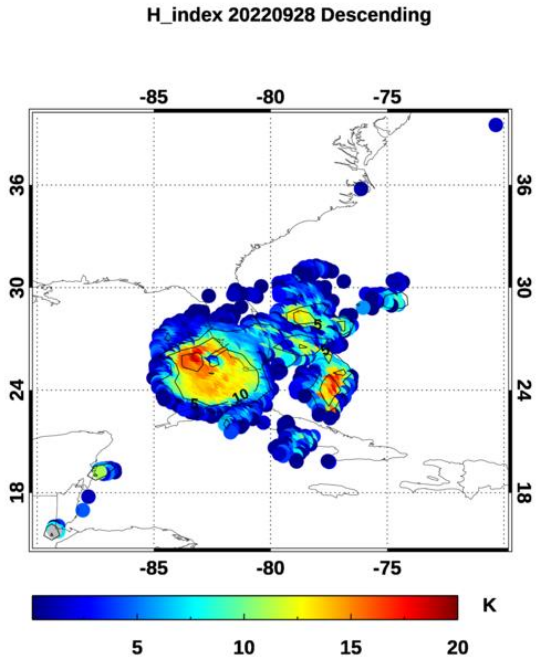


CTH can be determined using CrIS measured brightness temperature at window channel (11 μm), BT11, to fit the ERA-5 temperature profiles collocated with CrIS;

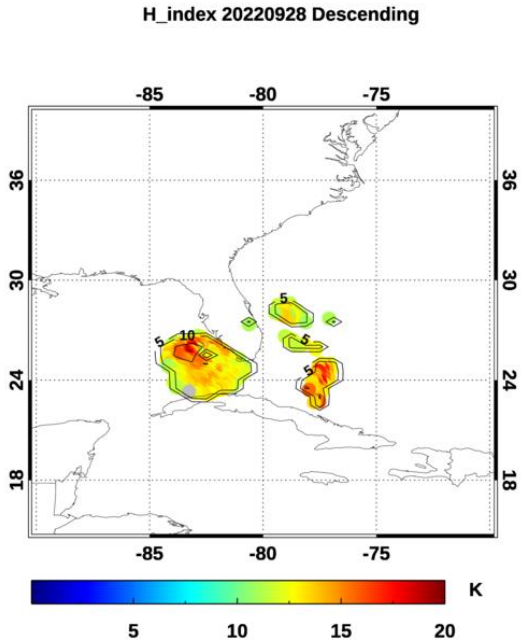
Deep Cloud Area of Ian - mapped using different methods



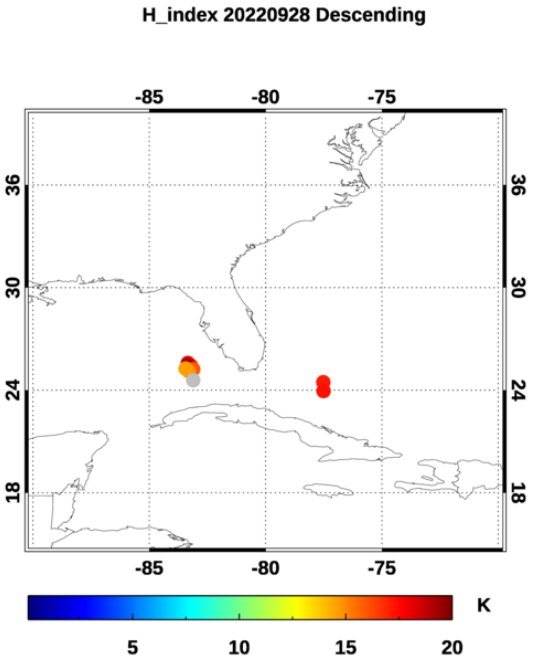
BT11 < -20º



H_index > 0



DT < - 2K



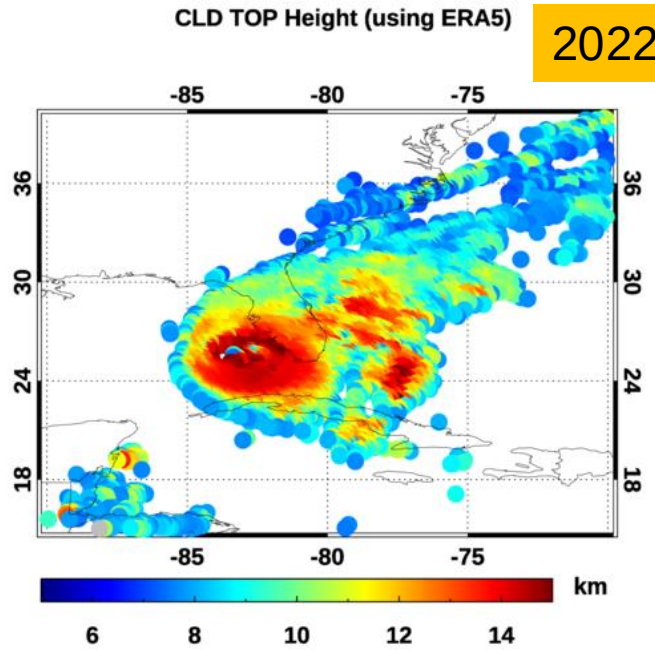
DC < 0 K

- Clouds identified with the simple DT<−2K threshold are within a few hPa of the tropopause.
- If the cloud top is below the tropopause, bt790 is colder than bt961, i.e. BTD>0 K; BTD <0 for cloud top above the tropopause.

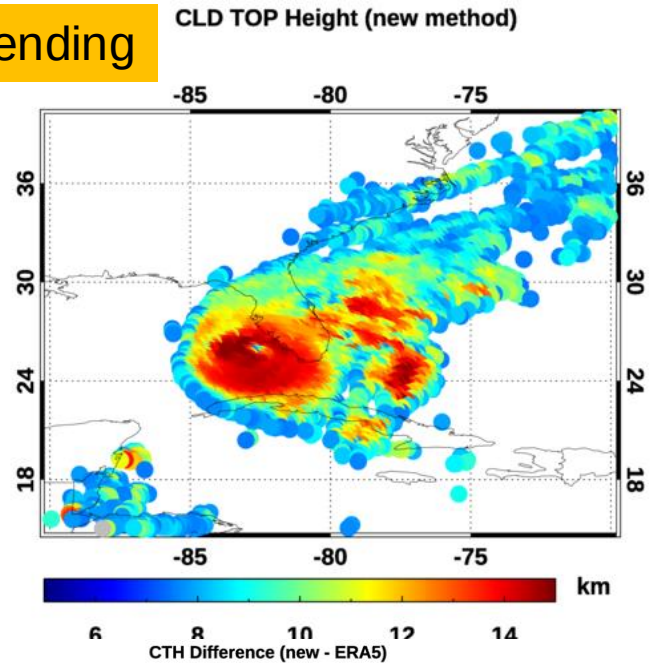
Deep convective clouds with CTH a few hPa of the tropopause

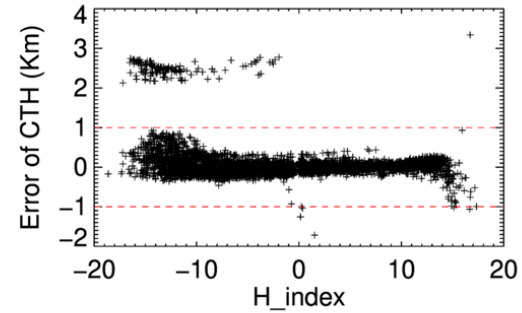
Clouds with CTH above tropopause

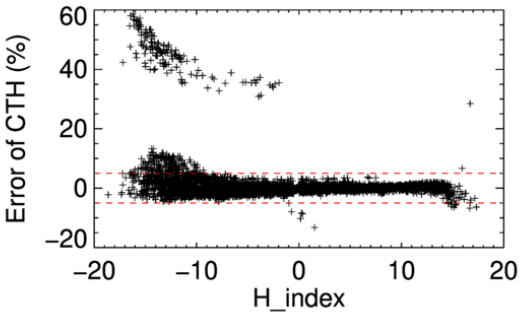
A New Method to Estimate CTH using H_index and BT11



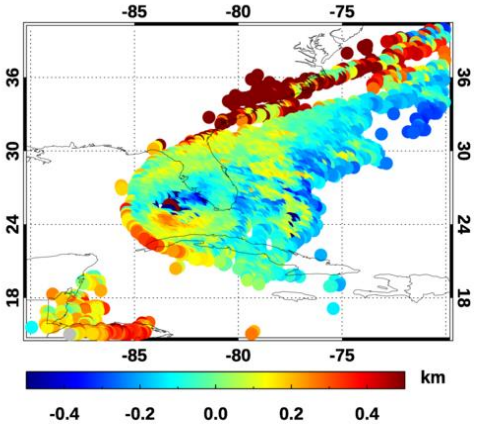
2022-09-28 descending

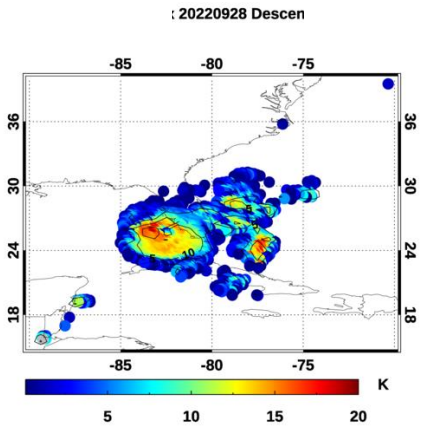






0.017± 0.186 km
(-0.19 ± 2.04 %)



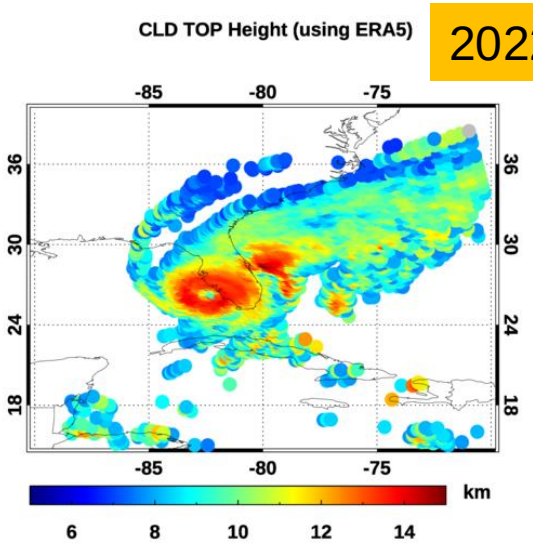


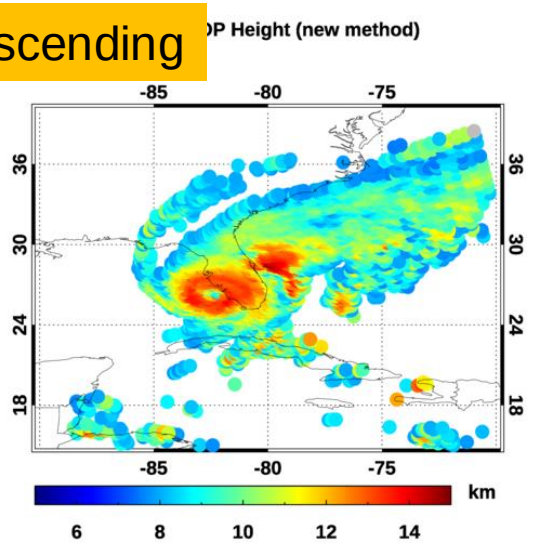
$$CTH = C0 + C1*H\_index + C2*BT11 + C3*Sin(VZA) + C4*BTD_{961\text{-}790}$$

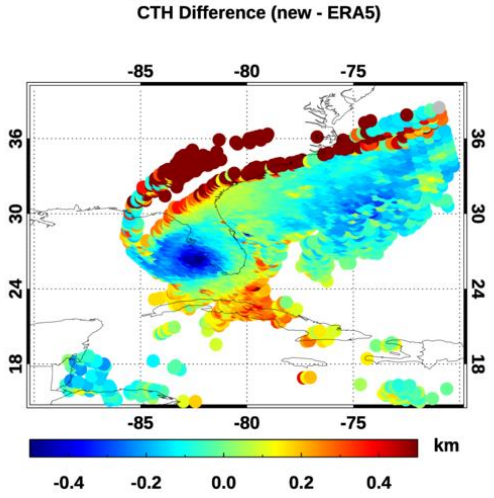
(Fitting using data H_index > 0)

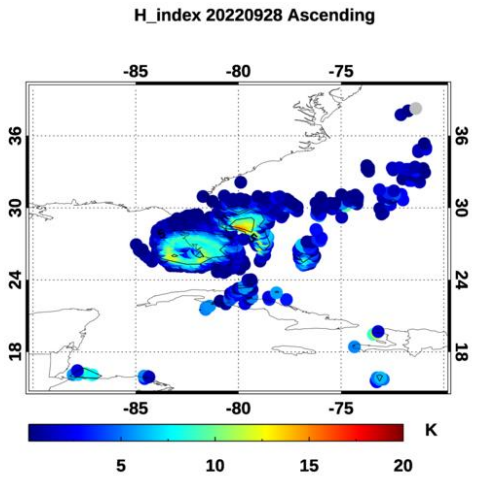
Validation and Applications

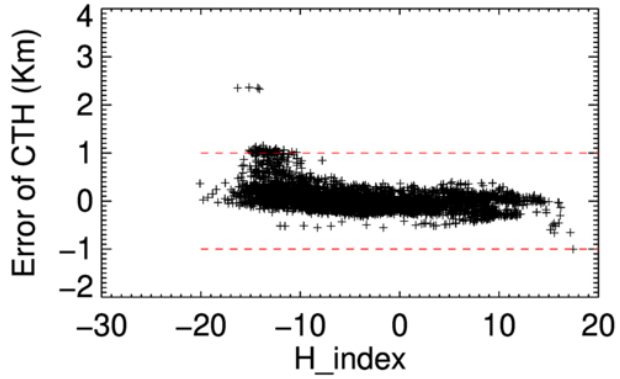
2022-09-28 Ascending

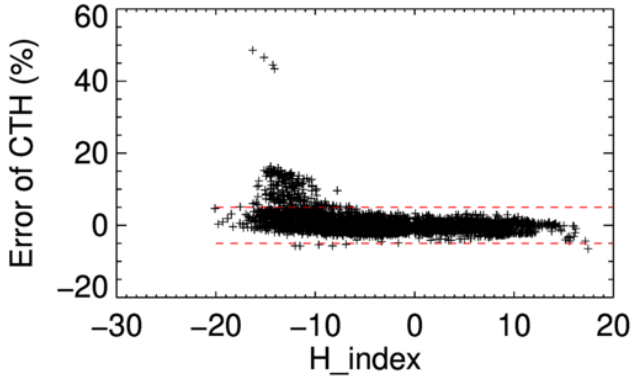






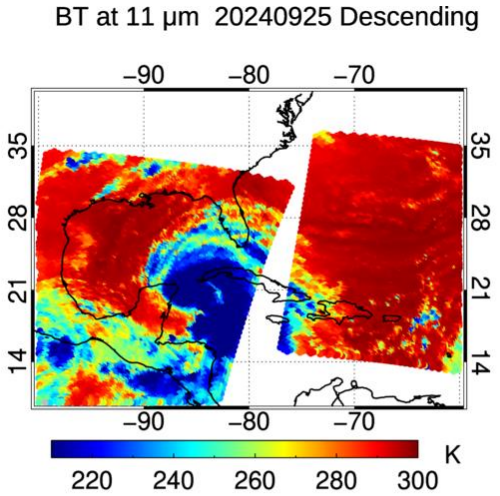


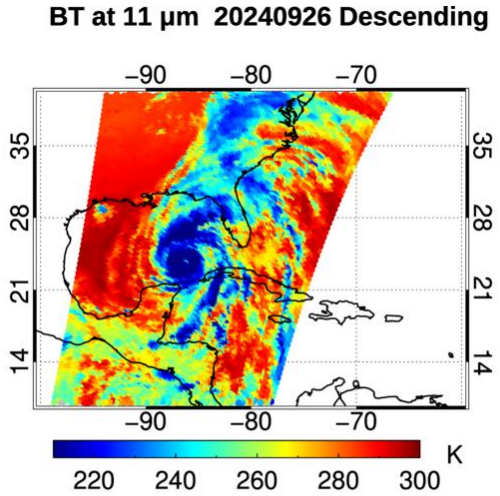


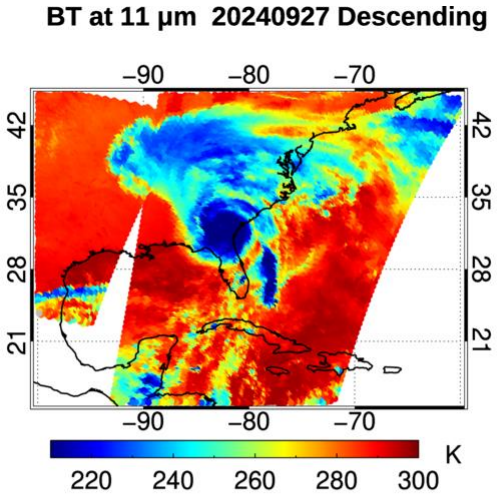


0.361± 0.167 km
(-0.24 ± 1.77 %)

Hurricane Helene



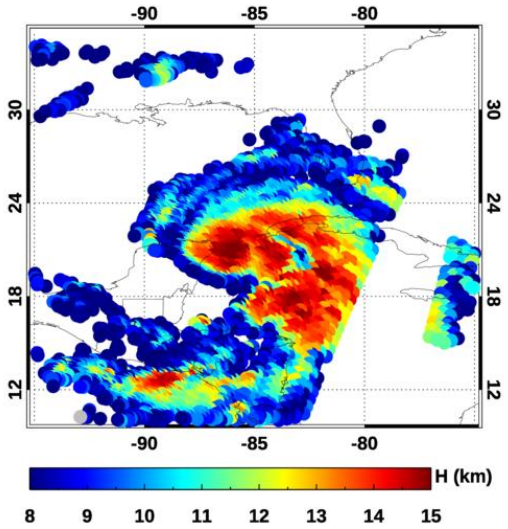




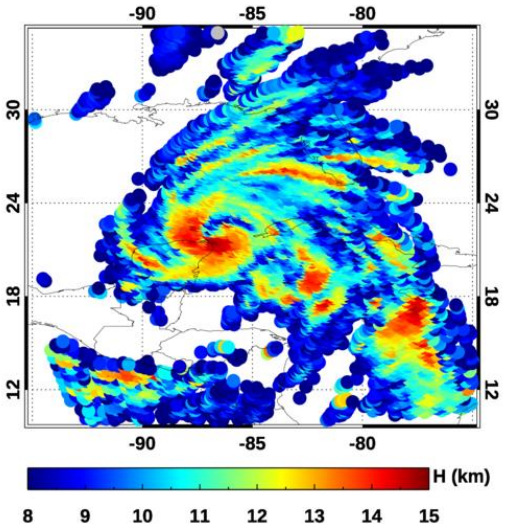
- Helen was the strongest hurricane on record to strike the big Bend region of Florida, and the deadliest to strike the mainland U.S. since Katrina in 2005;
- It became a hurricane early on September 25, 2024, and reached Category 4 intensity on the evening of September 26;
- Helene weakened as it moved quickly inland before degenerating to a tropical cyclone over Tennessee on September 27.

(from https://en.wikipedia.org/wiki/Hurricane_Helene)

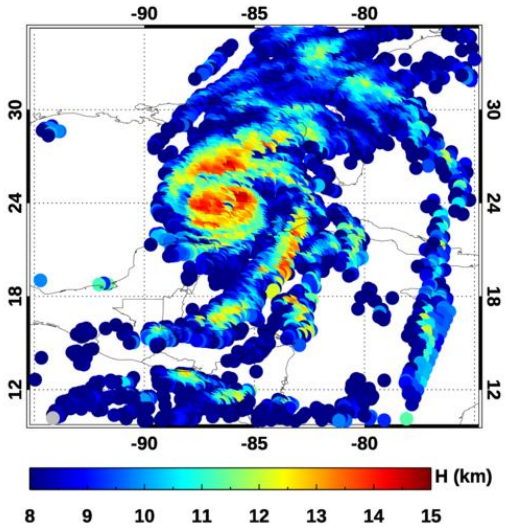
Cloud Top Height 20240925 Descending



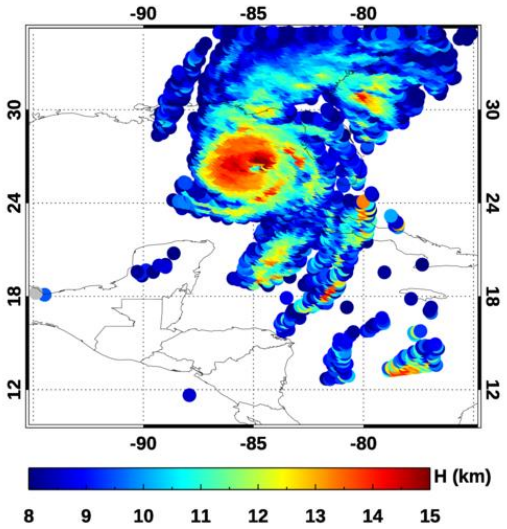
Cloud Top Height 20240925 Ascending



Cloud Top Height 20240926 Descending

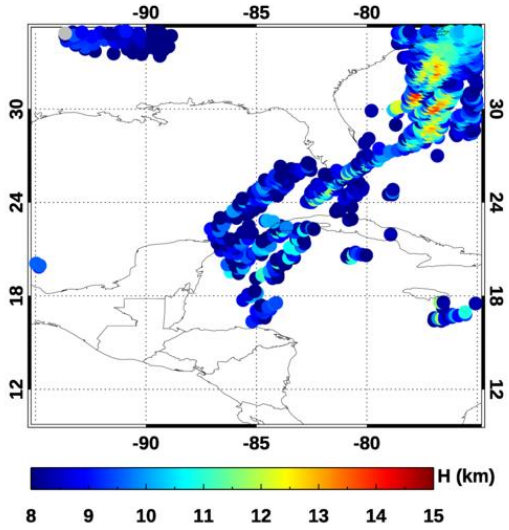


Cloud Top Height 20240926 Ascending

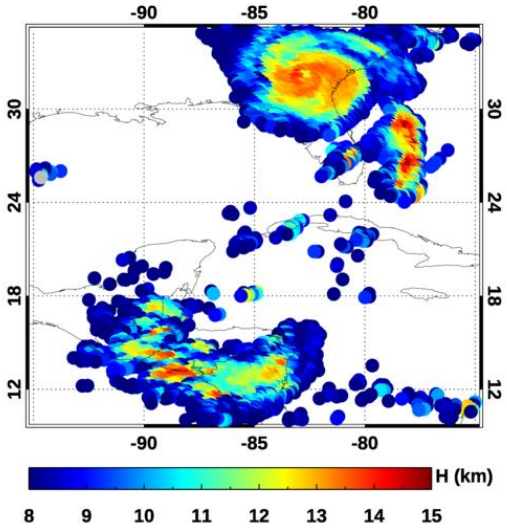


CTH for Hurricane Helene
Sept.25-27
(from J-1)

Cloud Top Height 20240927 Ascending



Cloud Top Height 20240927 Descending



Observation of Hurricane using SiFSAP Products

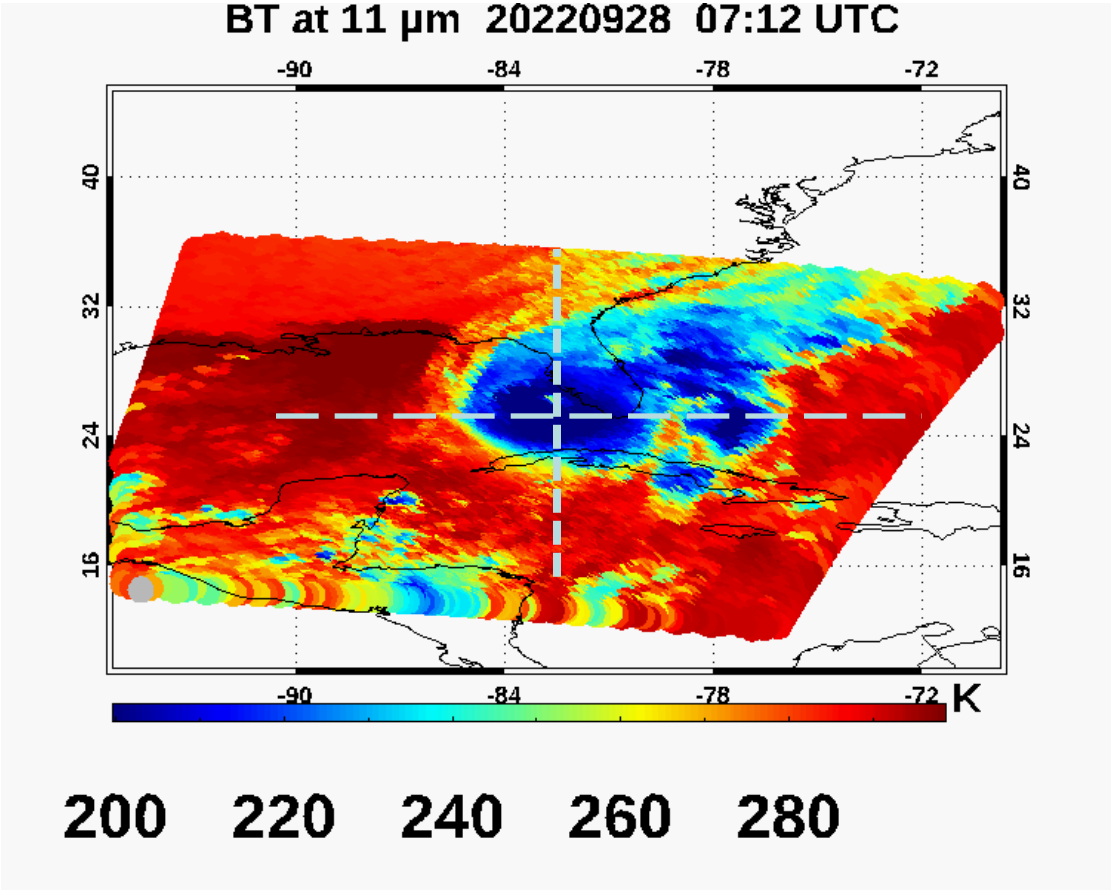
- **The *Cross-track Infrared Sounder (CrIS)* is an advanced Fourier transform spectrometer that measures the thermal infrared radiances in the long-wave IR band 1 (648.75–1096.25 cm^{-1}), the mid-wave IR band 2 (1208.75– 1751.25 cm^{-1}), and the short-wave IR band 3 (2153.75– 2551.25 cm^{-1}) on S-NPP and JPSS series.**

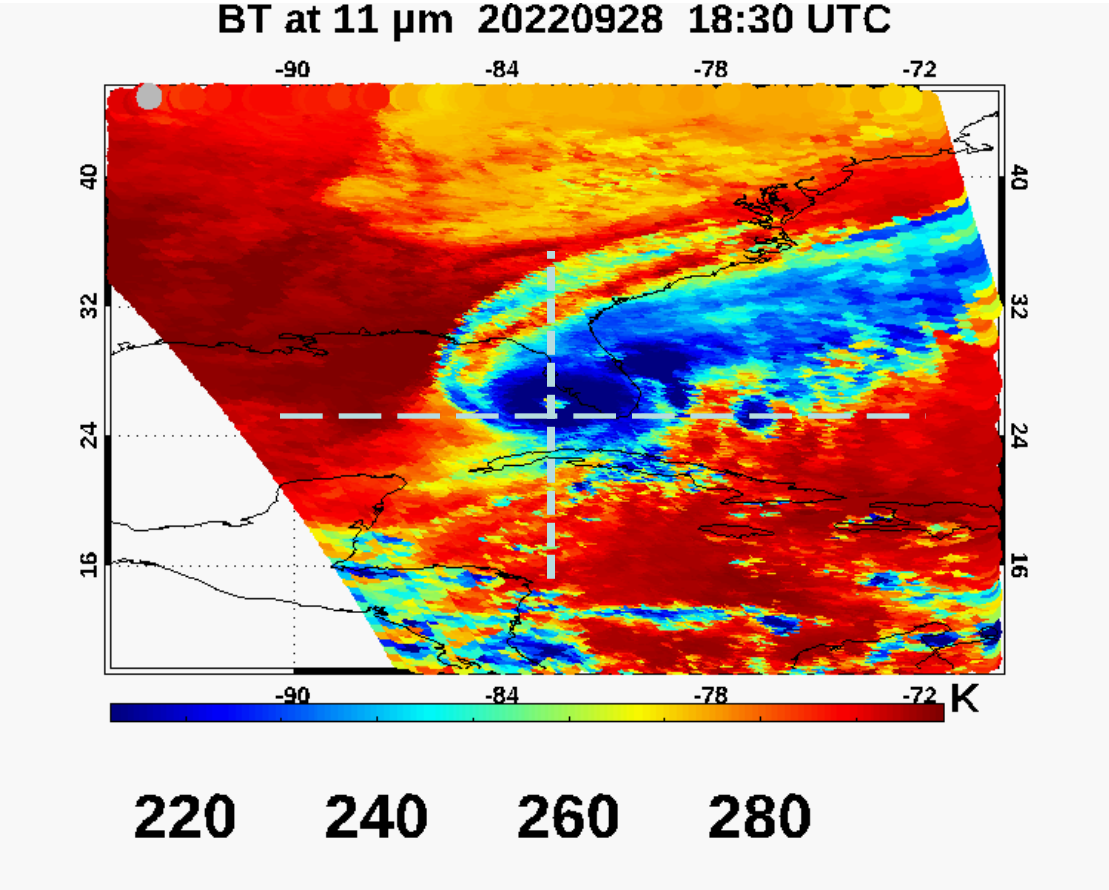
- **SiFSAP is a Single Field-of-View Sounder Atmospheric Products retrieved using CrIS and the Advance Technology Microwave Sounder ATMS. It is based on Principal Component (PC) Radiative Transfer Model (PCRTM) and Optimal Estimation (OE) method. Use of PCRTM**
  - *Enable calculations of whole CrIS spectrum with very fast speed;*
  - *Able to compute cloud multiple scattering accurately;*
  - *Provides Jacobian needed for a physical retrieval algorithm;*

  Using Optimal Estimation (OE) method to do simultaneous retrieval in PC domain
  - *Uses 120-200 PCs- equivalent to use all spectral channels;*
  - *Uses all available spectral information to separate contributions from atmospheric trace gases, cloud and surfaces;*
  - *Uses PCA to reduce random measurement noises;*
  - *No need to account for errors due to non-retrieved parameters (such as those in a sequential inversion algorithm);*

  SiFSAP products (with a high resolution of ~ 14 km at nadir) include
  - *Atmospheric Temperature, Water, CO_2, CO, CH_4, O_3, and N_2O profiles;*
  - *Cloud phase, height, temperature, size, optical depth;*
  - *Surface emissivity spectrum and skin temperature;*

Hurricane Ian on 28 Sept 2022 – “Eye” from Window Channel

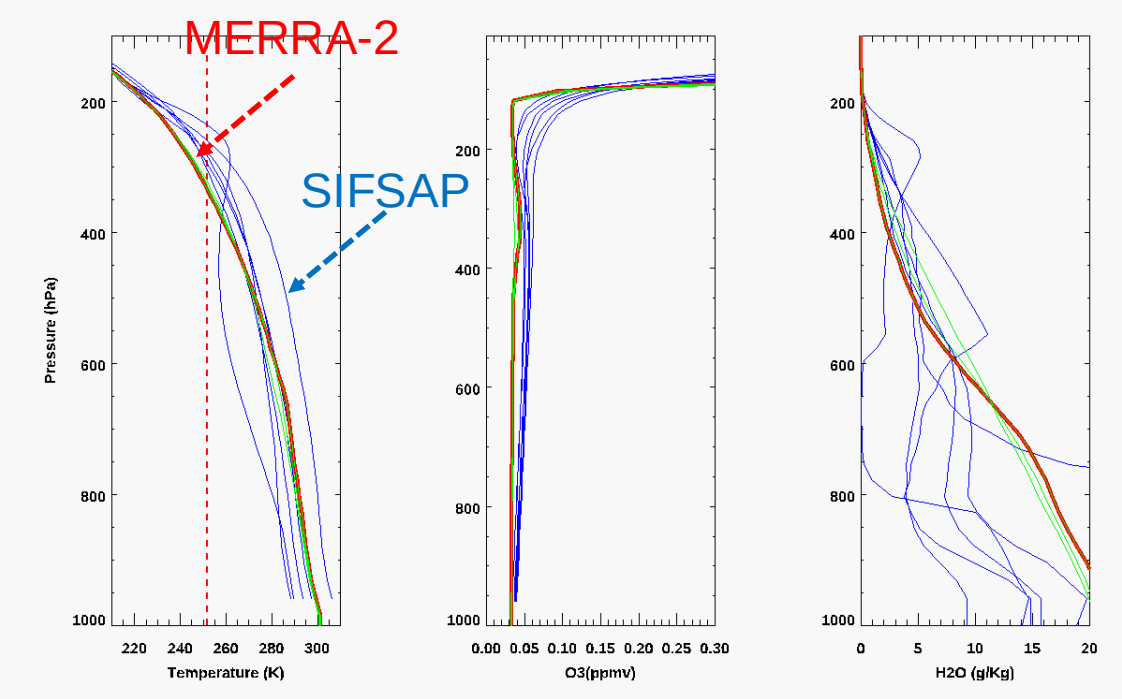


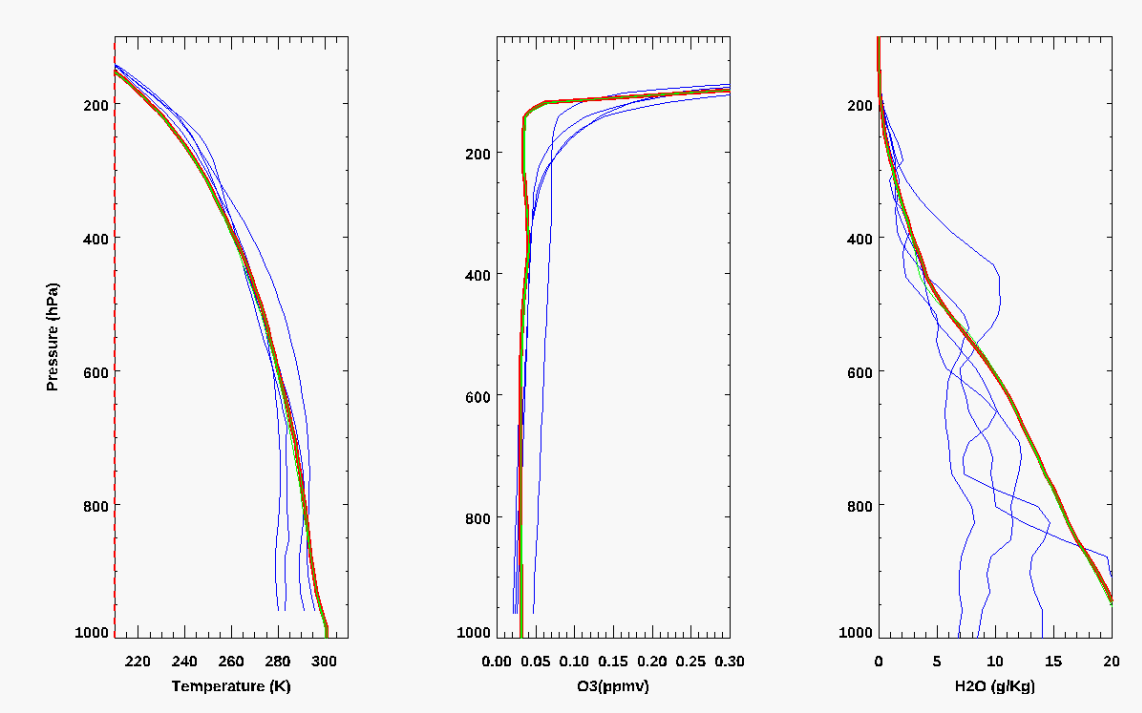


Location of hurricane eye:
(-82.83º, 25.66º) BT11=251.98 K

Eye: (-82.50º, 26.48º,265.3 K)
(-82.35º, 26.45º,260.2 K)
(-82.49º, 26.77º,266.4 K)
(-82.32º, 26.77º,262.0 K)

Comparison of the Profiles near the Hurricane Ian “Eye”





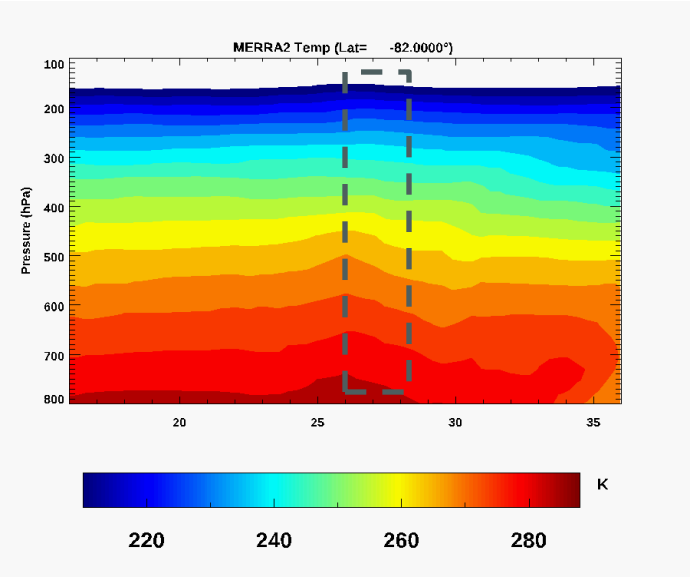
Descending: (-82.83+/-0.5^{o}, 25.66+/-0.5^{o})

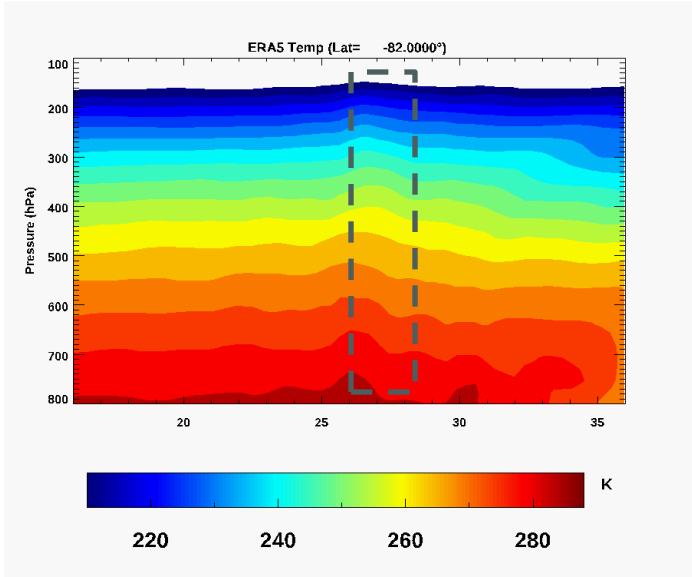
Ascending (right): (-82.69+/- 0.5^{o}, 26.35+/-0.5^{o})

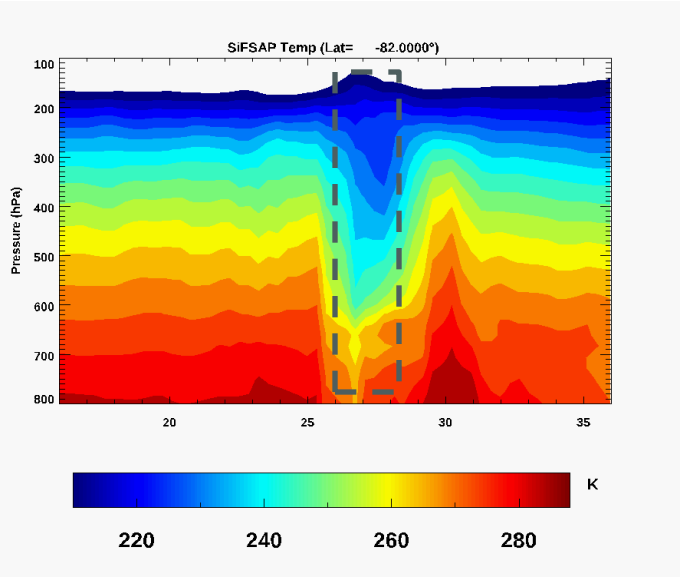
SiFSAP vs MERRA2: (Similar for ERA-5)

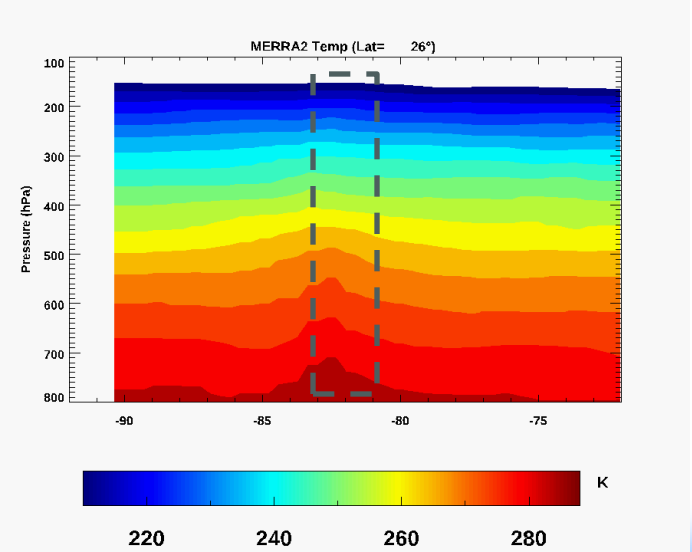
- Better agreement in temperature and ozone;
- Large variability of SiFSAP water vapor - suggesting retrieval of water vapor is harder

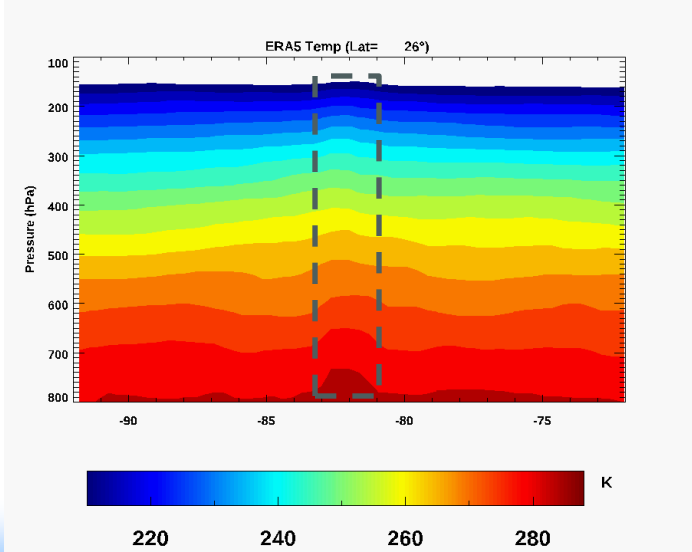
Vertical Cross-sections of Temp from MERRA-2, ERA-5 and SiFSAP
(28 Sept 2022, Ascending)

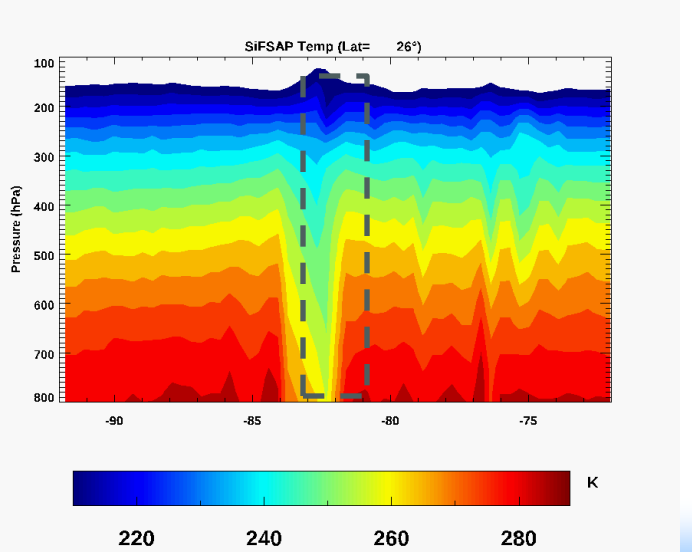












Summary

- **Observation of cloud top height (CTH) of hurricane is important for monitoring its development and dynamics study;**
- **A unique inverted "V" feature for the spectrum near O3 band (9.6 μm) from hyperspectral sounders can be used to identified deep convective cloud of TC, and its height of inverted V, H_index, can be used to estimate hurricane CTH;**
- **It is estimated that the difference of the CTH estimated using this new method is less than 0.5 km or 5% as compared to the CTH estimated using the BT11 fitted to the temperature profiles. More validation is ongoing!**
- **As this method uses the spectra information only, it can be used easily for near real-time monitoring of Hurricane;**
- The Single FOV Sounder Atmospheric Products (SiFSAP), with a spatial resolution of ~14km, can be used *to measure the temperature, water vapor, ozone profiles* ***near the eye of hurricane Ian***.

  Temperature:
  - Warm center around hurricane "Eye" at 200 hPa from SiFSAP, which is in consistent with with ERA-5 and MERRA-2;
  - Different from models that show a warm core of hurricane, SiFSAP shows a cold core from tropopause down to ~400 hPa.

  Water Vapor:
  - Large variation from SiFSAP demonstrates that it is very challenging in H_2O retrieval.

References

- Xiong, X., Liu, X. Wu, W., Knowland, K.E., Yang, Q., Welsh, J., Zhou, D.K., 2022: Satellite observation of stratospheric intrusions and ozone transport using CrIS on SNPP. *Atmos. Environ.* 2022, *273*, 118956. https://doi.org/10.1016/j.atmosenv.2022.118956.
- Xiong, X., Liu, X. Wu, W., Knowland, K.E., Yang, Q., Wyang, F., Zhou, D.K., 2022: Impact of Stratosphere on Cold Air Outbreak: Observed Evidence by CrIS on SNPP and Its Comparison with Models, *Atmosphere* 2022, *13*(6), 876; https://doi.org/10.3390/atmos13060876.
- Liu, X.; Smith, W.L.; Zhou, D.K.; Larar, A. Principal component-based radiative transfer model for hyperspectral sensors: Theoretical concept. *Appl. Opt.* 2006, *45*, 201–209.https://doi.org/10.1364/AO.45.000201.
- Liu, X.; Yang, Q.; Li, H.; Jin, Z.; Wu, W.; Kizer, S.; Zhou, D.K.; Yang, P. Development of a fast and accurate PCRTM radiative transfer model in the solar spectral region. *Appl. Opt*. 2016, *55*, 8236–8247.
- Liu, X.; Zhou, D.K.; Larar, A.M.; Smith, W.L.; Schluessel, P.; Newman, S.M.; Taylor, J.P.; Wu, W. Retrieval of atmospheric profiles and cloud properties from IASI spectra using super-channels. *Atmos. Chem*. *Phys*. 2009, *9*, 9121–9142. https://doi.org/10.5194/acp-9-9121-2009.
- Wu, W.; Liu, X.; Zhou, D.K.; Larar, A.; Yang, Q.; Kizer, S.; Liu, Q.The Application of PCRTM Physical Retrieval Methodology for IASI Cloudy Scene Analysis. *IEEE Trans. Geosci*. *Remote Sens.* 2017, *55*, 5042–5056 . https://doi.org/10.1109/TGRS.2017.2702006.

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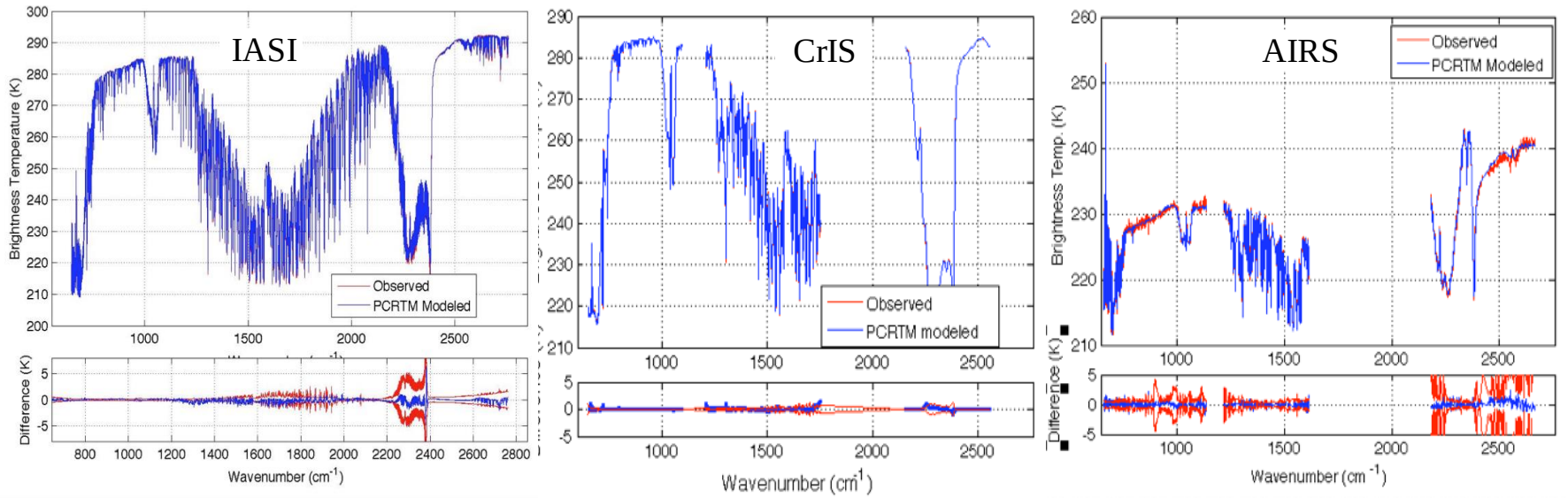
PCRTM Forward Model is Accurate and Fast



Sensor	Channel Number	PC score (seconds)	PC score + radiance	PC score + PC Jacobian
CLARREO, 0.1 cm^{-1}	19901	0.014 s	0.022 s	0.052 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s	0.013 s	0.039 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s	0.012 s	0.036 s
IASI, 0.25 cm^{-1}	8461	0.011 s	0.012 s	0.044 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s	0.0074 s	0.031 s
CrIS,0.625-2.5 cm^{-1}	1317	0.0050 s	0.0060 s	0.021 s
NAST-I, 0.25 cm^{-1}	8632	0.010 s	0.013 s	0.045 s
S-HIS, 0.5 cm^{-1}	4316	0.008 s	0.008 s	0.038 s
CrIS, 0.625 cm^{-1}	2211	0.009 s	0.009 s	0.033 s

- Spectral coverage (50-3000 cm^{-1})
- Multilayer, multiple scattering clouds included
- 15 variable trace gases
- Output analytical Jacobians
- Very accurate relative to Line-by-Line RT
  - Bias error < 0.002 K
  - RMS error < 0.03K
- 4 orders of magnitude faster than LBLRTM