GEO IR Sounder Case Study: Multi-Band Retrieval Simulation and Forecast OSSE Results

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Overview

- **GEO IR Sounder was developed in response to BAA-NOAA-GEO-2019, capable of NWP and atmospheric composition measurements.**

- **GEO IR Sounder combines thermal emission and reflected solar bands (like combining CrIS and GeoCARB) in one integrated instrument package:**
  – Co-registered field of view in both bands
  – Both bands measured at same time of day
  – Reflected solar band improves sensitivity to lower troposphere and near surface
  – Greater societal impact than stand-alone NWP and atmospheric composition measurements

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Overview (Continued)

- **Instrument system simulations flow-down from scientific requirements to measurement requirements to instrument requirements:**
  - Simulated different choices of instrument and operation parameters into the retrieved temperature, water vapor and trace gas profiles.
  - Improved weather forecast accuracy by incorporating temperature and water vapor retrievals into regional OSSE framework.
- **Combined multi-band retrieval improves storm intensity, structure and track forecast accuracy, and benefits air quality and climate research.**

Contributors

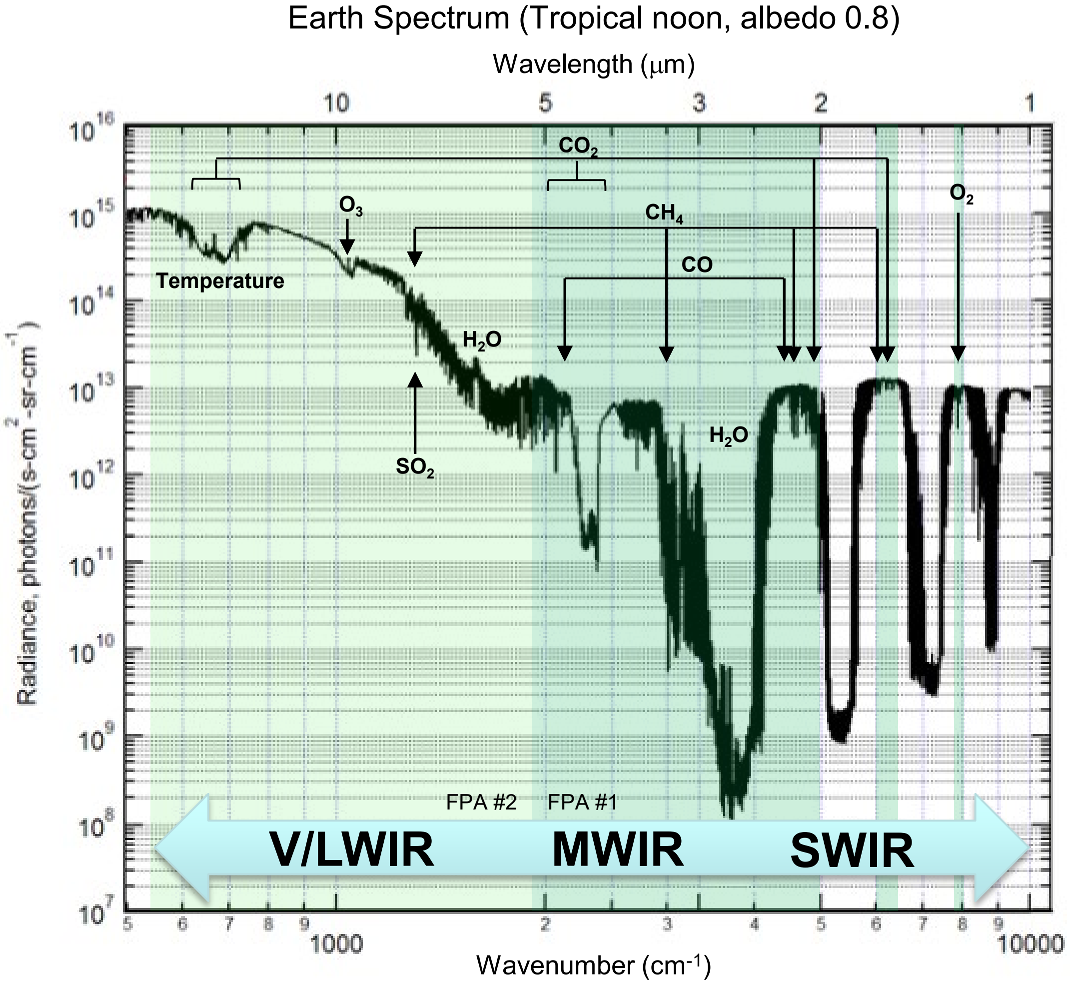
- **Simulated Retrievals**
  – Ming Luo, Jean-Francois Blavier, Vivienne Payne, Zhao-Cheng Zeng
- **Weather OSSE**
  – Longtao Wu, Jacola Roman
- **Instrument/Science/Management**
  – James Wu, Stan Sander, Len Dorsky

Definition of Spectral Ranges

Designation	Spectral Range (μm)	Spectral Range (cm^{-1})
VLWIR	> 10	< 1,000
LWIR	5-10	1,000-2,000
MWIR	3-5	2,000-3,333
SWIR	1-3	3,333-10,000
NIR	0.7-1	10,000-14,286
Visible	0.38-0.7	14,286-26,316
UV	< 0.38	> 26,316
TIR	> 3	< 3,333

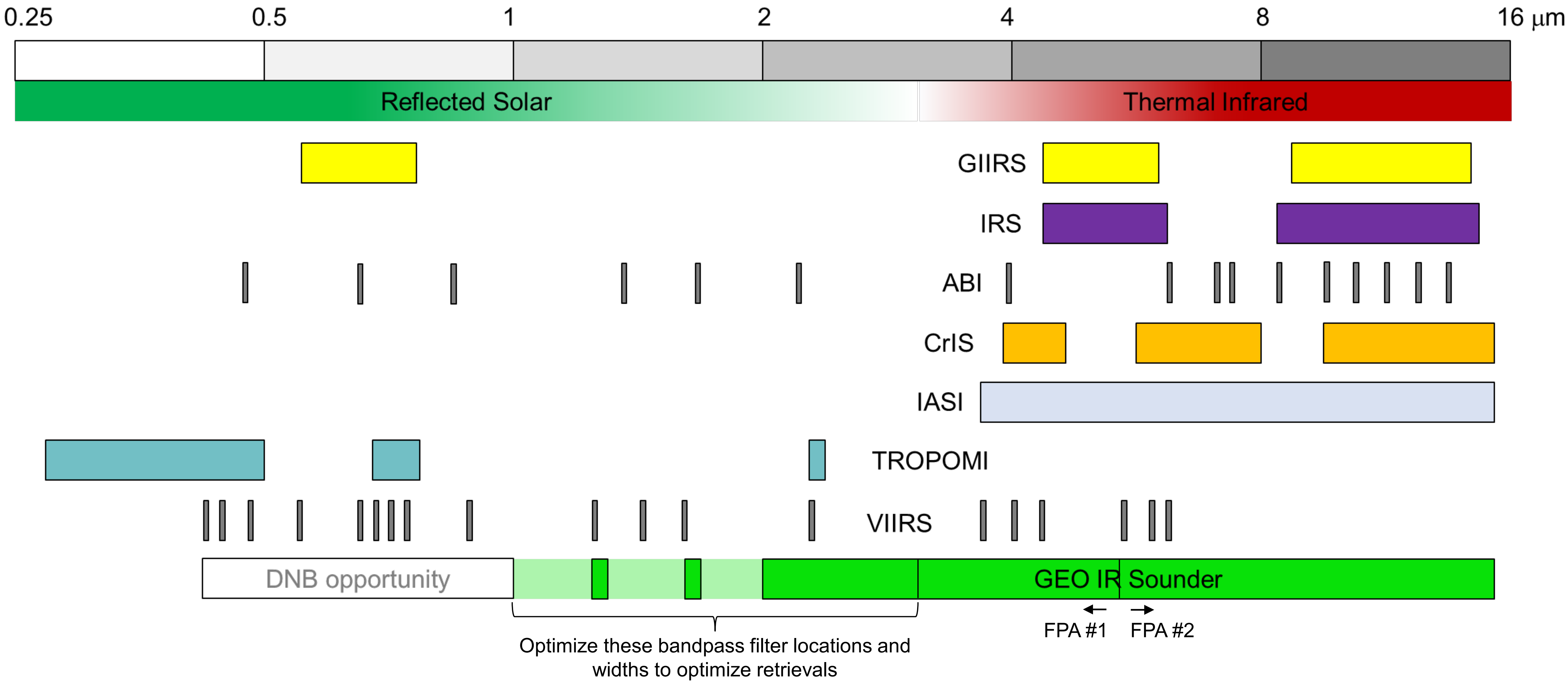
Wide Spectral Range Improves Vertical Profiling of Temperature, Water Vapor and Trace Gases

The combination of wide spectral range, megapixel chemical imaging and high spectral resolution meets and exceeds NOAA's requirements for its next-generation geostationary sounder suite



- The wide spectral range of GEO IR Sounder permits operation in multiple wavebands (thermal infrared to short wave infrared).
- This capability increases the information content of retrievals to improve vertical profiling.
- High spectral resolution (up to 0.1 cm^{-1}) and wide spectral range (1-15.4 μm) enable simultaneous observations of reflected sunlight and thermal emission (day/night) for meteorological sounding (temperature, humidity) for NWP and trace gases (CO_2, CH_4, CO, SO_2, O_3) targeted by the NOAA AC4 program.

Comparisons to State-of-the-Art, Spectral Range



Considerations for Simulated Retrievals

- **The impact of satellite observations on our ability to forecast and monitor weather and air quality events depends on characteristics of the satellite products, including:**
  - Accuracy
  - Vertical resolution
  - Horizontal resolution

- **The characteristics of the remotely sensed products depend on the details of the instrument.**

- **Factors to consider:**
  - Spectral coverage
  - Spectral resolution
  - Signal-to-noise

Approach

- **Multispectral: SWIR and TIR to match the 1–15.4 μm spectral range of the GEO-IR instrument and to maximize information content**

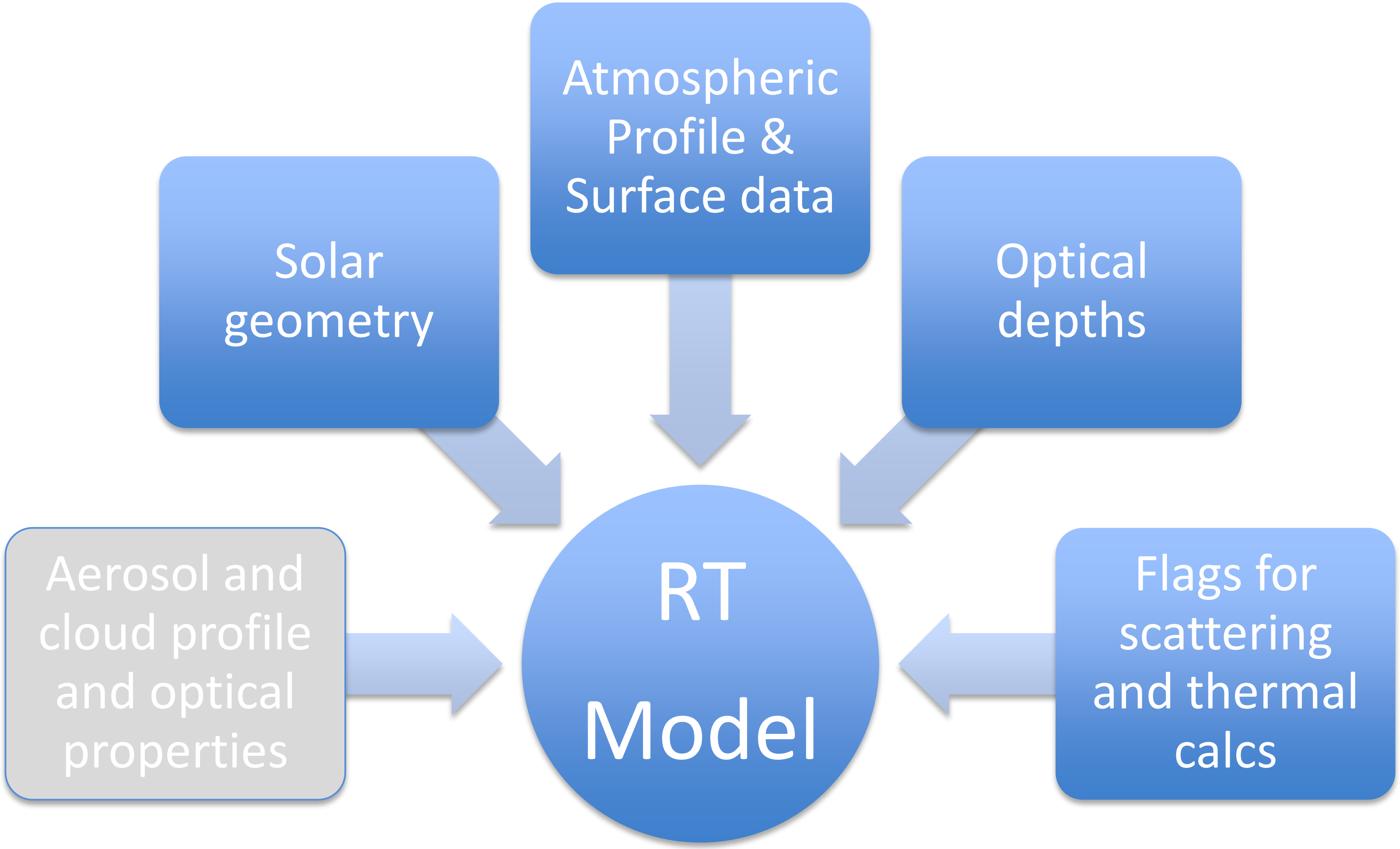
- **Multispecies: Temperature, H_2O, O_3, CO, CO_2, CH_4**

- **Radiative transfer: Two-Stream-Exact-Single-Scattering (2S-ESS) model (fast/accurate)**

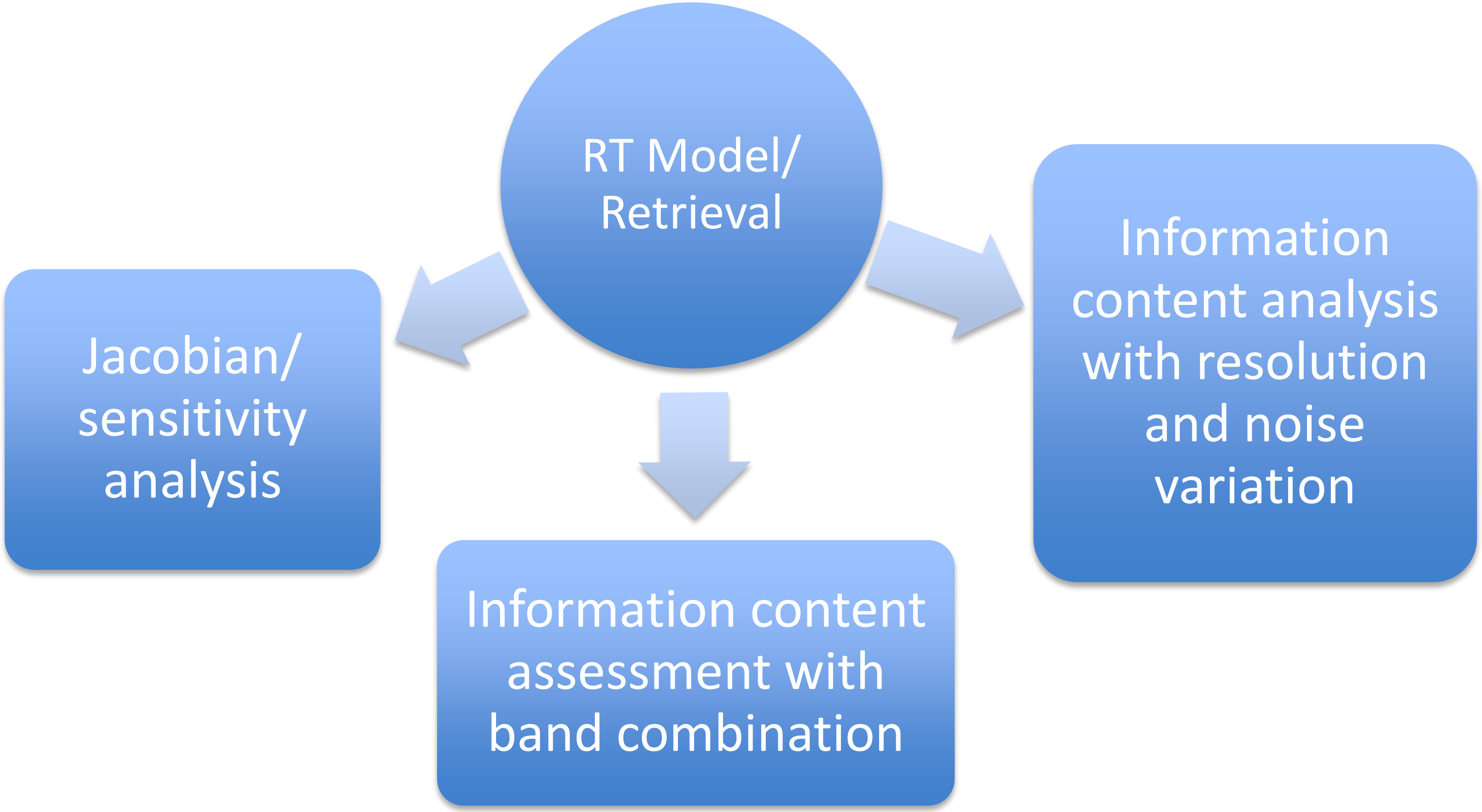
- **Retrievals: optimal estimation**

- **Profiles obtained from WRF-Chem simulations over Houston and W. Virginia**

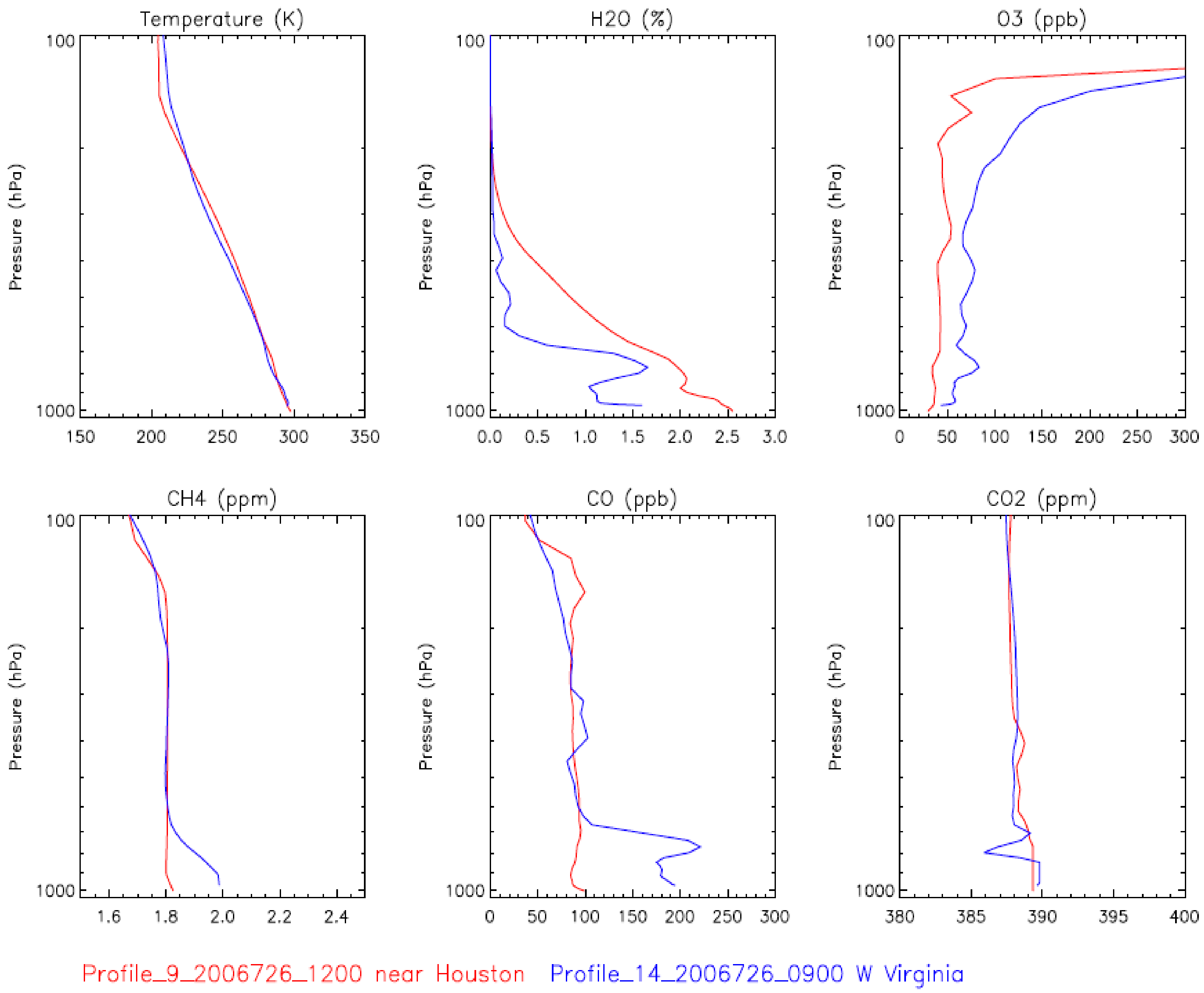
Inputs to the Radiative Transfer Simulations



Radiative Transfer/Retrieval Outputs

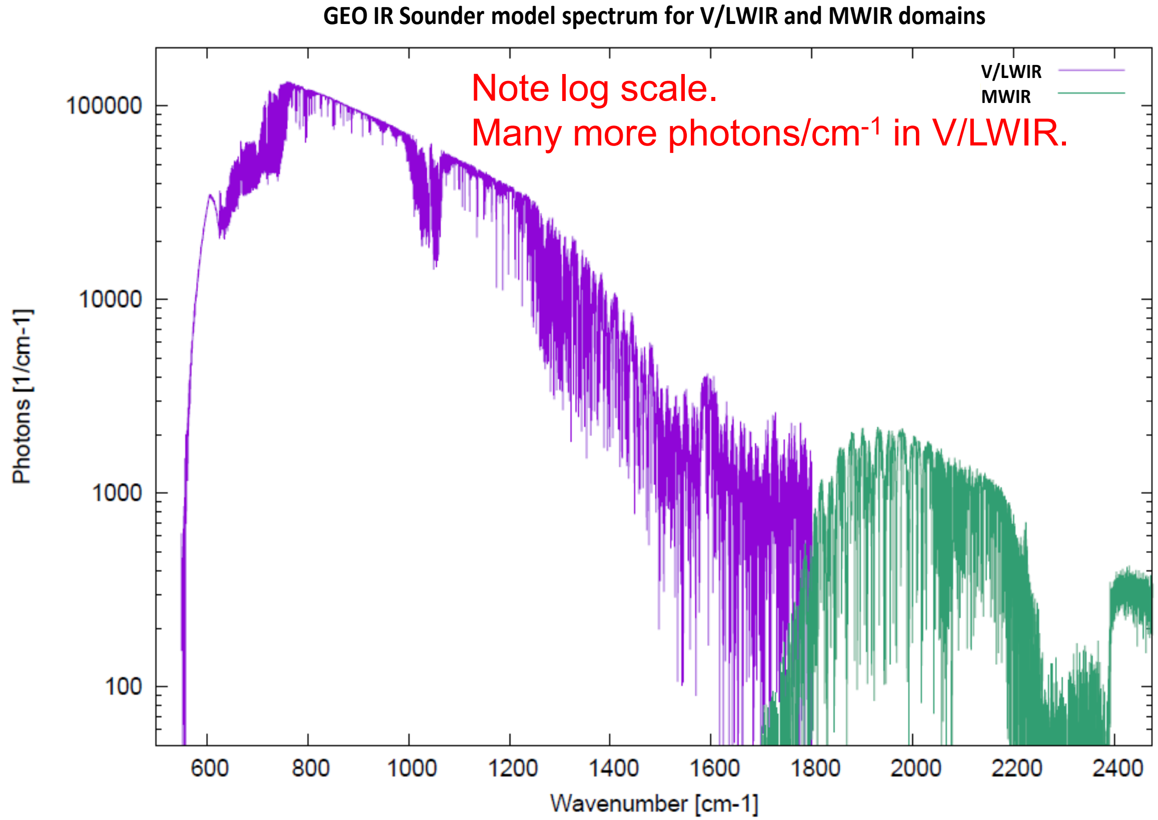


Profiles

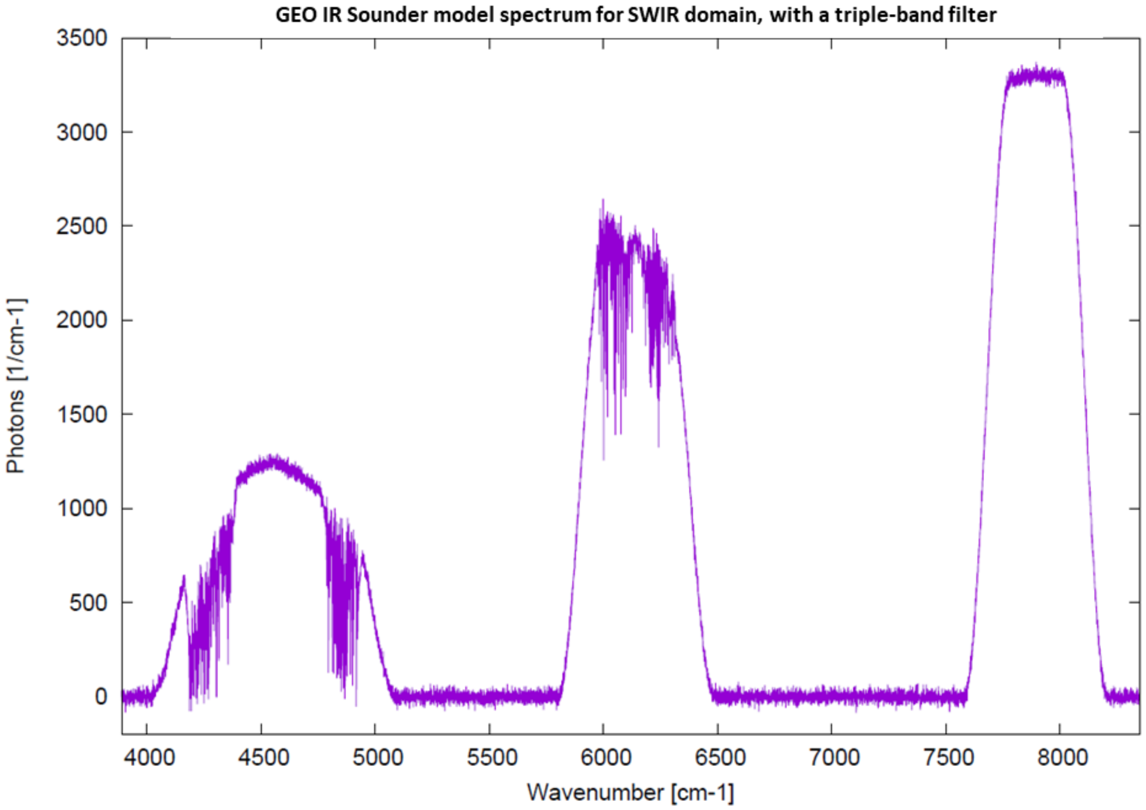

Temperature (K)
Pressure (hPa)
100
1000
150 200 250 300 350
H2O (%)
Pressure (hPa)
100
1000
0.0 0.5 1.0 1.5 2.0 2.5 3.0
O3 (ppb)
Pressure (hPa)
100
1000
0 50 100 150 200 250 300
CH4 (ppm)
Pressure (hPa)
100
1000
1.6 1.8 2.0 2.2 2.4
CO (ppb)
Pressure (hPa)
100
1000
0 50 100 150 200 250 300
CO2 (ppm)
Pressure (hPa)
100
1000
380 385 390 395 400
Profile_9_2006726_1200 near Houston
Profile_14_2006726_0900 W Virginia

Instrument Model

Thermal IR

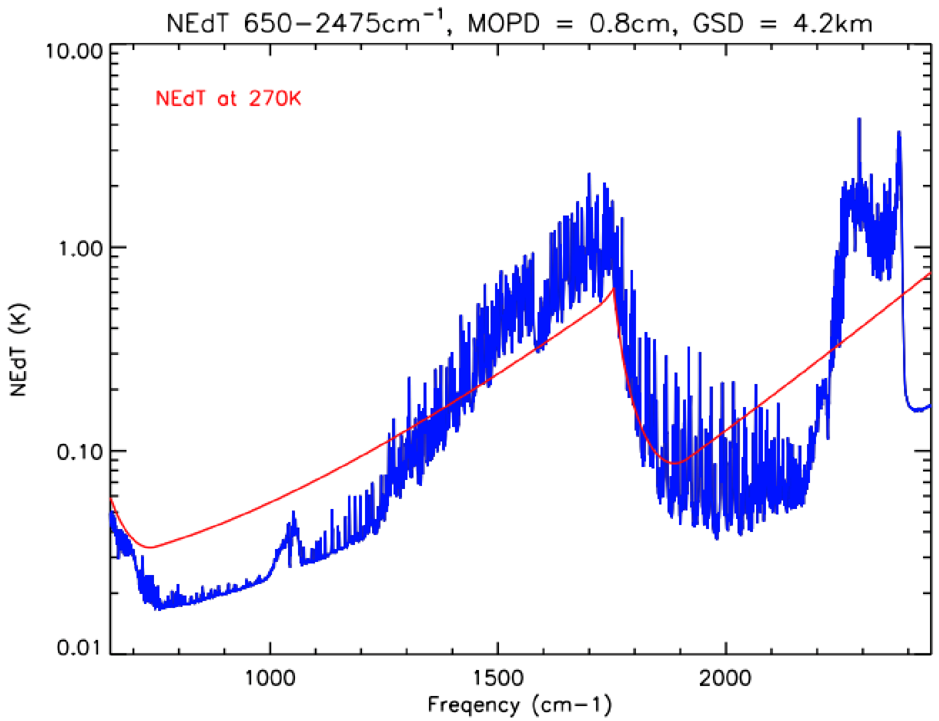


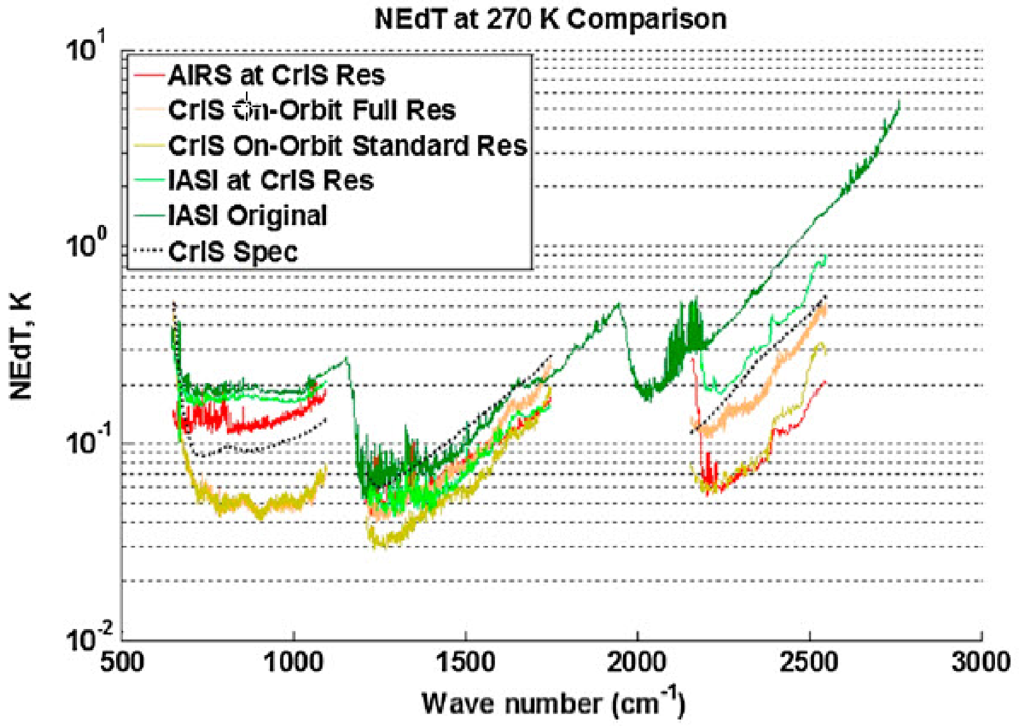
Shortwave IR



- **SWIR region includes spectral information that adds near-surface information for CH_4, CO_2 and CO**
- **SWIR has been band-limited here to maximize signal-to-noise in region where radiance is low**
- **Selected bands are configurable. Possible to include additional band, e.g., targeted for PBL H_2O**

Instrument Noise: Example for 4.2 km GSD





- Instrument noise model accounts for
  - Trade-offs between spectral resolution and noise
  - Trade-offs between horizontal resolution (GSD) and noise (4.2 km GSD results in lower noise)
  - Impacts of choice of spectral bands on noise

Optimal Estimation Approach

- **Optimal estimation retrieval provides estimates of**
  - Vertical sensitivity and retrieval error
- **Averaging kernels (AK)**
  - Sensitivity of retrieval to true atmospheric state
  - Depends both on instrument characteristics and choice of retrieval constraints
- **Trace of AK: Degrees of Freedom for Signal (DOFS)**
  - Number of **independent pieces of vertical information** in the retrieval
- **Width of the rows of AK**
  - Measure of **vertical resolution**

DOFS: Temperature Retrievals

Frequency Domain	DOFS (MOPD = 5 cm)		DOFS (MOPD = 2 cm)		DOFS (MOPD = 0.8 cm)	
	2.1 km GSD	4.2 km GSD	2.1 km GSD	4.2 km GSD	2.1 km GSD	4.2 km GSD
V/LWIR	13.6	17.6	14.2	17.9	14.3	17.9
MWIR	5.1	7.9	5.8	8.3	6	8.1
V/LWIR+MWIR	13.8	17.8	14.4	18.1	14.5	18.1
SWIR	0.2	1.6	0.3	1.8	0.4	2.0
V/LWIR+MWIR+SWIR	13.8	17.9	14.6	18.3	14.7	18.4

- Small changes with MOPD, but systematic errors ignored here
- 4.2 km GSD provides larger DOFS than 2.1 km
- Most information comes from LWIR

DOFS: H_2O Retrievals

Frequency Domain	DOFS (MOPD = 5 cm)		DOFS (MOPD = 2 cm)		DOFS (MOPD = 0.8 cm)	
	2.1 km GSD	4.2 km GSD	2.1 km GSD	4.2 km GSD	2.1 km GSD	4.2 km GSD
V/LWIR	7.9	11.2	8.2	11.3	8.2	11.2
MWIR	4.6	6.9	5.0	7.3	4.6	6.6
V/LWIR+MWIR	8.3	11.8	8.8	12.1	8.6	11.9
SWIR	1.2	2.2	1.3	2.1	1.4	2.1
V/LWIR+MWIR+SWIR	8.3	12.1	8.9	12.3	8.7	12.1

- Small changes with MOPD, but systematic errors ignored here
- 4.2 km GSD provides larger DOFS than 2.1 km
- Most information comes from LWIR+MWIR

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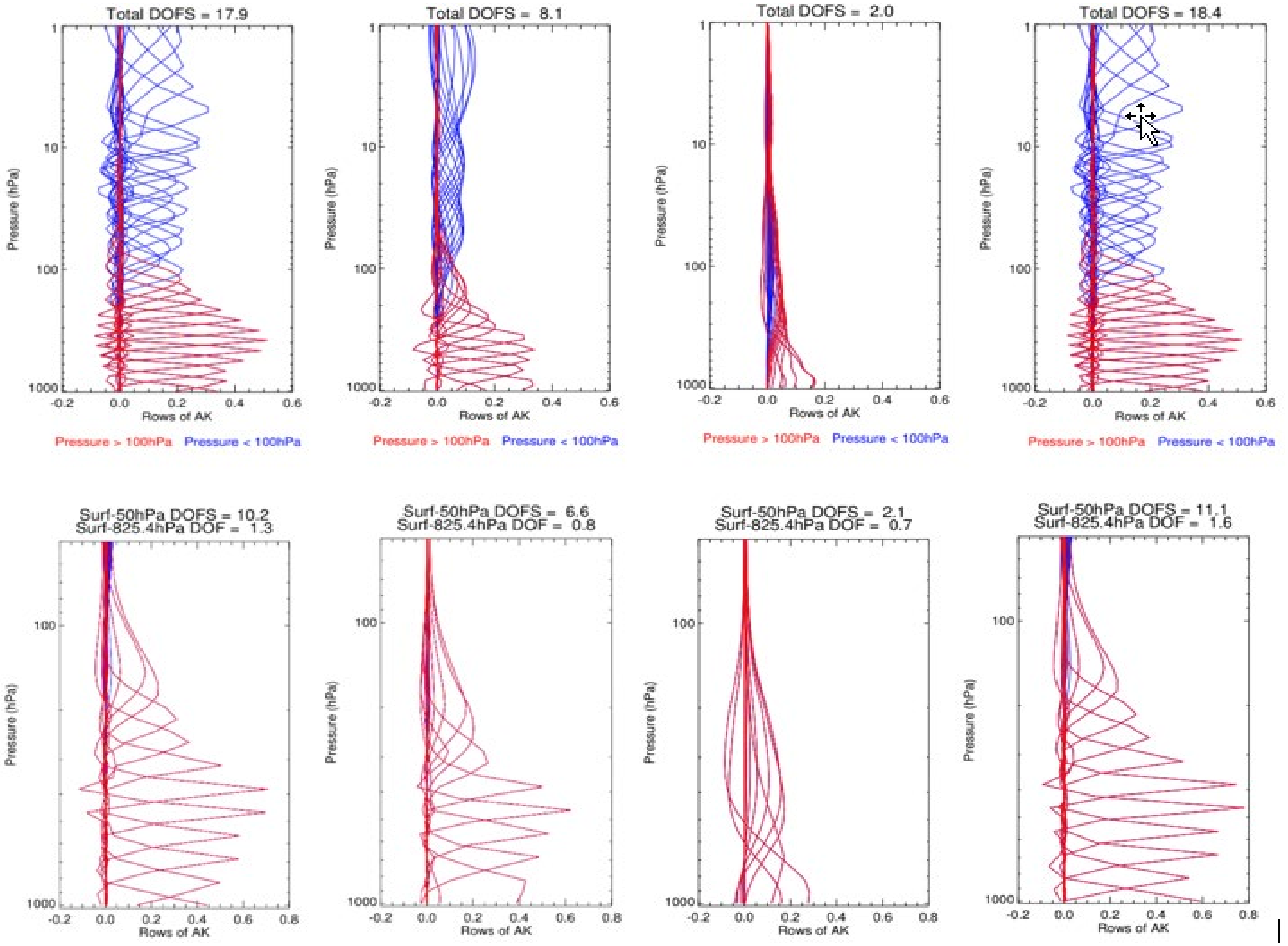
Averaging Kernels: T/H_2O

Temperature

H_2O



V/LWIR **MWIR** **SWIR** **Combined**

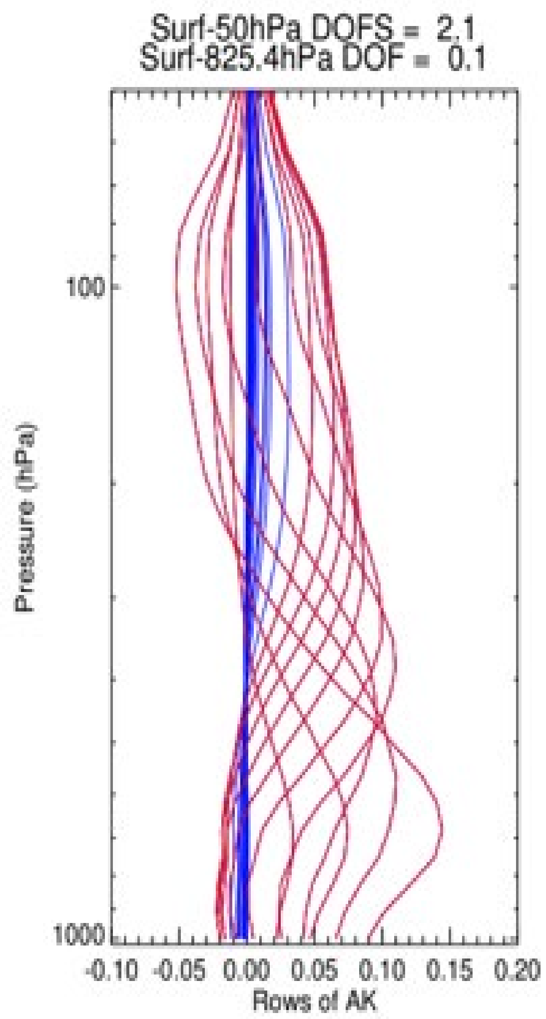
DOFS: AQ/Climate Relevant Gases

Retrieved Species	Frequency Domain	DOFS (MOPD = 2 cm)		DOFS (MOPD = 0.8 cm)	
		2.1 km GSD	4.2 km GSD	2.1 km GSD	4.2 km GSD
Ozone ($TATM$, H_2O)	LWIR	3.5	4.0	3.4	4.0
CO	MWIR	1.7	2.1	1.6	2.1
	SWIR	0.08	0.96*	0.1	0.96*
	MWIR+SWIR	1.7	2.3*	1.7	2.3*
CH_4 (TATM, H_2O)	LWIR	1.5	2.0	1.6	2.1
	SWIR	0.7	1.9*	0.8	1.9*
	LWIR+SWIR	1.6*	2.7*	1.8*	2.8*
CO_2 (TATM, H_2O)	VLWIR	1.0	1.5	1.1	1.6
	VLWIR+MWIR	1.0	1.5	1.2	1.6
	SWIR	0.3	1.1*	0.4	1.1*
	VLWIR+MWIR+SWIR	1.0	1.7*	1.2	1.9*

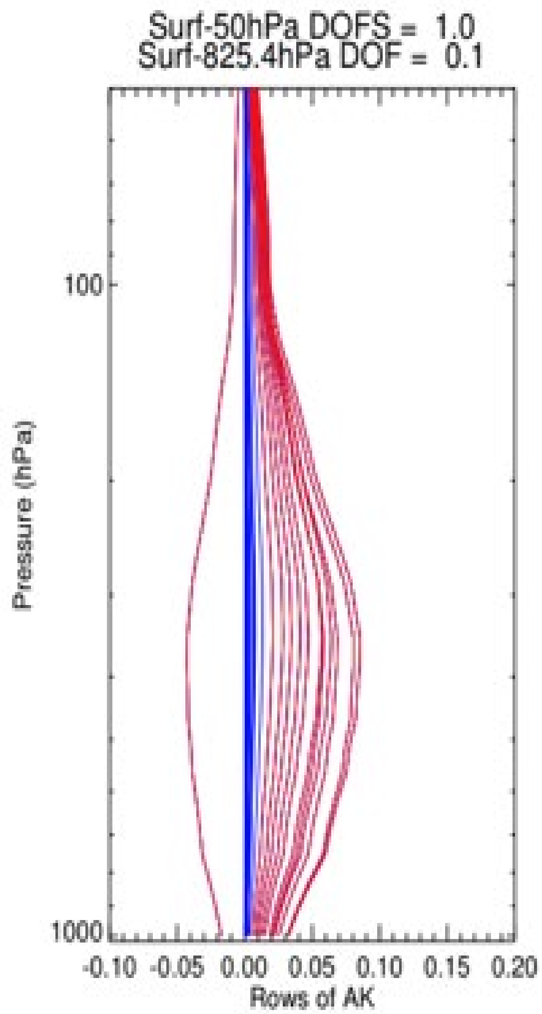
* Instrument noise for GSD = 4.2 km reduced by factor of 5 as a result of footprint averaging

- DOFS broadly consistent with prior results from TES, CrIS, IASI, MOPITT, TROPOMI, … teams
- Small changes with MOPD, but this is idealized scenario (perfect FM, perfect knowledge of interferences)
- For real scenarios, high spectral resolution will reduce systematic errors

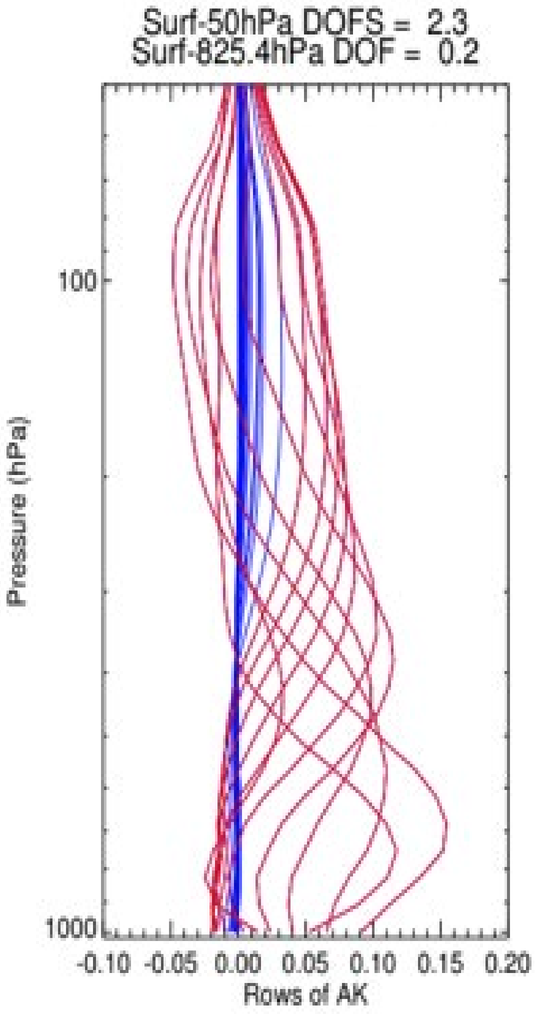
Averaging Kernels: CO



MWIR

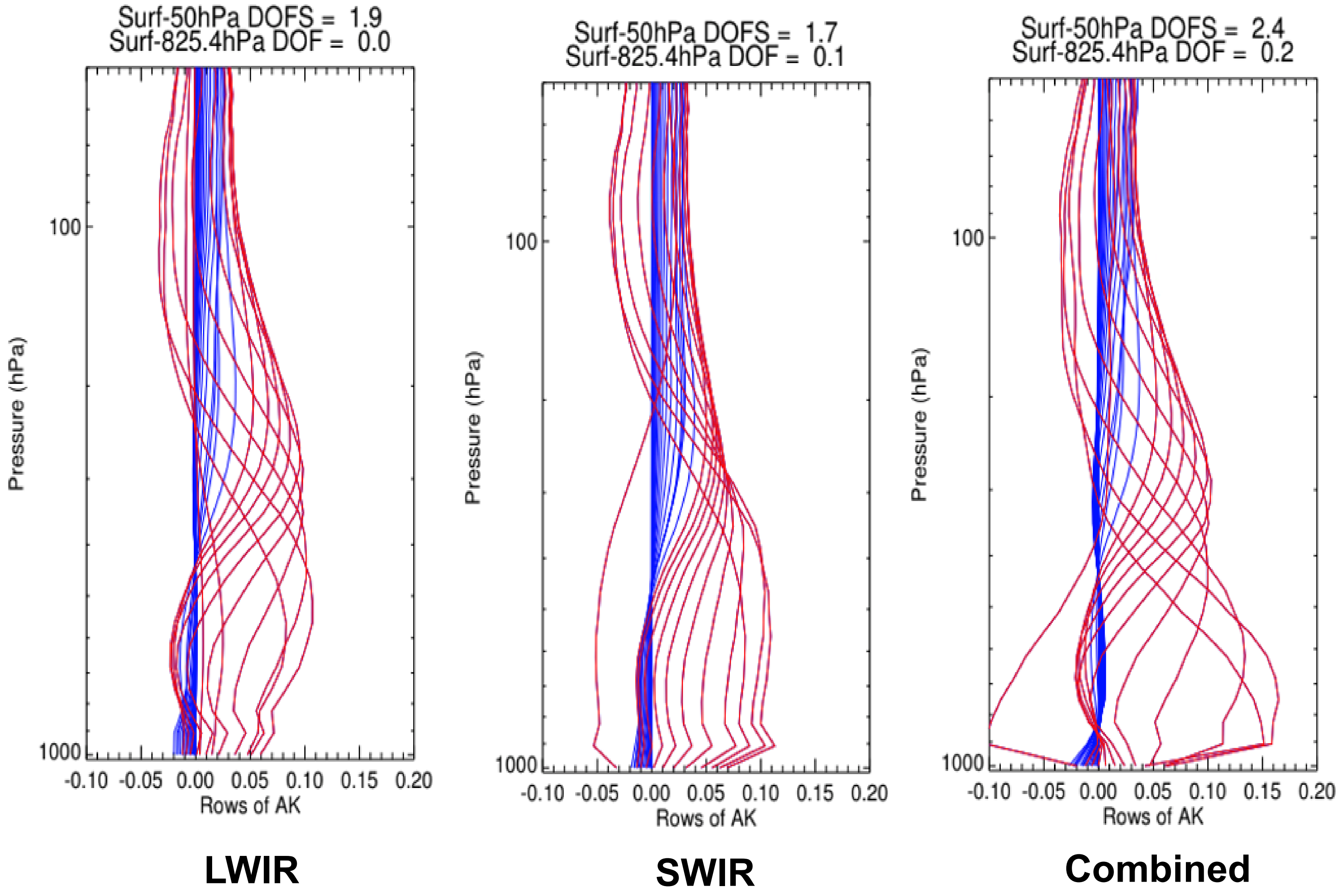


SWIR

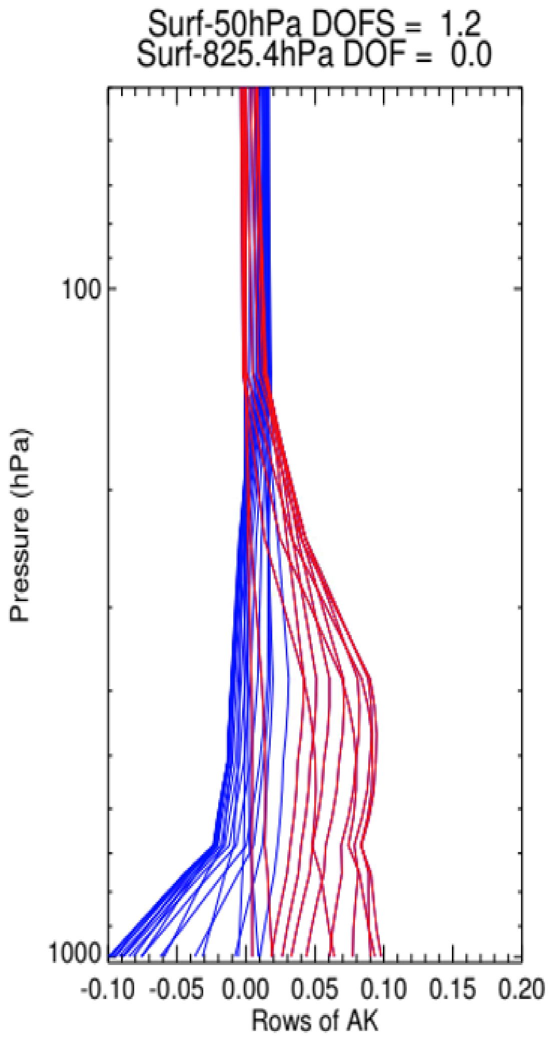


Combined

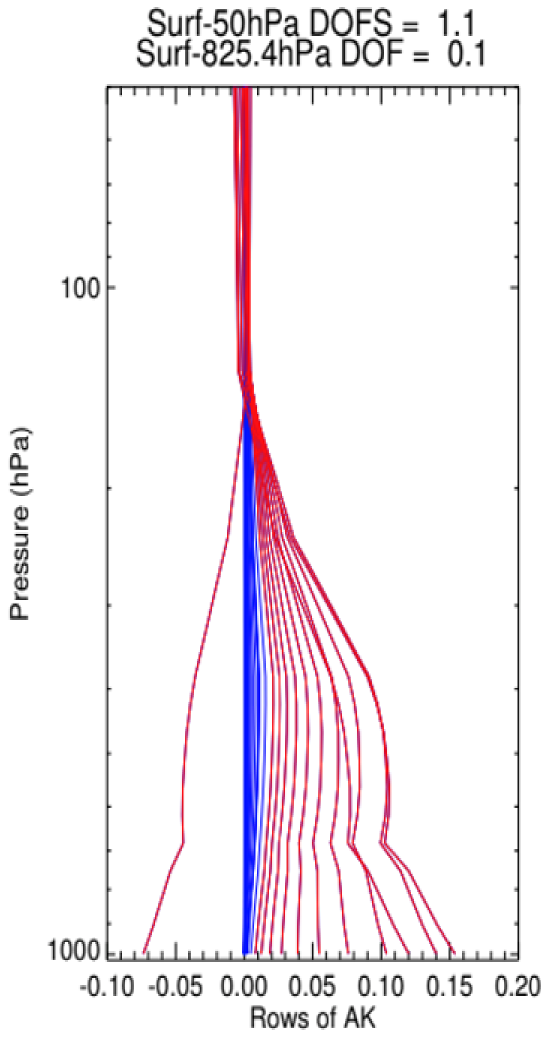
Averaging Kernels: CH_4



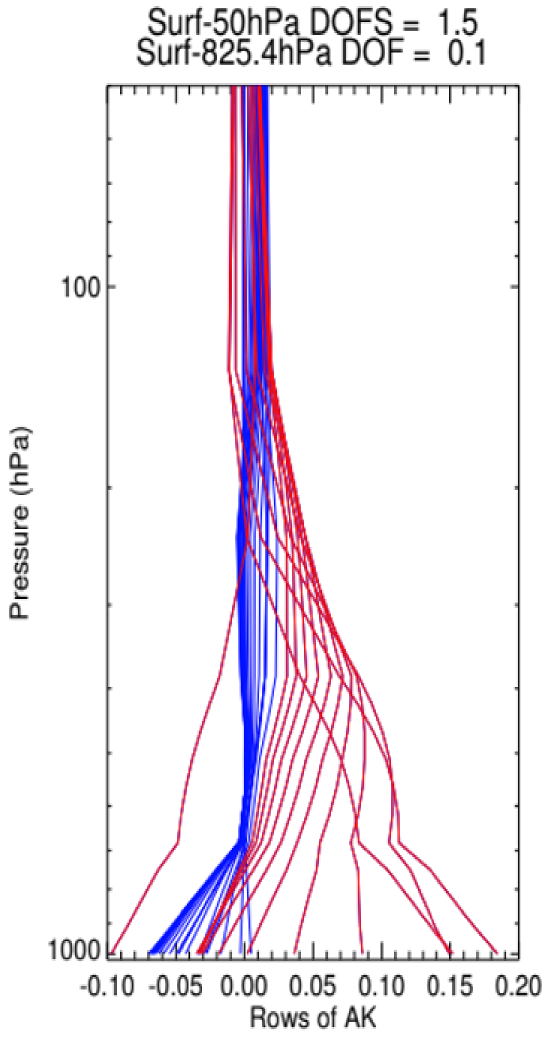
Averaging Kernels: CO_2



VLWIR+MWIR



SWIR



Combined

Simulated Retrievals: Summary

- **High spectral resolution provides improved ability to**
  - distinguish absorption lines of target species from interferents
  - separate tropospheric signal from stratospheric signal

- **Trade-off between spectral resolution and noise**
  - comparable DOFS for idealized retrievals
  - reduction in systematic errors for real scenarios

- **Combination of spectral bands enhances lower tropospheric and near-surface sensitivity**

Simulated Retrievals: Summary (Continued)

- **GSD = 2.1 km and 4.2 km both provide excellent results for T and H_2O**

- **SWIR provides clear benefit for CO, CH_4 and CO_2 when footprints are aggregated**

- **Performance of GEO-IR Sounder is similar to or better than currently operational instruments.**

Weather OSSE Outline

1. **OSSE overview: objectives, timeline, and status**
2. **Regional OSSE system: description and configuration**
    1. Nature run
    2. Forecast system
3. **Regional OSSE results**
    1. Control forecast
    2. Impact of assimilating Geo FTS profiles
        1. TC intensity and track
        2. Environment
        3. TC vertical structure
4. **Summary and Conclusions**

Observing System Simulation Experiments

- **Traditionally: evaluation of potential impact of new observations on a NWP forecast (Hoffman and Atlas, 2016; BAMS)**
- **Fundamentally: quantify information provided by a future observing system**
- **This study uses 2 types of OSSE:**
  - Do measurements provide enough information to estimate geophysical quantities of interest? What are the uncertainties? **(retrieval OSSE)**
  - How does assimilation of new observations affect/improve a weather forecast? **(forecast OSSE)**

OSSE Timeline

- **Credible forecast OSSEs typically take years to complete**
- **We were able to complete multiple experiments within 5 months:**
  - Well tested and calibrated forecast and data assimilation system
  - Available high fidelity simulation of a real event
  - Assimilation of data that is very similar to types of data already assimilated
- **OSSE milestones:**
  - 1 September 2020: nature run complete
  - 15 October 2020: control forecast and conventional data assimilation complete
  - 18 November 2020: First Geo IR assimilation results finished
  - 11 January 2021: Comparisons among various averaging kernels finished, analysis of impact on storm structure and environment finished

Regional OSSEs with the WRF EnKF

- Regional data assimilation / OSSEs assess impact on a weather event
- Focus on tropical cyclones, and utilize heritage in ensemble DA
- WRF-based ensemble Kalman filter (WRF-EnKF) developed at PSU
- Experiments based on successful ensemble simulation of hurricane Harvey (2017)
- Nature run: simulated high resolution TC very similar to Harvey
- Generate synthetic conventional and satellite observations, including variants of the proposed Geo FTS
- Use EnKF to assimilate observations into an ensemble forecast

Harvey OSSE Configuration: Nature Run

Initial Conditions	APSU analysis (assimilating GOES-16 all-sky BT + conv) The 3rd strongest ensemble member
Boundary Conditions (&environment)	ERA-5
Time Range	Initialized at 00Z/23 AUG 2017 To 00Z/28 AUG 2017
Resolution & Domain Size	D01: 378 x 243 (27 km) D02: 297 x 297 (9 km) D03: 597 x 597 (3 km) D04: 1197 x 1197 (1 km)
Microphysics	Thompson Scheme
Model	WRF3.9.1
Moving Nest	Preset: 00Z/23 – 00Z/24 (by following the TC positions of NR itself from preliminary simulation) Vortex-following: 00Z/24 – 00Z/28 AUG 2017

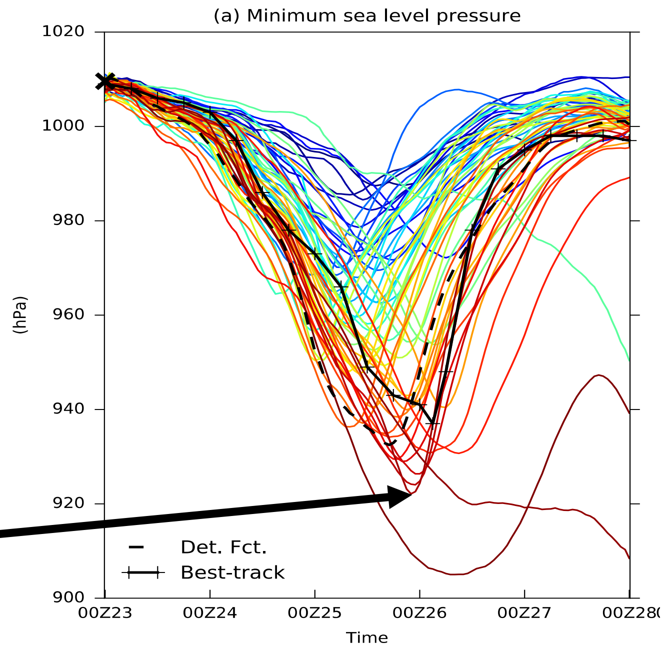
Harvey OSSE Configuration: OSSE DA Experiment

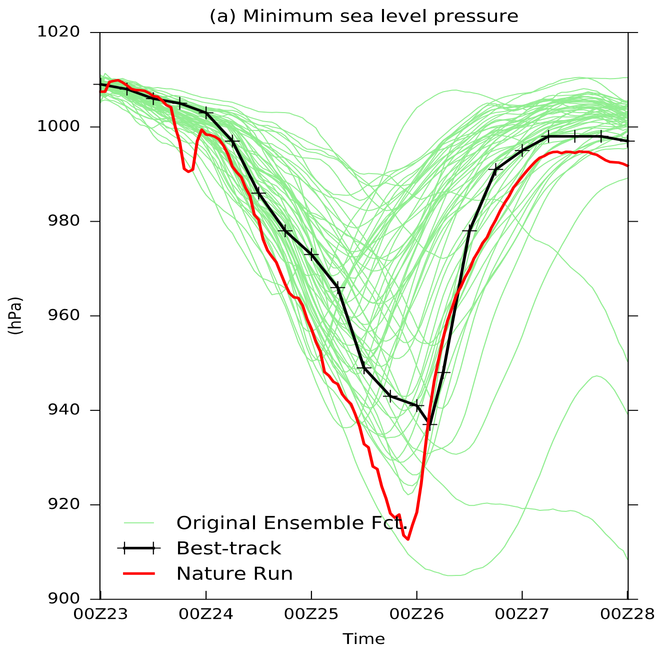
Red text denotes where forecast model differs from the nature run

Initial Conditions	Ensemble forecast from APSU analysis
Boundary Conditions (&environment)	NOAA FNL
Time Range	Spin-up: 00-06Z/23 AUG 2017 DA: 06Z/23 – 00Z/26 AUG 2017
Resolution & Domain size	D01: 378 x 243 (27 km) D02: 297 x 297 (9 km) D03: 297 x 297 (3 km) -
Microphysics	WSM6
Model	WRF3.6.1
Moving Nest	Preset (following the TC positions of NR)

Hurricane Harvey Nature Run

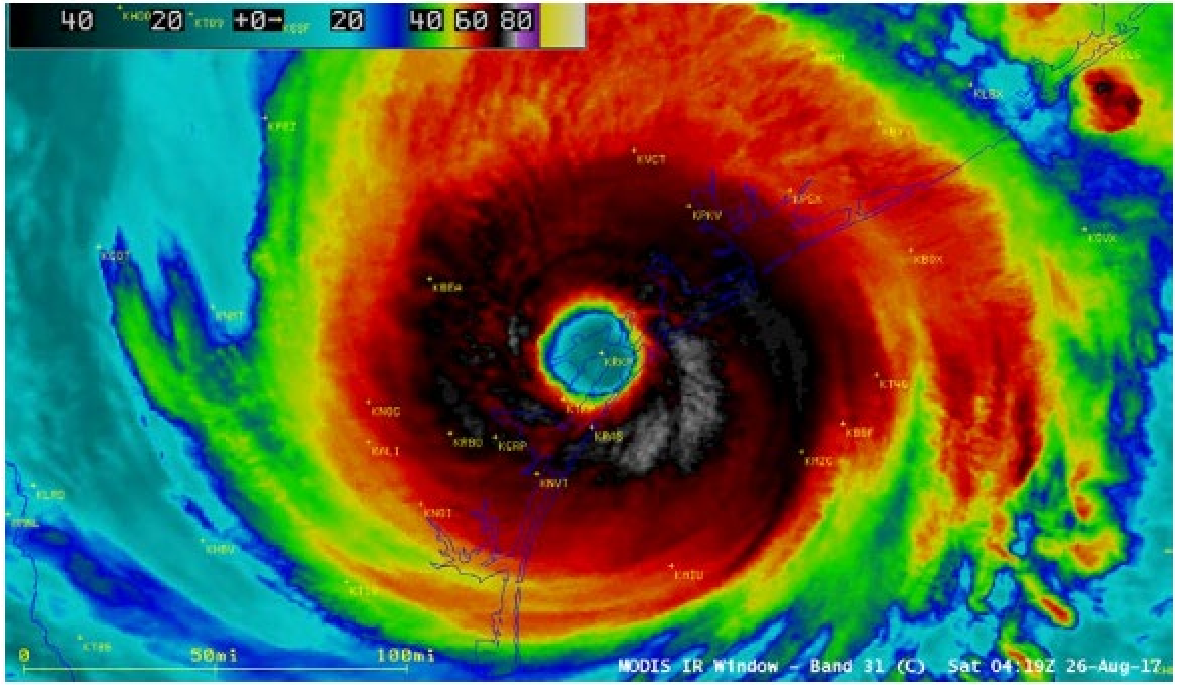
- **Based on real event (Hurricane Harvey, 2017)**
- **NR is a free-running forecast initialized from the 3rd strongest member of an EnKF experiment**
- **NR uses higher resolution, newer model version, different physical parameterizations, and different initial and boundary conditions**
- **Forecast uses lower resolution, older model version**



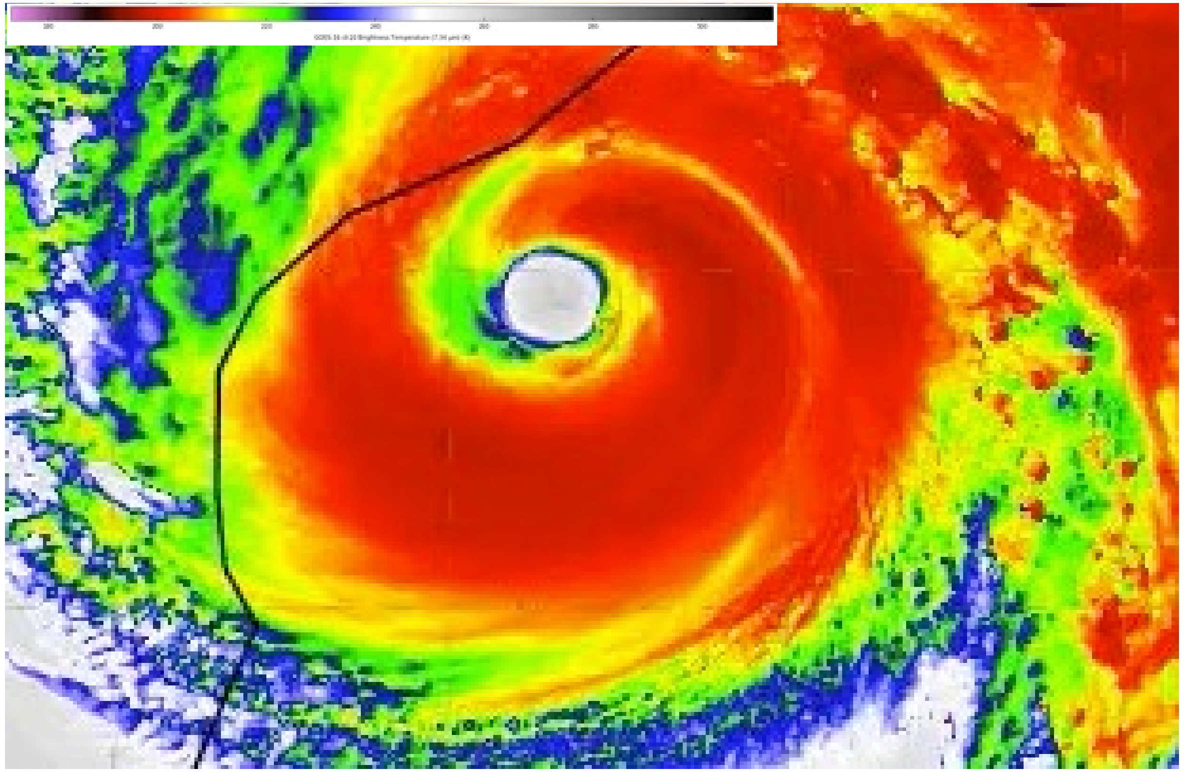


MODIS Brightness Temperatures vs Nature Run

MODIS obs

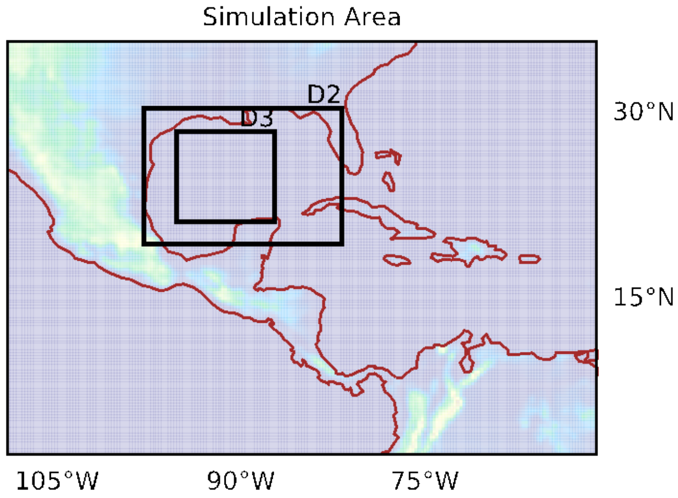


NR



Nature Run cloud fields are realistic – not meant to reproduce the observations

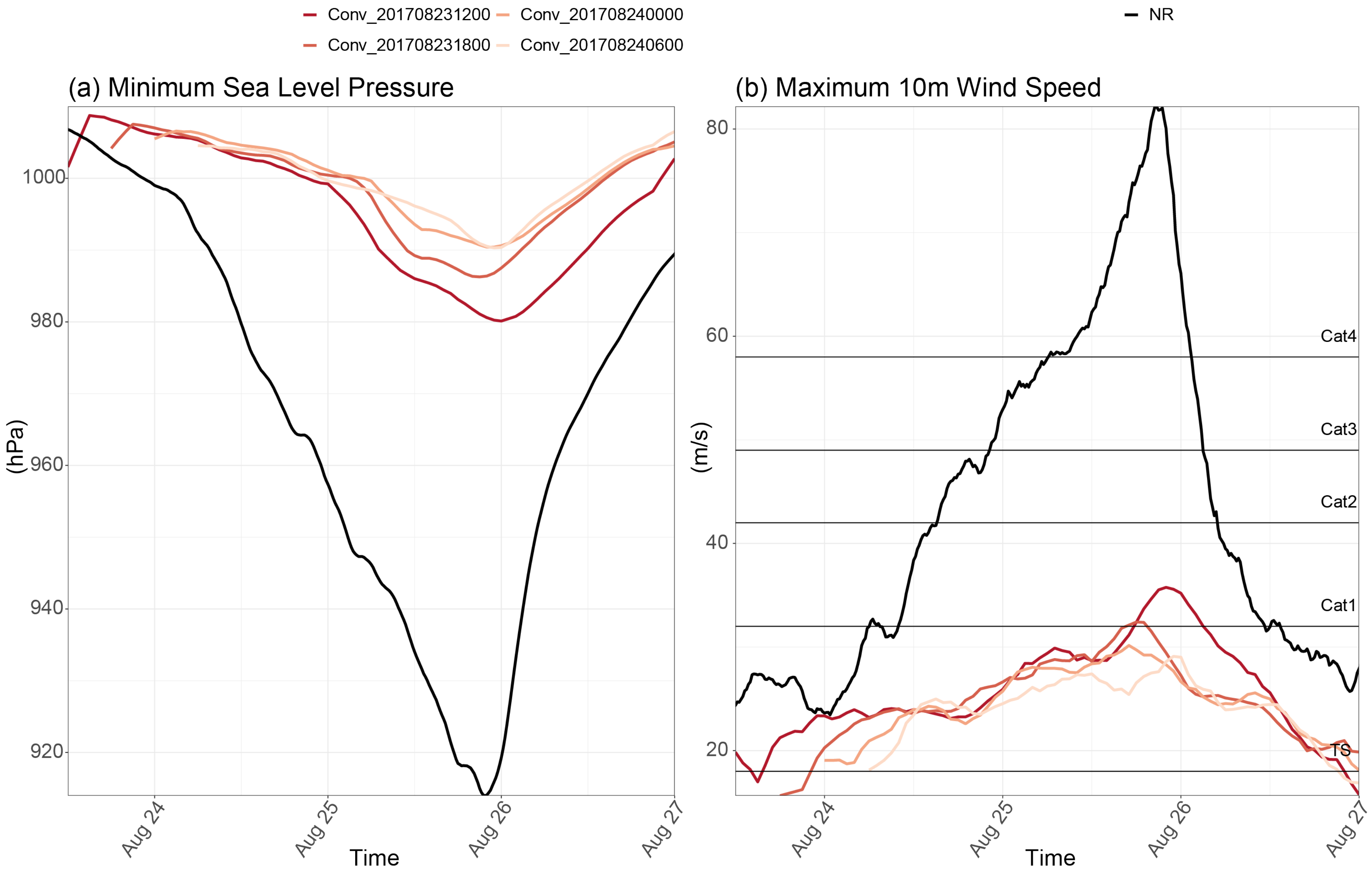
Regional OSSEs



- **Initial conditions: NCEP FNL, 60 member ensemble**
- **Start time: 2017/08/23 00UTC**
- **Spin up: 6 hour**
- **Data assimilation: 06 UTC 23 Aug 2017 – 06 UTC 24 Aug 2017**
- **Observational data = synthetic observations from nature run**
  - Conv: Conventional observations only (surface, ship, radiosonde, satwind), assimilated 3-hourly
  - Geo IR: Conventional + Geo IR T/qv soundings
    - Assimilate Geo IR soundings every hour
    - 4 x 4 km horizontal averaging to Geo IR pixels
    - Vertical smoothing using Geo IR averaging kernels
    - Mask clouds where OLR < 220 W/m^2
    - Observation errors consistent with information in T,qv retrievals
    - Run experiments with varying averaging kernels

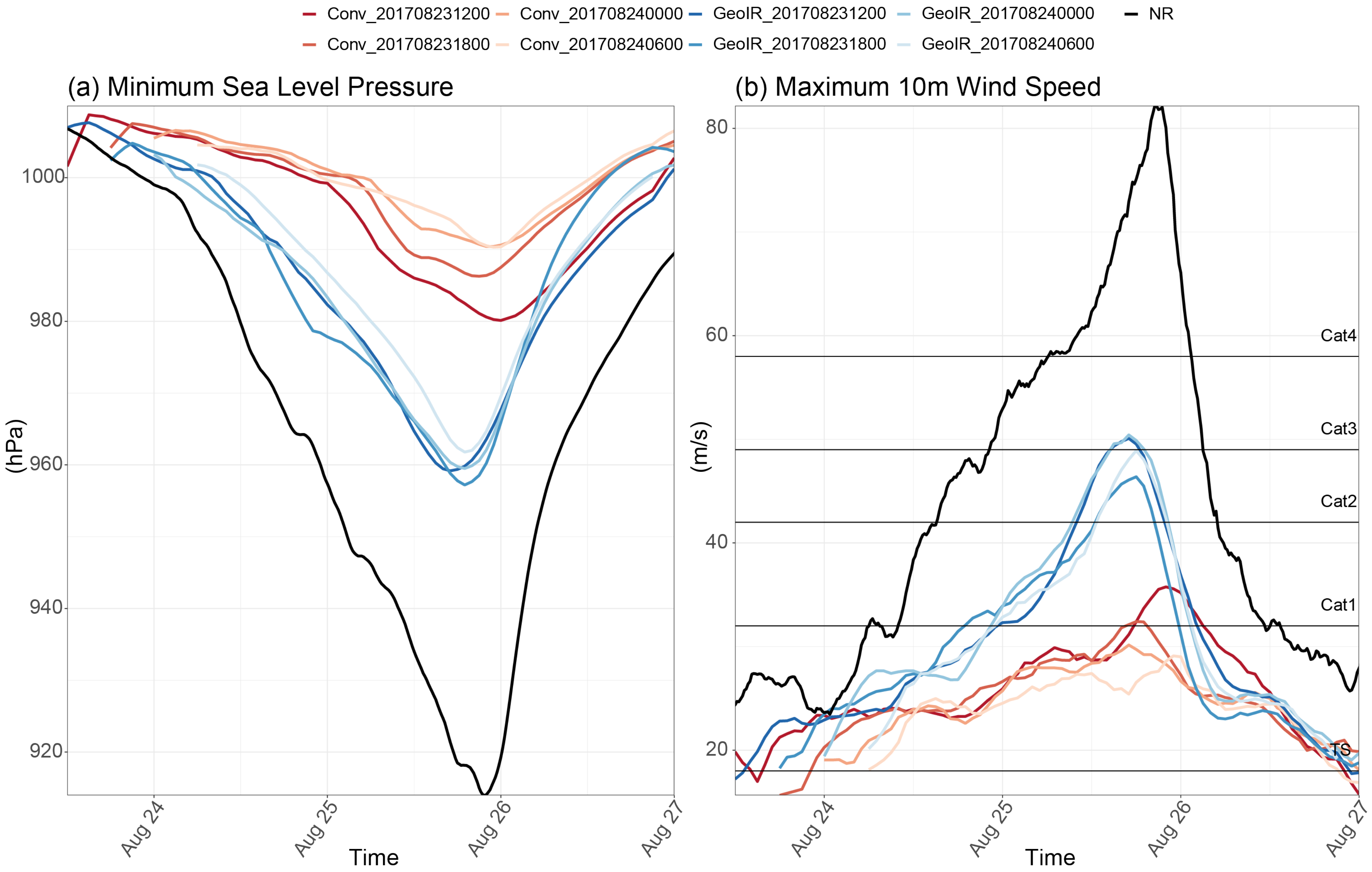
Forecast Performance: TC intensity

- Assimilation of conventional observations insufficient



Forecast Performance: TC intensity

- Assimilation of conventional observations insufficient
- Assimilation of Geo IR soundings significantly improves TC intensity



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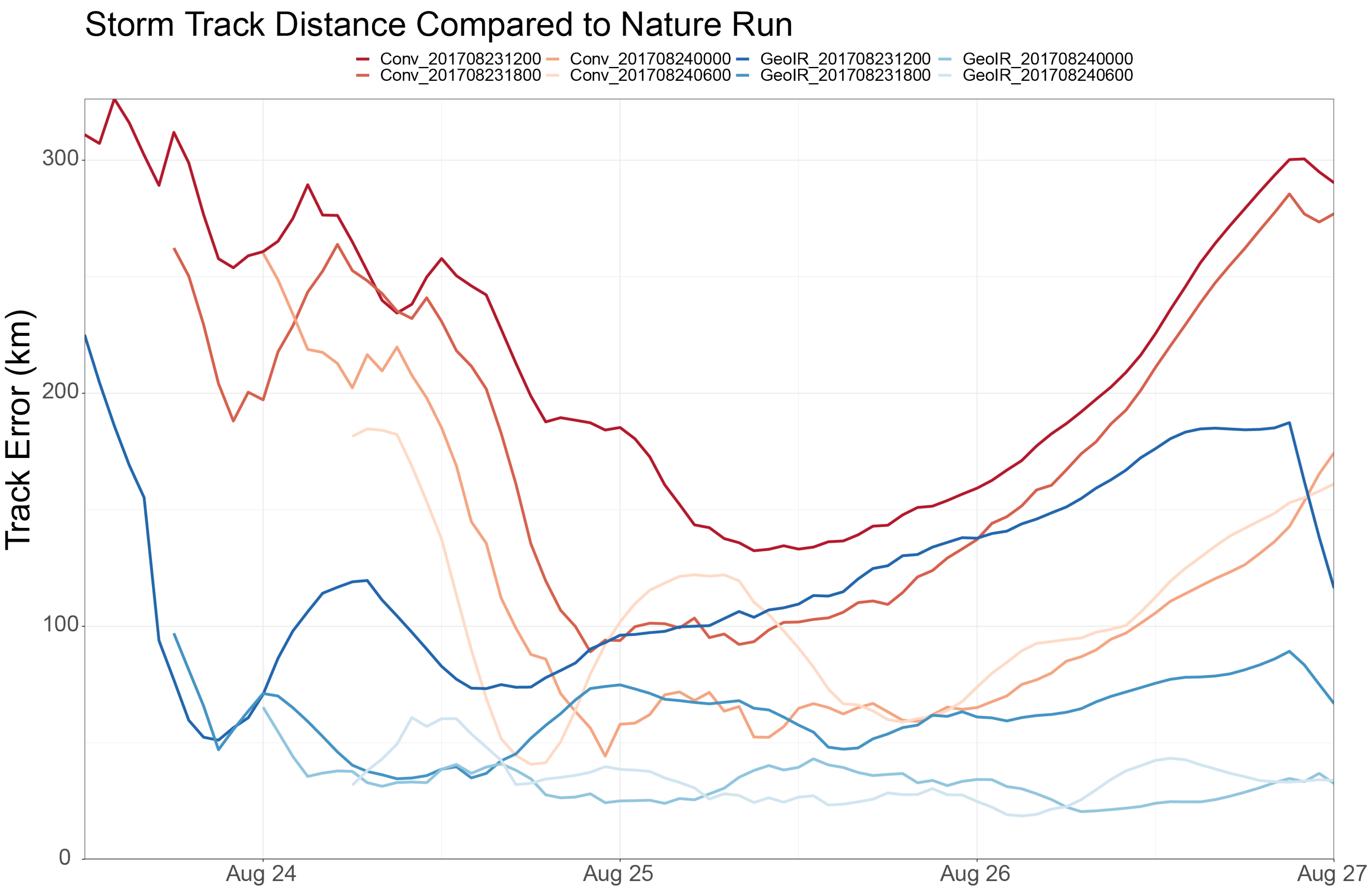
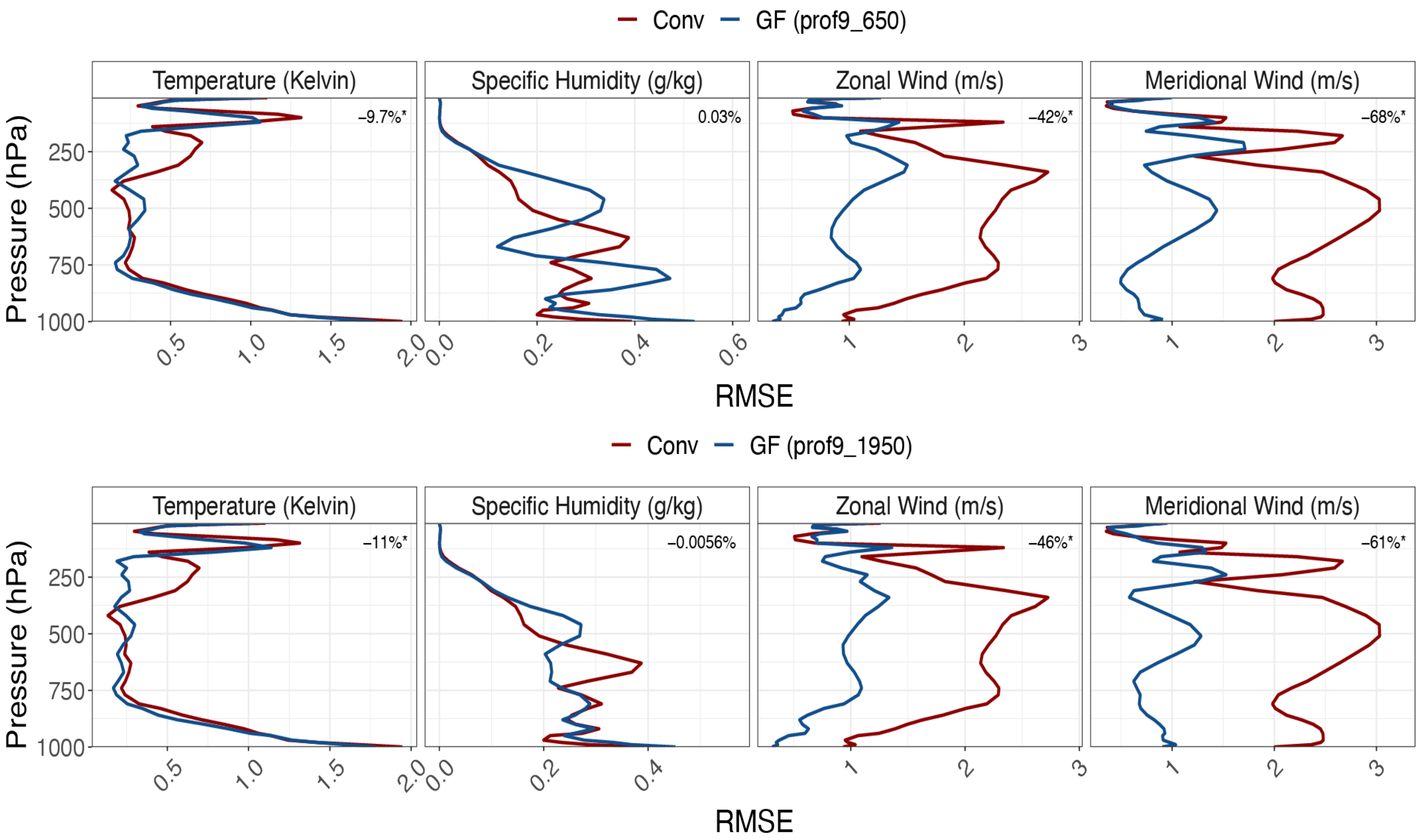
Track errors

Assimilation of Geo IR Sounder data reduced track errors at all forecast times, and especially for forecasts initialized at 00 and 06 UTC 24 August

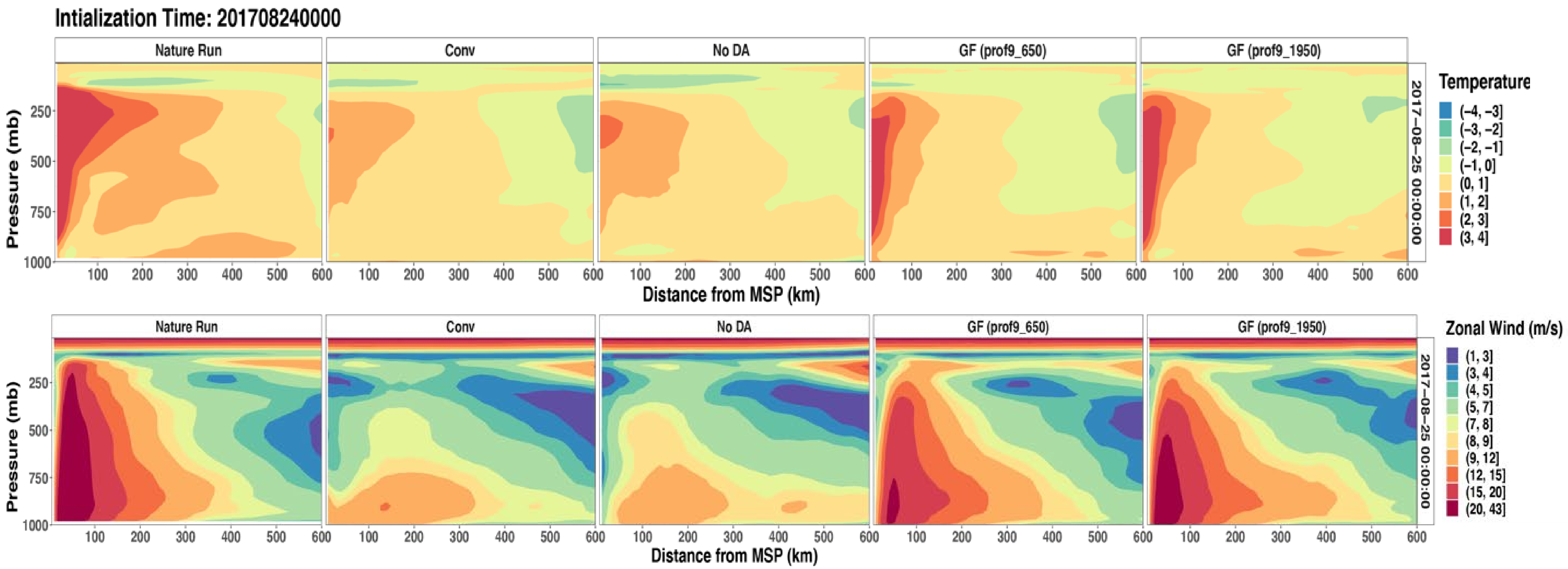


Impact on Thermodynamic and Dynamic State

- **Fields averaged in the horizontal over the full inner domain (d03)**
- **Blue = Geo FTS**
- **Red = Conventional**
- **Key points:**
  - Temperature already very accurate. Largest improvements in upper troposphere.
  - Water vapor signal is mixed, with most improvements in the lower to middle troposphere
  - **Assimilation of temperature and water vapor has a significant positive effect on wind through the depth of the troposphere**



Impact on Thermodynamic and Dynamic State



- **T,U horizontally averaged in the TC azimuthal direction and time averaged over 12 hours**
- **Key points:**
  - Geo FTS assimilation results in **clear improvements in the wind structure**
  - The **warm core structure (temperature perturbation) is much improved**

OSSE Summary

- **Assimilation of Geo IR Sounder profiles during the first 24 hours of storm development (prior to rapid intensification) resulted in improved:**
  - storm intensity and track
  - warm core temperature perturbation
  - environmental winds
- **Care was taken to ensure credibility of the OSSE:**
  - We have created a realistic nature run of a strong hurricane
  - Nature run is sufficiently different from the forecast model
  - Profiles smoothed horizontally and vertically using averaging derived from Geo IR Sounder retrieval system
  - Errors in observations quantified and derived from the retrieval