Enhancing Atmospheric Profiling with the AMETHYST Hyperspectral Inversion System

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The Changing Approaches for Satellite DA

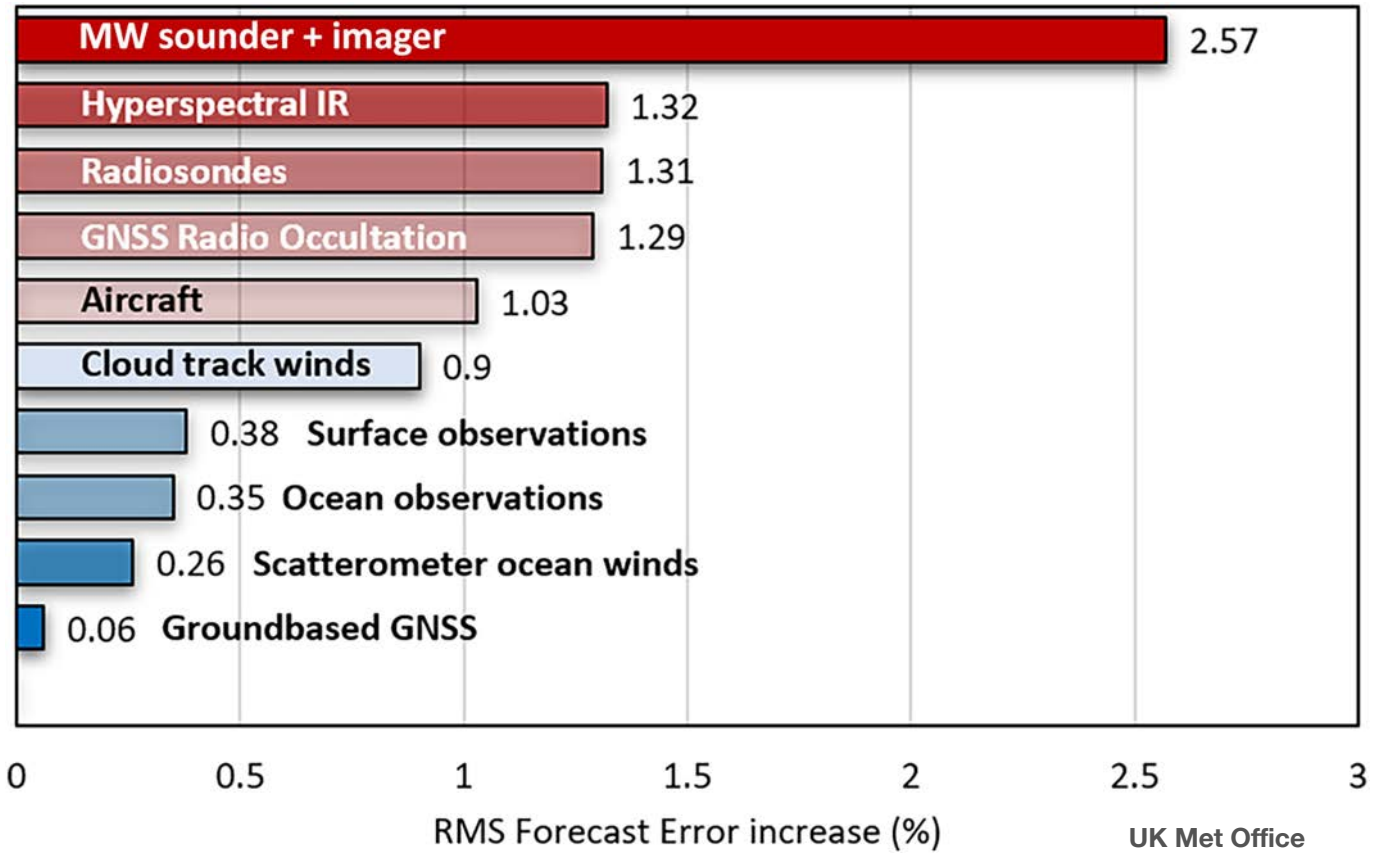
Historical Context

- Early Assimilation of Satellite Retrievals had Issues with first guess contamination and with observation error covariance.
- Later, Assimilation of Satellite Radiances only partially exploit the full range of hyperspectral IR observations.
- Assimilation of Satellite *Transformed Retrievals* (Migliorini and C. Rogers in 2008) mitigates the retrieval first guess contamination, properly handles the observation error covariance, and includes the full range of radiance spectra.

New Directions

- Future advances in data assimilation and weather forecasting will likely include hybrid models that combine the strengths of physically based models with deep learning.
- Hybrid models can use deep learning for tasks like pattern recognition and short-term prediction while relying on physical models for long-term forecasts and understanding underlying processes.

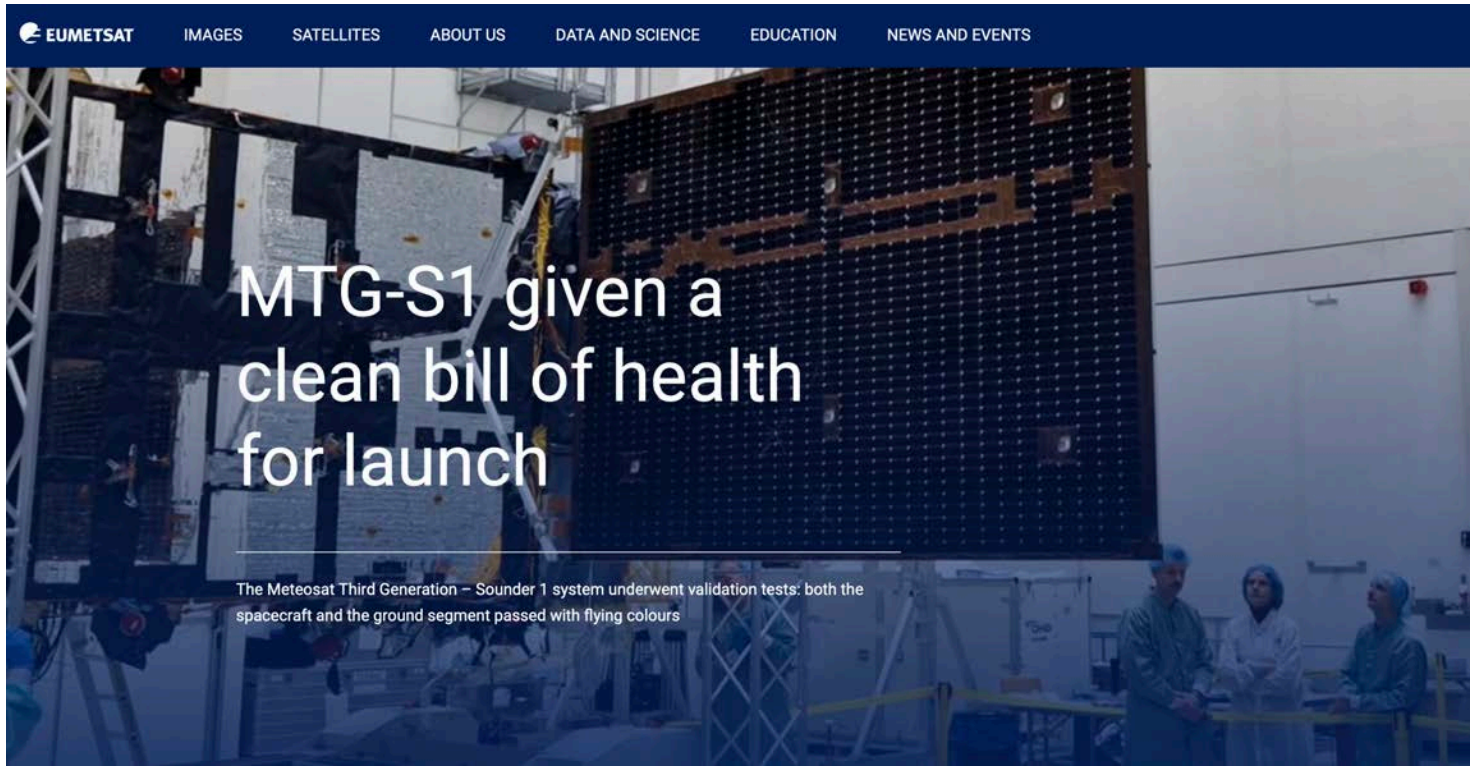
Hyperspectral IR - are Underutilized



Roger Saunders 2021: https://doi.org/10.1002/wea.3913

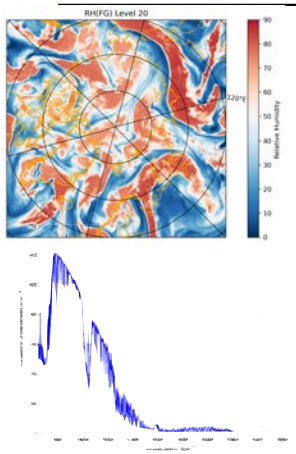
MTG-IRS Hyperspectral Instrument

Scheduled to launch in July 2025 into a Geostationary Orbit

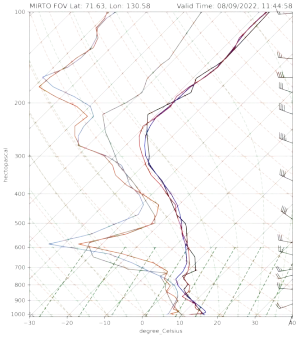


The MTG - IRS (Infrared Sounder) is the first hyperspectral IR instrument to be launched into geostationary orbit. The new instrument provides a powerful opportunity to showcase our new inversion system for IR retrievals.

MIRTO Retrieval Processor Produces Physical and Transformed Retrievals

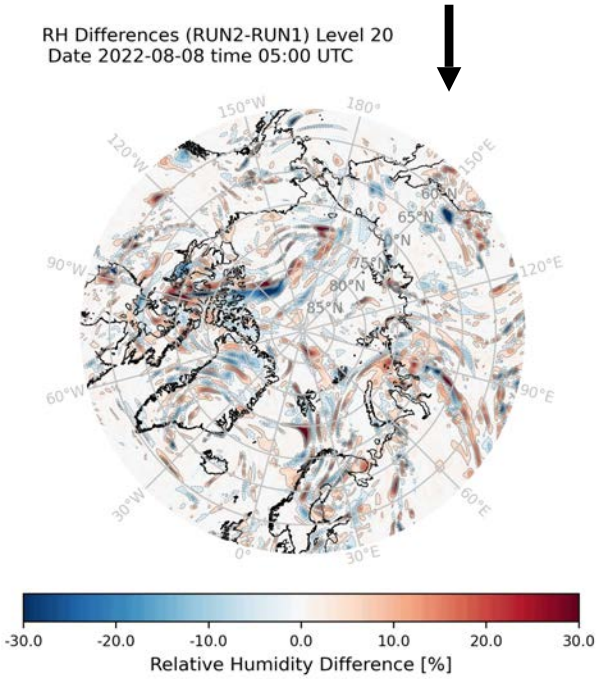


A-priori WRF model knowledge regarding the atmospheric state + hyperspectral space-borne observations

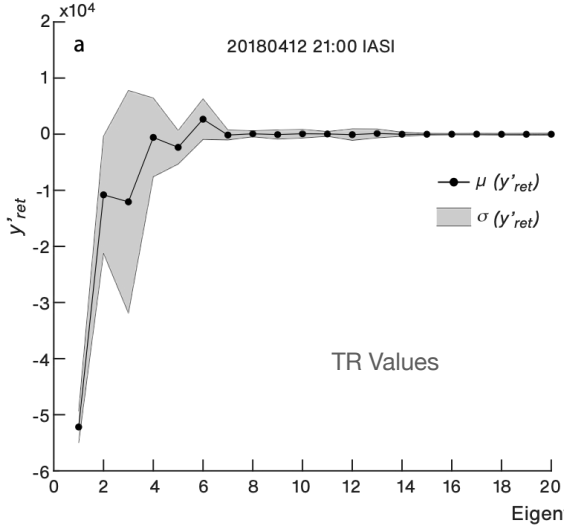


Physical Retrievals provide updated knowledge of the atmospheric state

The animation below shows RH Innovations at 430 mb due to Physical Retrievals above clouds with a priori + Transformed Retrievals in clear skies without a priori assimilated into WRF in rapid a update cycle.

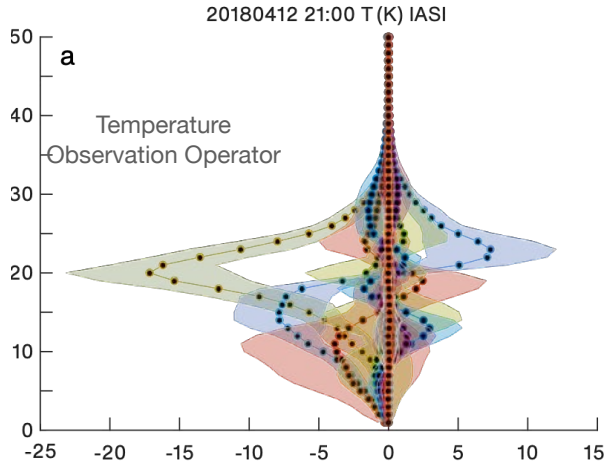


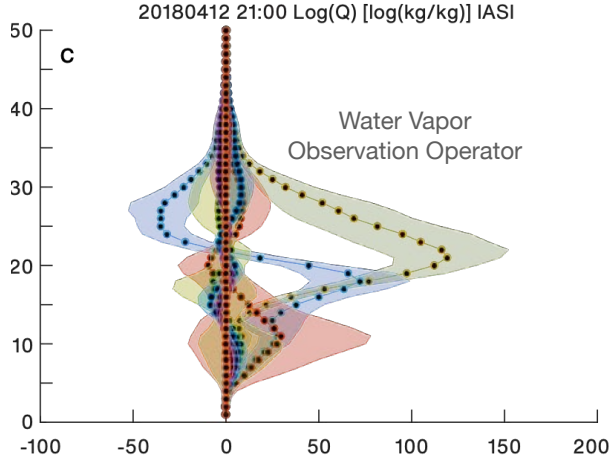
MIRTO Transformed Retrievals



Transformed Retrievals (TRs) can be seen (in a simplified view) as scaled projection of the physical retrievals on the eigenvectors of the Signal to Noise Matrix defined as $S = \Sigma^{-\frac{1}{2}} K B^{\frac{1}{2}}$ where Σ is the satellite observation error covariance, K is the Jacobian Matrix, and B is the a-priori covariance matrix. TRs are linear combinations of the physically retrieved atmospheric parameters.

Transformed Retrievals (TRs) are assimilated into NWP models through the use of the Temperature and Water Vapor observation operators (on the right), with an estimated associated observation error equal to the unit matrix.





Assimilation of Transformed Retrievals over the Pacific in RUC mode

We conducted a baseline study to validate approach
- synergy with MKWC which does operational regional model runs
- availability of Direct Broadcast Antenna (CrIS, VIIRS, IASI)
- clear sky conditions

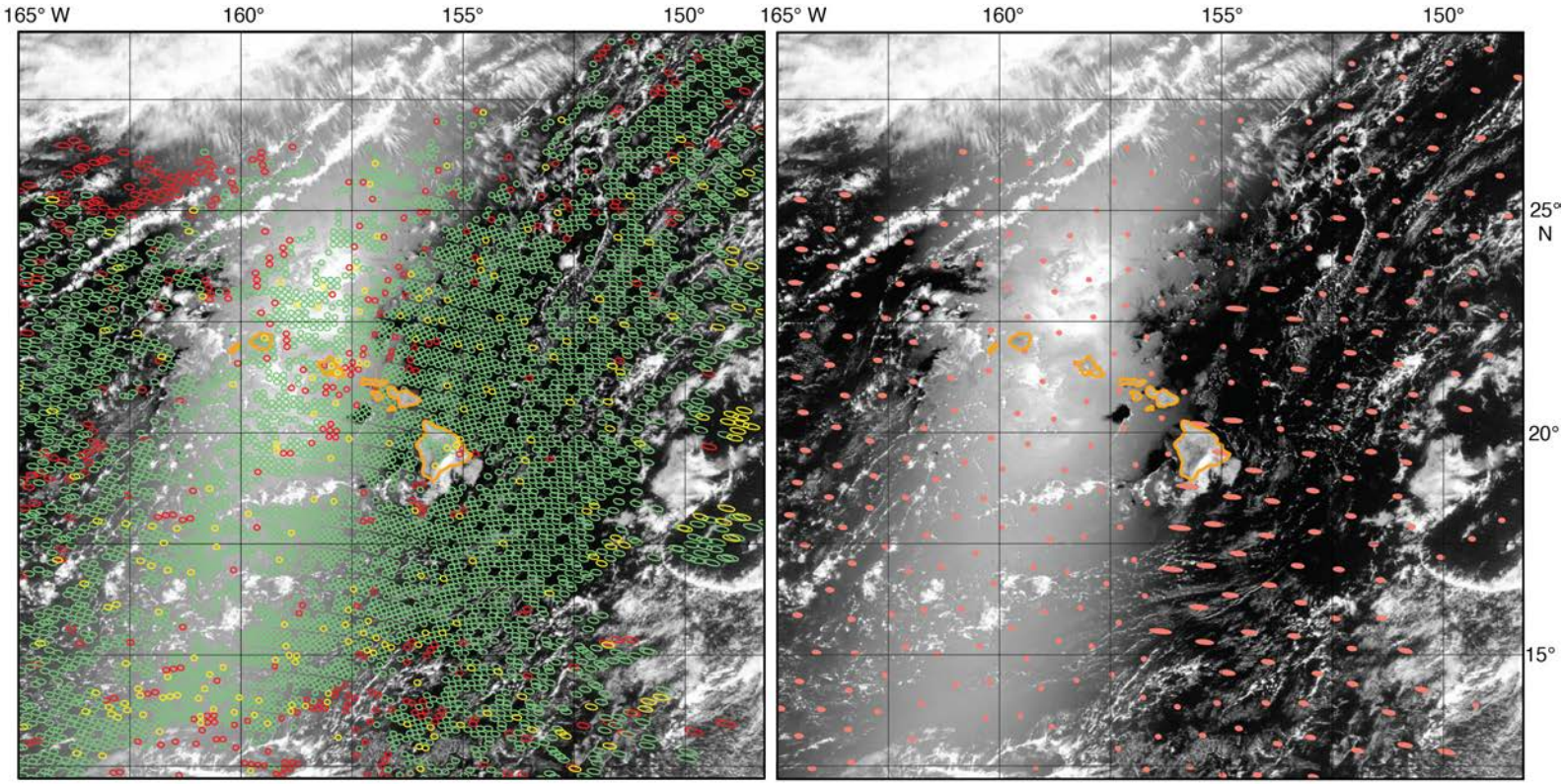
Dr. Tiziana Cherubini - lead modeler

Data Assimilation Experiments

The WRF/WRFDA experiments with 3h cycling mode extend over a period of about 30 days from mid Nov to mid Dec 2020:

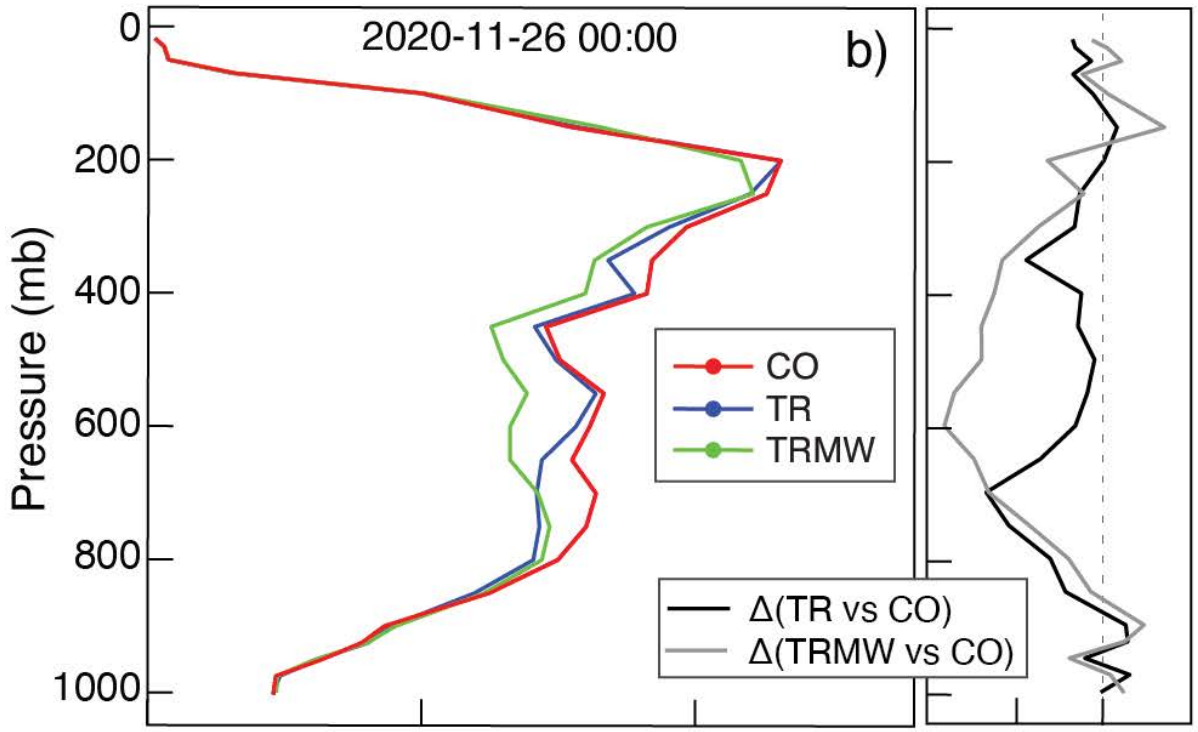
1. Control Experiment:
   - Assimilation of **Conventional Observations (CO)**: Surface, maritime, aircraft, observations, quickscat, atmospheric winds, etc ;
2. TR Experiment: CO + TR
   - Assimilation of **Transformed Retrievals (TR)** from hyper-spectral InfraRed satellite observations, produced from raw satellite data directly;
3. TR+MW Experiment: CO + TR + MW
   - Assimilation of **Microwave radiances (MW): AMSU-A** (Aqua,NOAA-18/19,MetOP-A/B), **ATMS** (SuomiNPP), **MHS** (NOAA-18/19; MetOP-A/B).

CrIS Retrieval Density



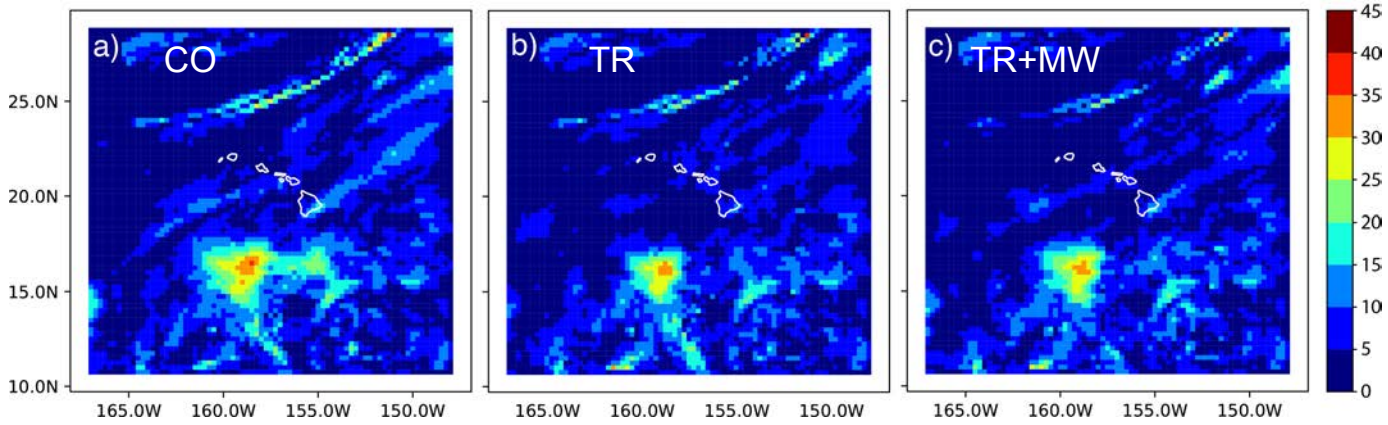
CrIS retrievals (RH < 100% for any level) obtained from two adjacent Suomi-NPP overpasses, before (a) and after (b) the 80 km thinning is applied.

Greatest Impact of Assimilation in Midlevels

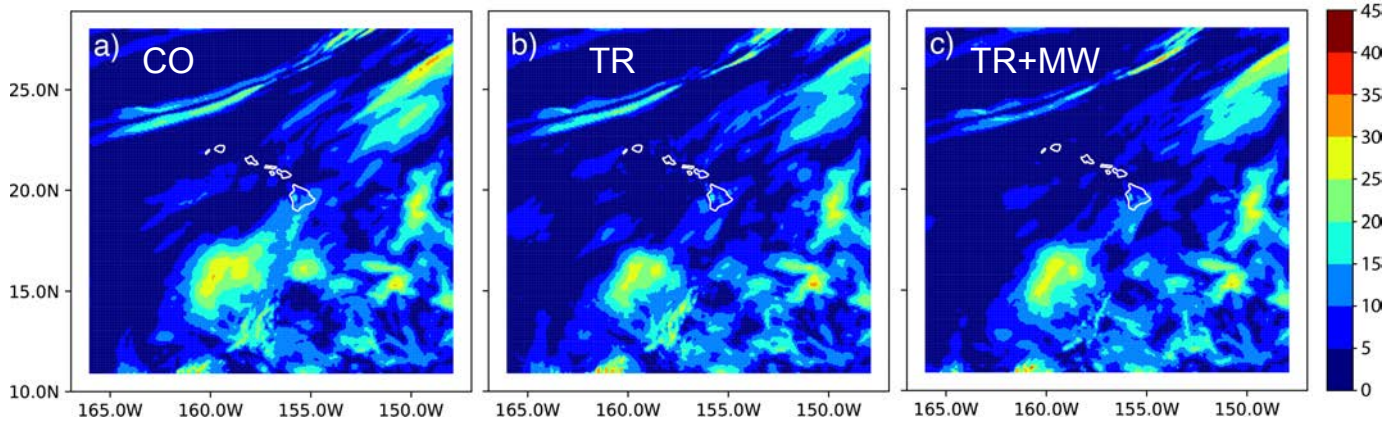


Vertical profiles of RH $RMSE_b$ for the 3h forecast started on 25 November 2020 at 21:00 UTC. Profile is obtained by averaging throughout the model domain with GFS as the reference.

Synoptic Scale Improvements: Front/Convergence Zone



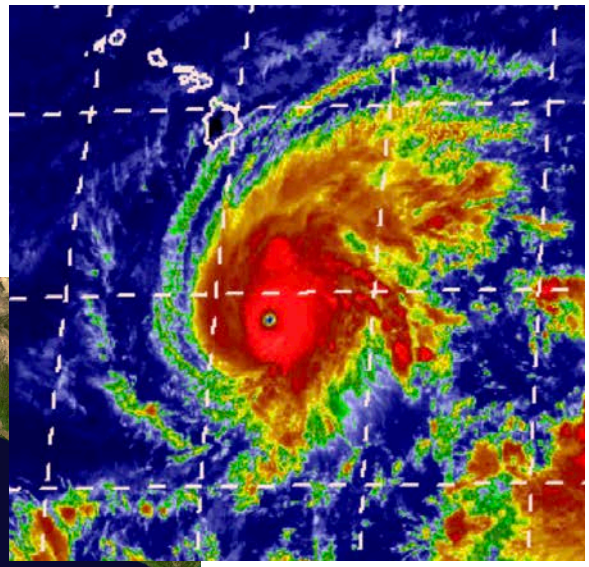
GFS (top) and ECMWF (bottom) are used as reference field in the statistics



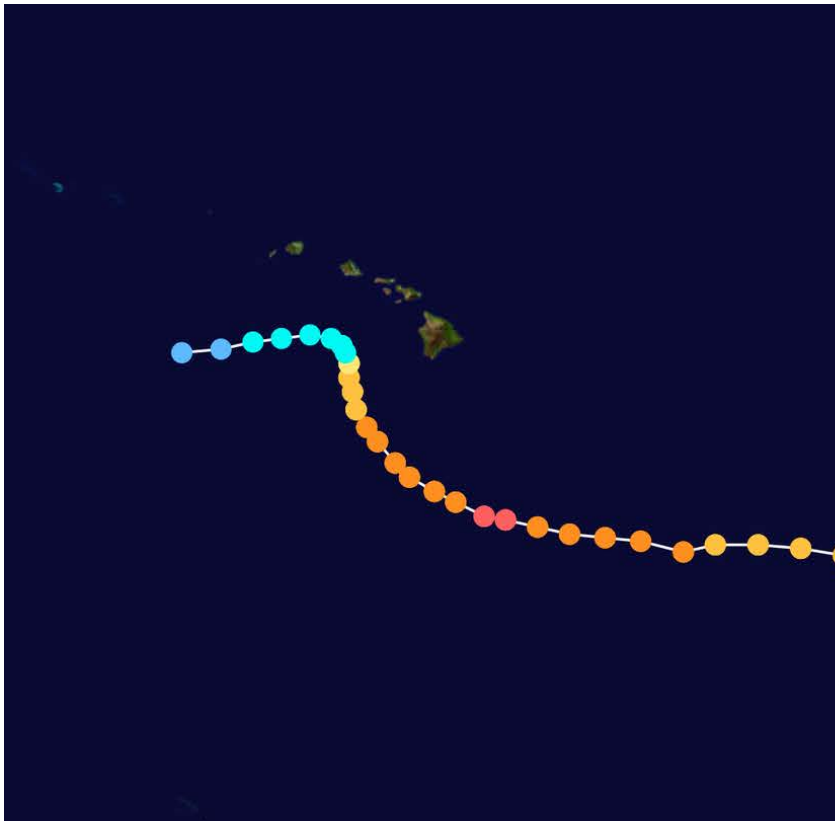
$RMSE_b$ for the 3 hour forecasts started at 09 UTC on 02 December 2020.

Predictability of Hurricane Lane

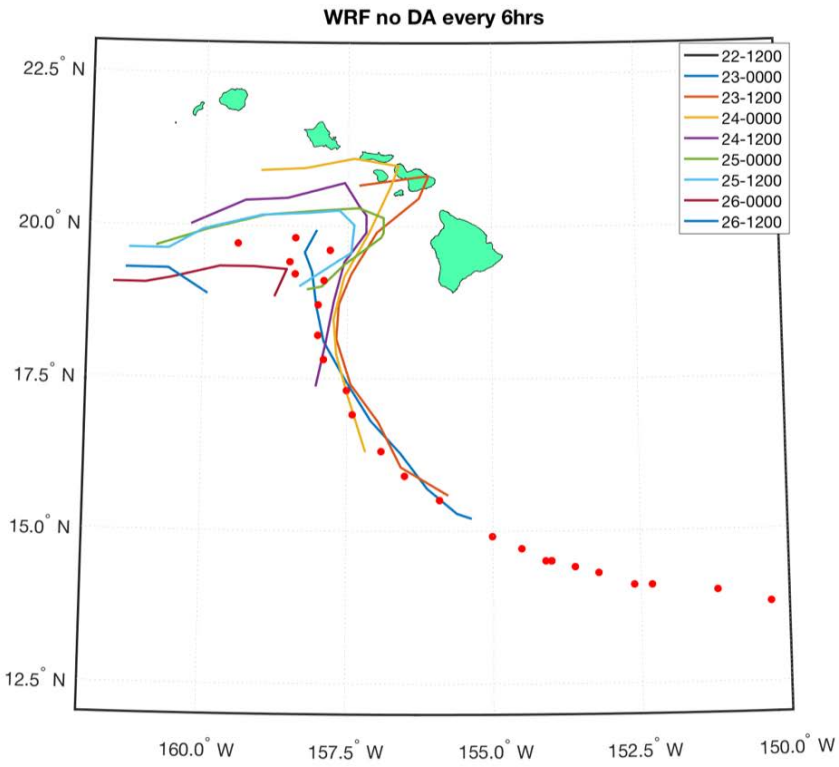
- Evaluate the performance of the WRF modeling system in cycling mode with TR data assimilation for Hurricane Lane.
- Hurricane Lane entered the Central Pacific Area on 19 August 2018 and passed close to the main Hawaiian Islands during the following days. It was a powerful category 5 Hurricane when just SE of the Big Island.



WRF Track Forecast Without TRs and Cycling

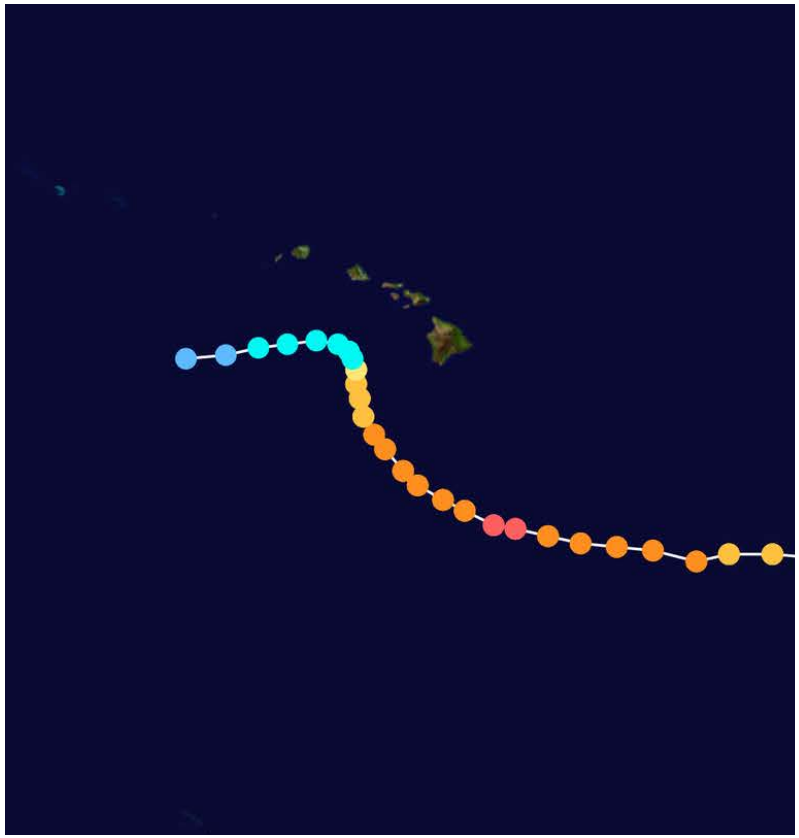


Observed Best Track

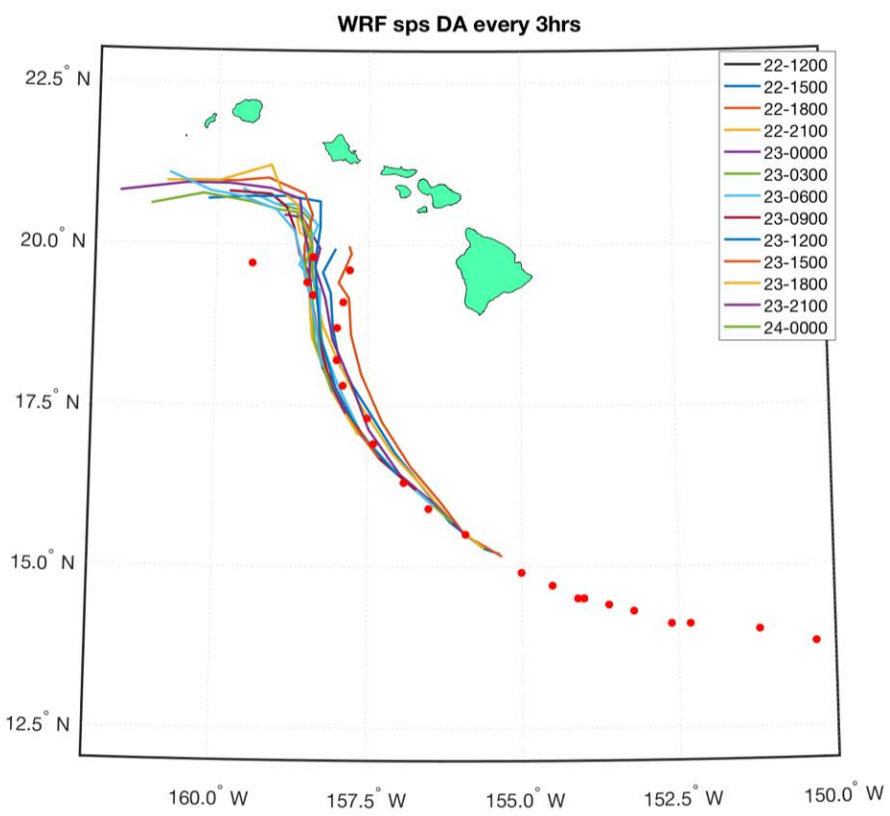


WRF 60-h tracks from every 12-h cold run

WRF Track Forecast With TRs and Cycling

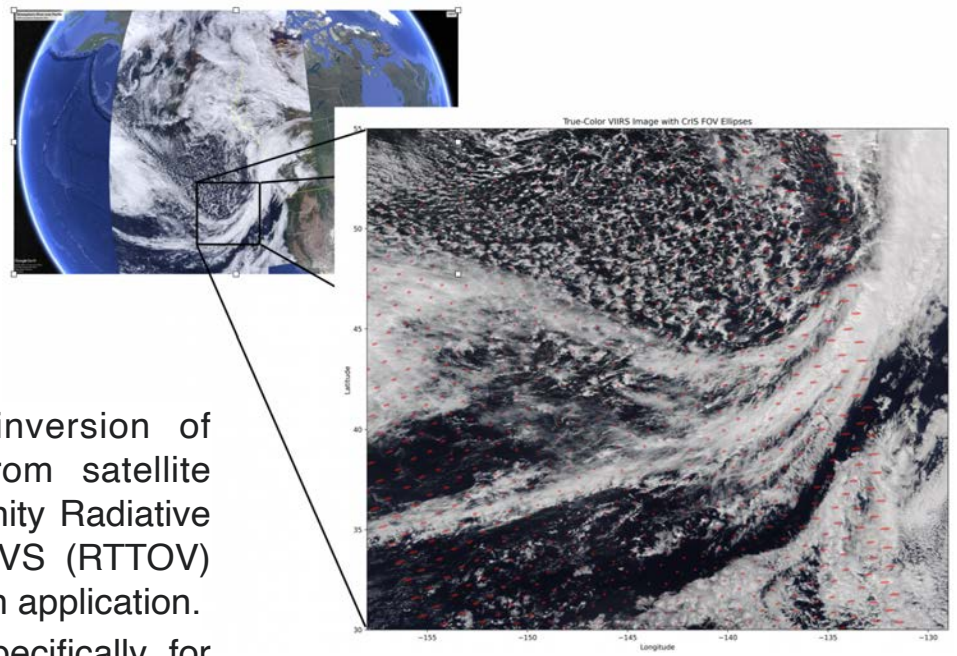


Observed Best Track



WRF 60h tracks with TR assimilation

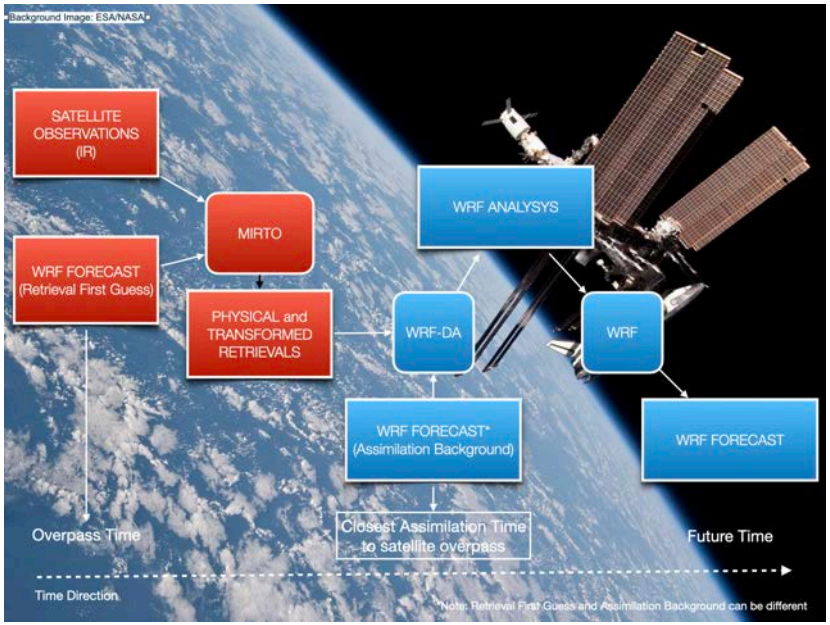
New Directions

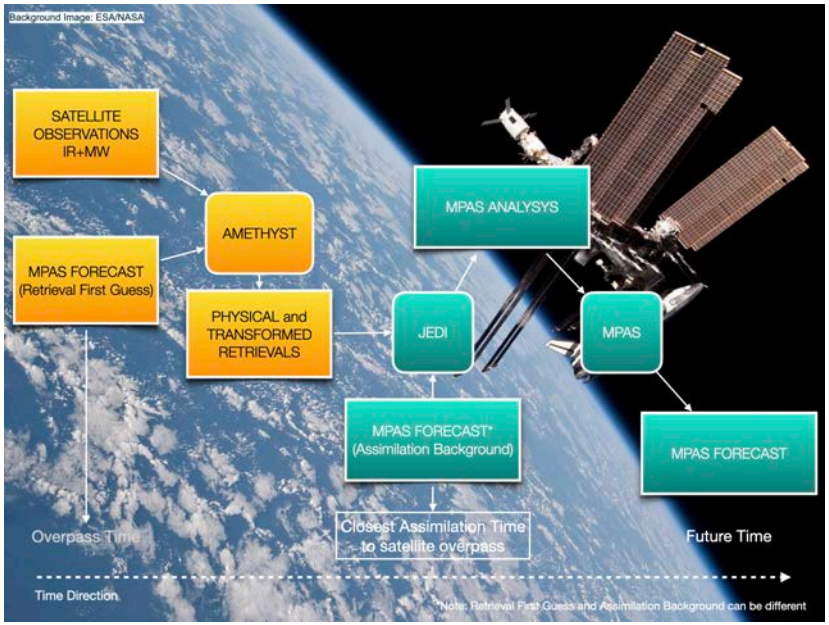


Our new AURORA project has two overarching goals.

1. to maximize the extraction of information from the inversion of hyperspectral infrared and microwave data obtained from satellite instruments. This will be achieved by employing the Community Radiative Transfer Model (CRTM) and the Radiative Transfer for TOVS (RTTOV) within our advanced version of the hyperspectral data inversion application.
2. to develop an advanced data assimilation (DA) module specifically for hyperspectral *Transformed Retrievals*. This initiative will be undertaken in collaboration with the Joint Center for Satellite Data Assimilation (JCSDA). The anticipated outcome is a significant enhancement in the resolution of initial conditions within the MPAS global model, paving the way for more accurate and reliable weather forecasts.

Hyperspectral Processing System Evolution





Mirto:
- mainly clear sky
- based on single forward model
- no explicit cloud representation

WRF-DA:
- traditional data assimilation system widely used
- development stopped

WRF:
- traditional grid-based approach
- global or regional spatial resolution

Amethyst:
- clear and cloudy sky
- adaptable to multi forward models
- explicit cloud representation

JEDI:
- advanced data assimilation techniques
- flexibility integrating various NWP models

MPAS:
- finite-volume method that better handles complex terrain and physical processes
- high flexibility in spatial resolution (variable mesh spatial resolution)

Conclusions

Conclusions: Current Results for satellite retrievals and data assimilation

- We have demonstrated the utility of TR assimilation to improve WRF forecasts over the Central North Pacific over a month long experiment, and in forecasting the track and intensity of Hurricane Lane
- Next step will be to assimilate IR and MW data together in a framework that allows for retrievals under clear and cloudy conditions.

Future Synergy

- The future likely lies in *hybrid models* that combine the strengths of physically based models and deep learning. These models can use deep learning for tasks like pattern recognition and short-term prediction while relying on physical models for long-term forecasts and understanding underlying processes.
- The advent of deep learning in weather forecasting is set to enhance and transform the role of physically based models and traditional data assimilation methods. The future will likely see a synergistic approach, leveraging the strengths of both deep learning and physically based models to achieve more accurate, timely, and reliable weather forecasts. The key to success will be in harnessing the complementary strengths of these technologies while addressing challenges related to data quality, model interpretability, and integration complexity. In this regard the availability of TRs will be a key element for the development of Hybrid Systems.

References

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Questions?

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