MIIDAPS:
A Consistent Variational Approach for the Inversion & Assimilation Preprocessing of Microwave and Infrared Satellite Data

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Content

Background & Heritage (Science)

- Satellite data are sensitive to many parameters. Scientifically, it is preferable to invert all products simultaneously and use all measurements together.

- Increased information content at radiometric level before inversion, is superior to inversion separately. Advocate for MW+IR synergy. (2-channels > 1 channel)

- Basically no difference between IR and MW sensing phenomena besides different sensitivity, spectroscopy, NeDT, …handled by variational approach.

- Radiative Transfer Modeling already handles uniformly MW and IR measurements simulations (including Jacobians): ex: CRTM

- Coupled data assimilation is a major focus: will lead to using DA analysis beyond NWP (to ocean, land, cryosphere, hydrometeors, etc). Same drivers should apply to Inversion Approaches (coupled inversion: sounding, surface, cryosphere, hydrometeors,..).

- MiRS algorithm, operational since 07 in NOAA, is proof of concept. Applied to microwave sensors (conical, cross-track, polar, low-orbit,..), generating sounding, hydrometeors, cryosphere, land and ocean products

Trends Foreseen (non-scientific)

- **Budget Pressure to continue, leading to innovations in cost effectiveness**
  - Need for Consolidating Algorithms into Enterprise Approaches
  - Leveraging Existing investments (i.e radiative Transfer, Inversion,..)

- **Multiplication of Satellites: International, Commercial, Small Satellites**
  - Need for Agile Approaches for handling satellite data
  - Need for consistent processing with single algorithms to avoid discrepancies

- **Increased spatial and temporal resolutions will lead to usage of data assimilation for situational awareness (nowcasting and short term forecasting)**
  - Relevance of separate inversions? (different orbits, formats, quality, etc)
  - Blurriness between retrieval and data assimilation/fusion for nowcasting applications
  - Advocate for making retrieval algors **'dual use'**: for Inversion and DA pre-processing
  - Radiances vs retrieval Assimilation: Integration of algorithms *technology* as an alternative

Content

MIIDAPS Concept

3 years ago (In 2014), a New generation System started was initiated (as a pilot project)

Goal was to build on MiRS heritage and develop a system with a dual use: Retrieval and Data Assimilation Pre-processing.

Goal is also to generalize it to all sensors including IR and Hyperspectral IR

Goal is to cross-fertilize DA and retrieval applications. Similar in concept to the CRTM (used for inversion, calibration, climate applications and at the same time to data assimilation)

Variational Mathematical Basis

- Cost Function to Minimize (similar between retrieval& assimilation):

$$J(X) = \left[\frac{1}{2}(X-X_0)^T \times B^{-1} \times (X-X_0)\right] + \left[\frac{1}{}\left(\quad\right)^T \quad \left(\quad\right)\right]$$

Jacobians & Radiance Simulation from Forward Operator: CRTM

- To find the optimal solution, solve for: $\frac{\partial J(X)}{\partial X} = J'(X) = 0$

- Ass[...] $X_0]$

Same Methodology applied to all parameters:

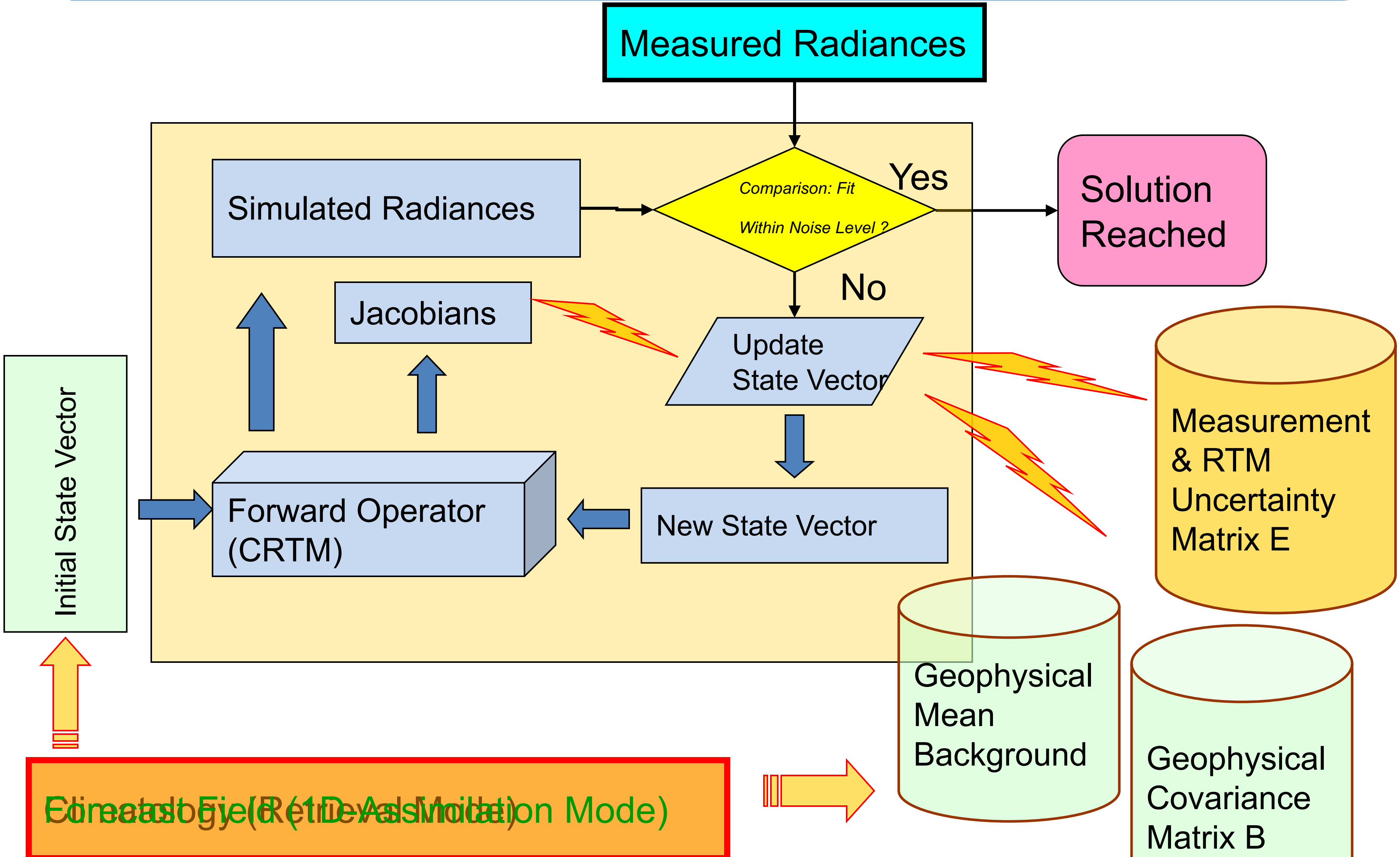
State Vector X contains:

- T(p), Q(p), Tskin
- Emissivity Vector
- Hydrometeors (frozen and liquid water)

- This leads to iterative solution:

$$\Delta X_{n+1} = \left\{B K_n^T \left(K_n B K_n^T + E\right)^{-1}\right\}\left[\left(Y^m - Y(X_n)\right) + K_n \Delta X_n\right]$$

MIIDAPS Variational Retrieval/Assimilation



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MIIDAPS Algorithm Concept

Multi-Instrument Inversion and Data Assimilation Preprocessing System

Motivation: Universal retrieval and Data Assimilation preprocessor for all satellite observations

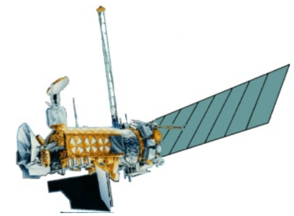
S-NPP& JPSS ATMS/CrIS

Megha-Tropiques SAPHIR

MetOp-A AMSU/MHS/IASI
MetOp-B AMSU/MHS/IASI

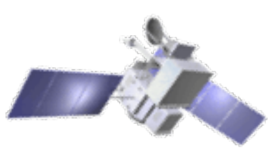
NOAA-18 AMSU/MHS/AVHRR
NOAA-19 AMSU/MHS/AVHRR

MIIDAPS

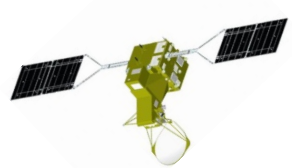


DMSP F16 SSMI/S
DMSP F17 SSMI/S
DMSP F18 SSMI/S

TRMM TMI



GPM GMI



GCOM-W1 AMSR2

Inversion Process

- Inversion consistent across sensors
- All parameters included in state vector
- CRTM for forward/Jacobian operators
- Valid over all surfaces/all-sky conditions
- Use forecast, fast regression or climatology as first guess/background

****MIIDAPS also applicable to GOES-16 Sounder, Meteosat SEVIRI, AHI, ABI, MODIS, AIRS, etc**

DA Pre-Processing

- Consistent Quality Control (rr,ice,..)
- Consistent pre-processing for non-analyzed parameters
- Corrects displacements (fronts,..)
- Modular design, scalable
- Use of MPI for HPC

Content

1 Introduction, Background, Heritage and Motivation

2 Overview of MIIDAPS Concept

3 **Highlight of MIIDAPS Applications**

- In Standalone retrieval Mode (for IR and MW)
- In Data Assimilation Pre-processing Mode

4 Summary & Conclusion

MIIDAPS :

AS STANDALONE INVERSION SYSTEM
(FOR IR and MW SENSORS)

- Applied to MW and IR sensors
- Coupled Inversion: Sounding, Hydrometors, and Surface Parameters
- Quality of Products inverted depends on Information Content

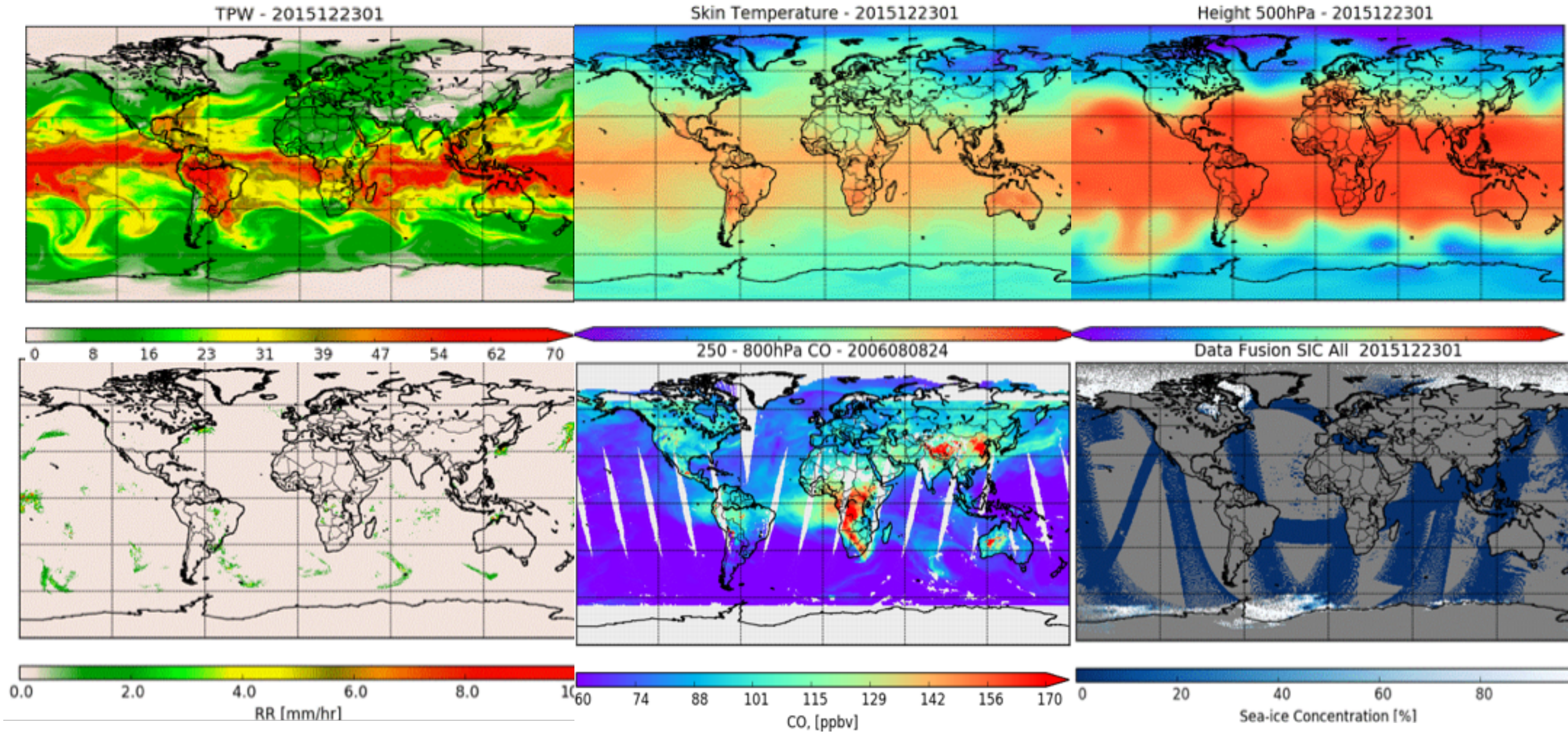
MIIDAPS Capabilities (Sensors & Geophysical)

MIIDAPS Satellite Products

	T(p)	Q(p)	SST/LST	TPW	Cloud & Ice Amt	Cld Type/Top	Precip	Sfc Emiss	SIC/SWE	Trace Gas	QC (ChiSq)
NOAA-18 AMSU/MHS	Green	Green	Green	Green	Green		Green	Green	Green		Green
NOAA-18 AVHRR			Green	Yellow		Yellow		Green			Green
NOAA-19 AMSU/MHS	Green	Green	Green	Green	Green		Green	Green	Green		Green
NOAA-19 AVHRR			Green	Yellow		Yellow		Green			Green
Metop-A AMSU/MHS	Green	Green	Green	Green	Green		Green	Green	Green		Green
Metop-A IASI	Green	Green	Green	Green		Green		Green		Green	Green
Metop-B AMSU/MHS	Green	Green	Green	Green	Green		Green	Green	Green		Green
Metop-B IASI	Green	Green	Green	Green		Green		Green		Green	Green
SNPP ATMS	Green	Green	Green	Green	Green		Green	Green	Green		Green
SNPP CrIS	Green	Green	Green	Green		Green		Green		Green	Green
DMSP SSMI/S	Green	Green	Green	Green	Green		Green	Green	Green		Green
Aqua AMSU	Green	Green	Green	Green	Green		Green	Green	Green		Green
Aqua AIRS	Green	Green	Green	Green		Green		Green		Green	Green
Megha-T SAPHIR		Green		Yellow	Yellow		Green	Yellow			Green
GPM GMI		Yellow	Green	Green	Green		Green	Green	Green		Green
GCOM-W1 AMSR2		Yellow	Green	Green	Green		Green	Green	Green		Green
GOES-15 Sndr/Imgr	Yellow	Yellow	Green	Green		Light green		Green		Yellow	Green
Meteosat SEVIRI		Yellow	Green	Green		Yellow		Green		Yellow	Green
Himawari-8 AHI		Yellow	Green	Green		Yellow		Green		Yellow	Green
GOES-16 ABI		Yellow	Green	Green		Yellow		Green		Yellow	Green

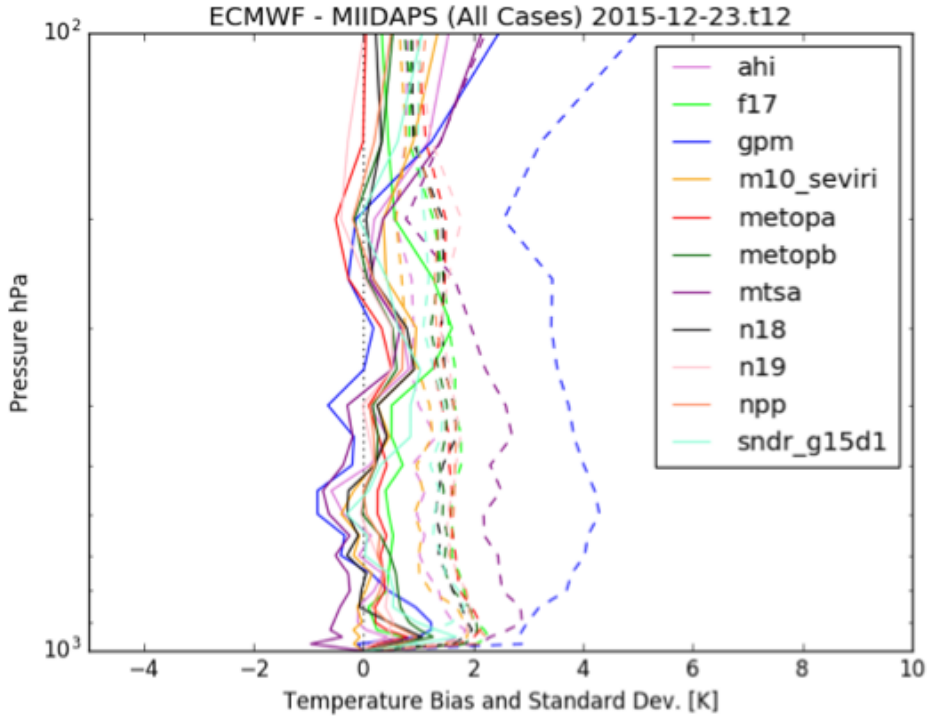
Illustration of the MIIDAPS Outputs

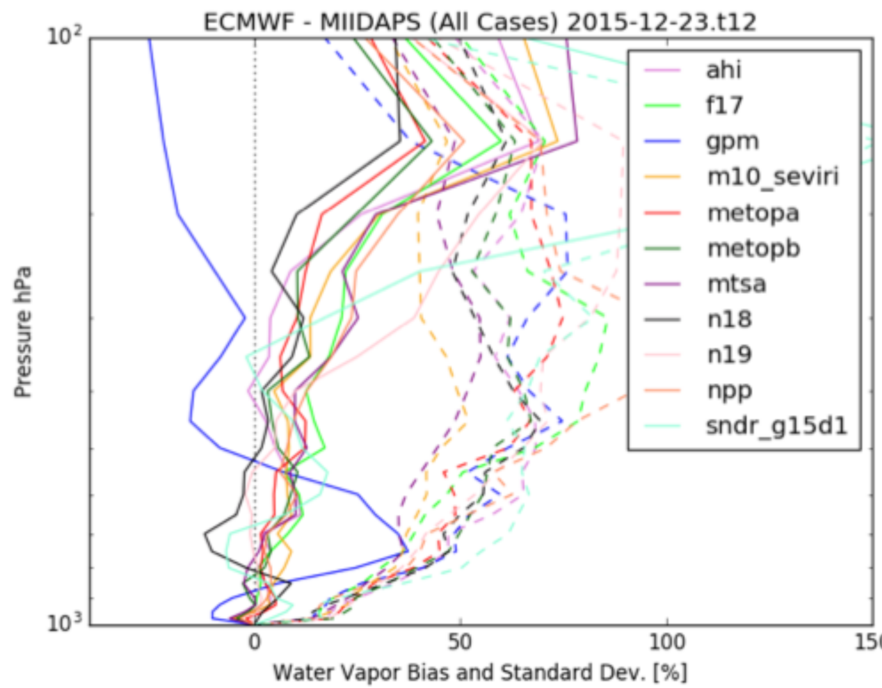
(geophysical parameters)



MIIDAPS Processes Microwave and Infrared Satellite Observations to Invert Atmospheric, Surface, Hydrometeors and Cryospheric products. It has Dual Use: It can be used as standalone for inversion applications and as a pre-processing system for data assimilation applications.

MIIDAPS Sounding Performances Assessment on 11 Sensors (Use ECMWF as a reference)

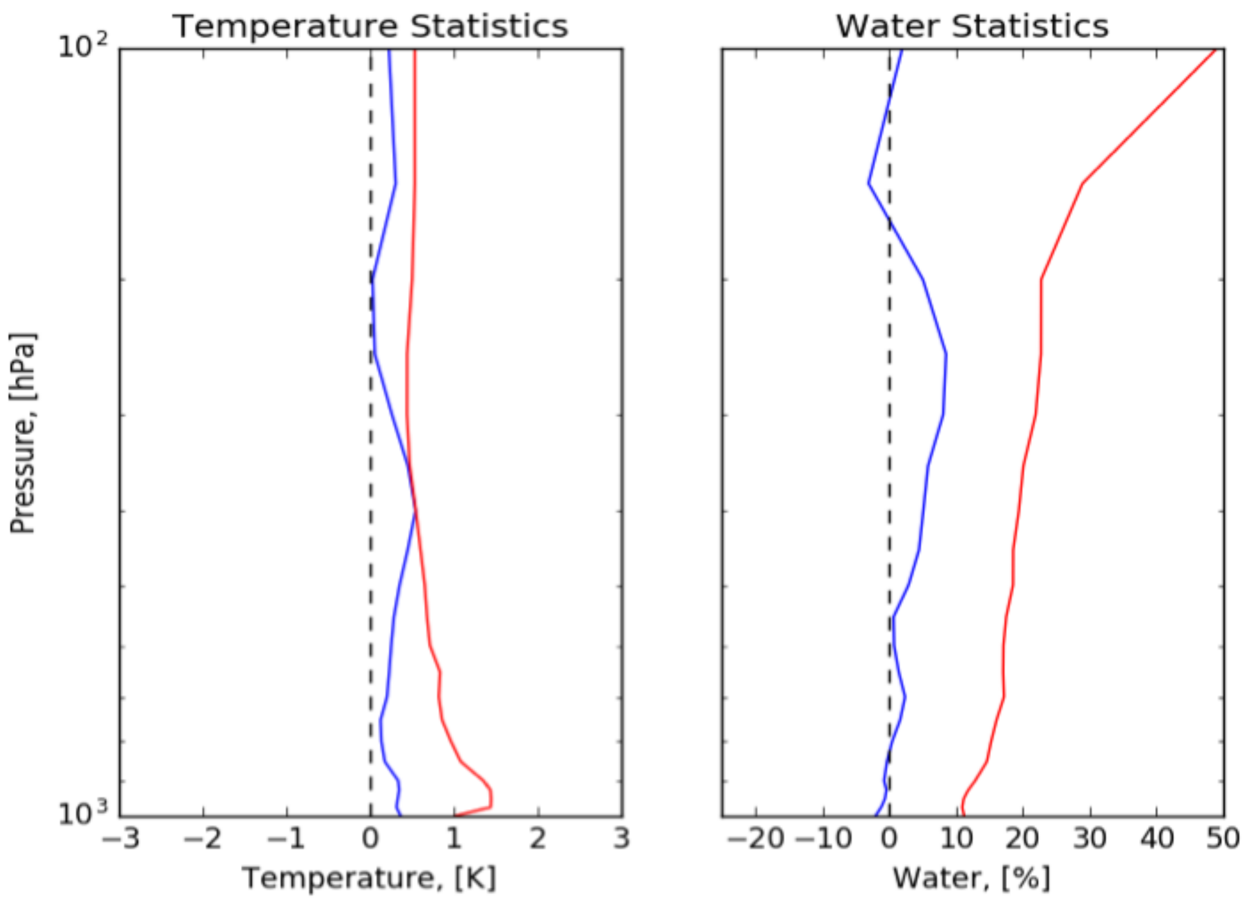




This is a rough assessment of the performances. This needs closer attention (margin for improvements). Examples: Assumed Obs Errors not tuned, all cases included (ocean, land, rainy, cloudy, clear-sky, etc). IR retrievals have clouds filtered out.

MIIDAPS Performances

Temperature and Water Vapor Profiles
Global Bias and Standard Deviation



- Clear Sky Data
- Land and Ocean
- No bias correction applied
- CrIS configuration
- Out-of-the-box testing (no optimization)
- Full spectrum used
- ECMWF Used as reference

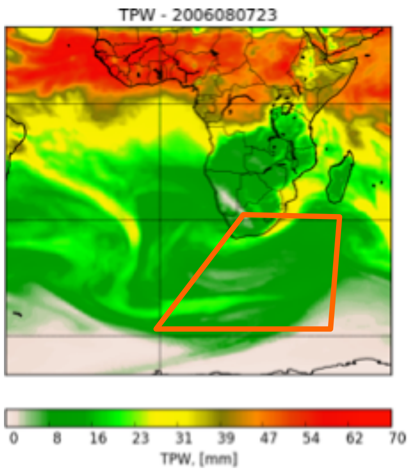
MIIDAPS :

AS PRE-PROCESSING FOR SATELLITE DATA ASSIMILATION (NWP)

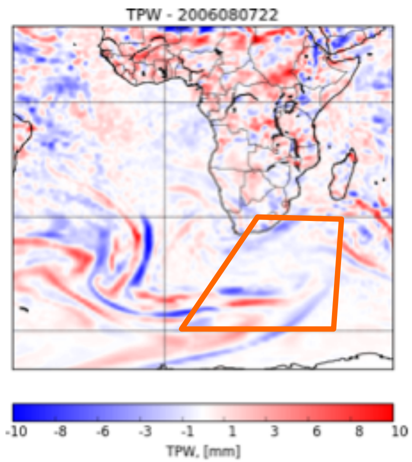
- Universal Quality Control Tool (Non-Convergence, Rain, Ice detection, etc)
- Pre-Processing system to provided non-analyzed data (add to the NWP analyses)
- Corrects forecast background displacement(s): cold/warm fronts, Cloud/storm position, etc

Assessment of Displacement Correction Using OSSE Testbed & Associated Nature Run (NR)

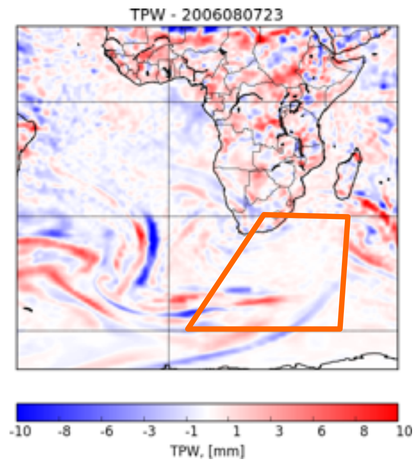
G5NR TPW



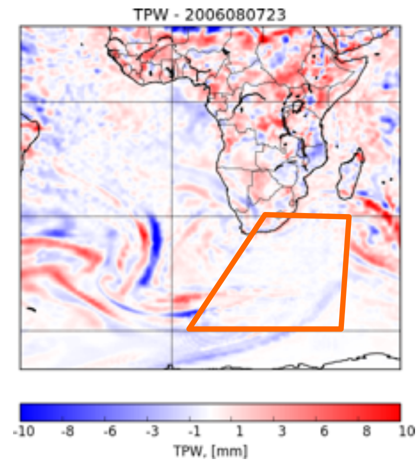
a) Background – G5NR



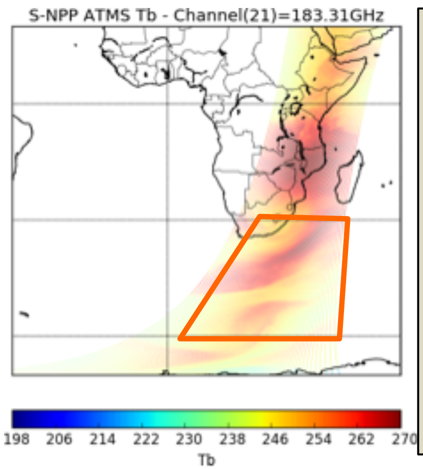
b) GSI analysis – G5NR



c) w MIIDAPS pre-processing



Location of ATMS obs.



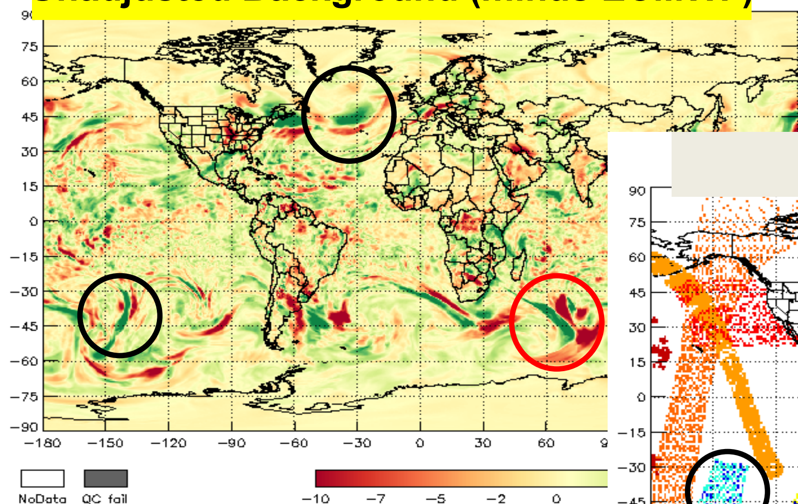
Example Analysis Cycle at 2006-08-07 23Z

a) Background-G5NR shows large displacements (dipoles) in TPW field
b) GSI analysis-G5NR reduces magnitude of dipoles slightly where SNPP ATMS data exists (red trapezoid)
c) Data Fusion analysis through MIIDAPS-based background adjustment removes most of dipole feature and reduces TPW differences where SNPP ATMS data exists

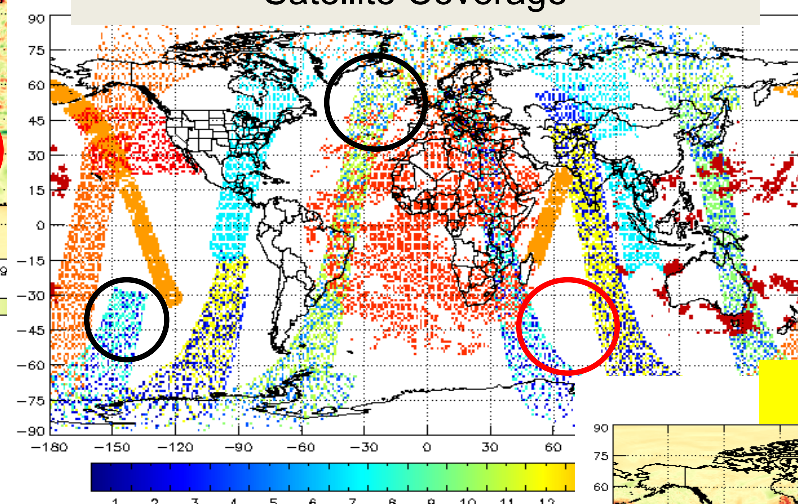
Illustrative Example with real Data: (of Displacement Correction)

Background Adjustment Example, All Satellite Data: December 23, 2015 00Z

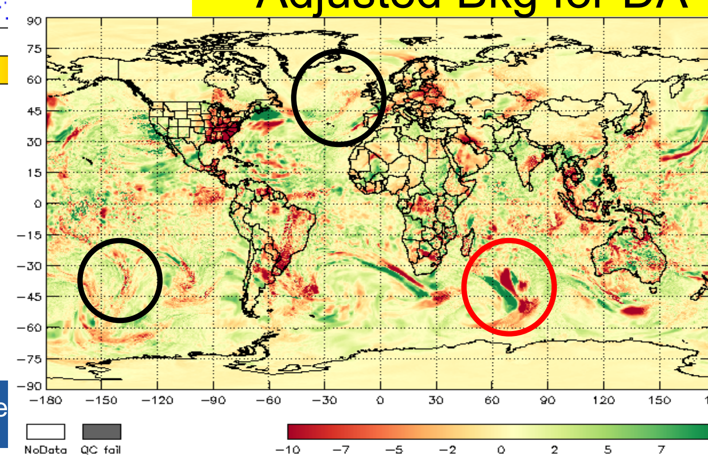
Unadjusted Background (minus ECMWF)



Satellite Coverage



Adjusted Bkg for DA



Main advantages of Using MIIDAPS in NWP:

- Complete analyses with more parameters including cryosphere, hydrometeors, land, ocean, trace gases, etc)
- Fit to observations (displacement correction)
- Flexible to extend to other sources of Obs.
- Provide QC and ice/rain detection to users to assimilation step

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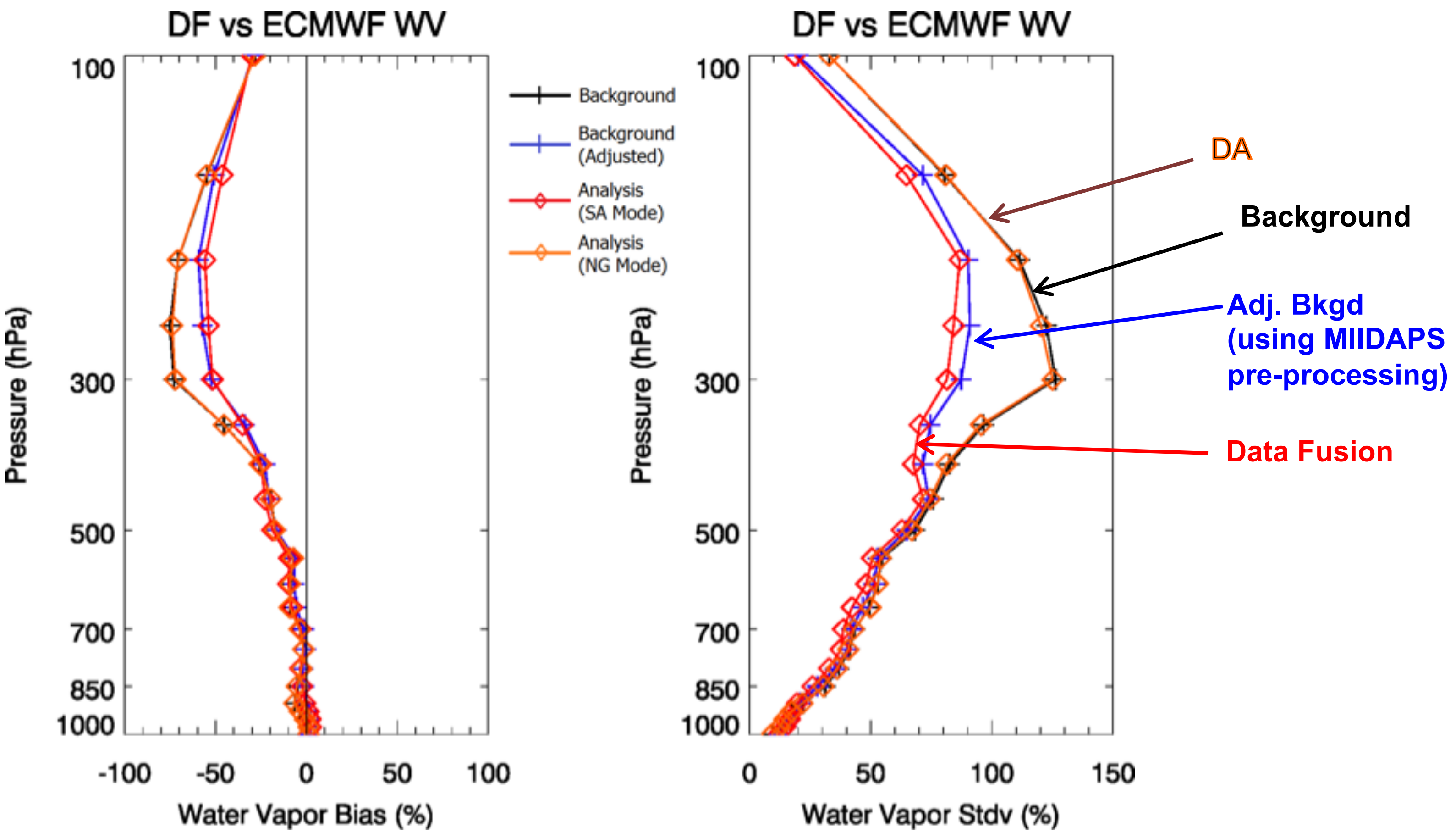
Performance Assessment

Example of Data Fusion Analyses for 2015-12-23 12Z Cycle

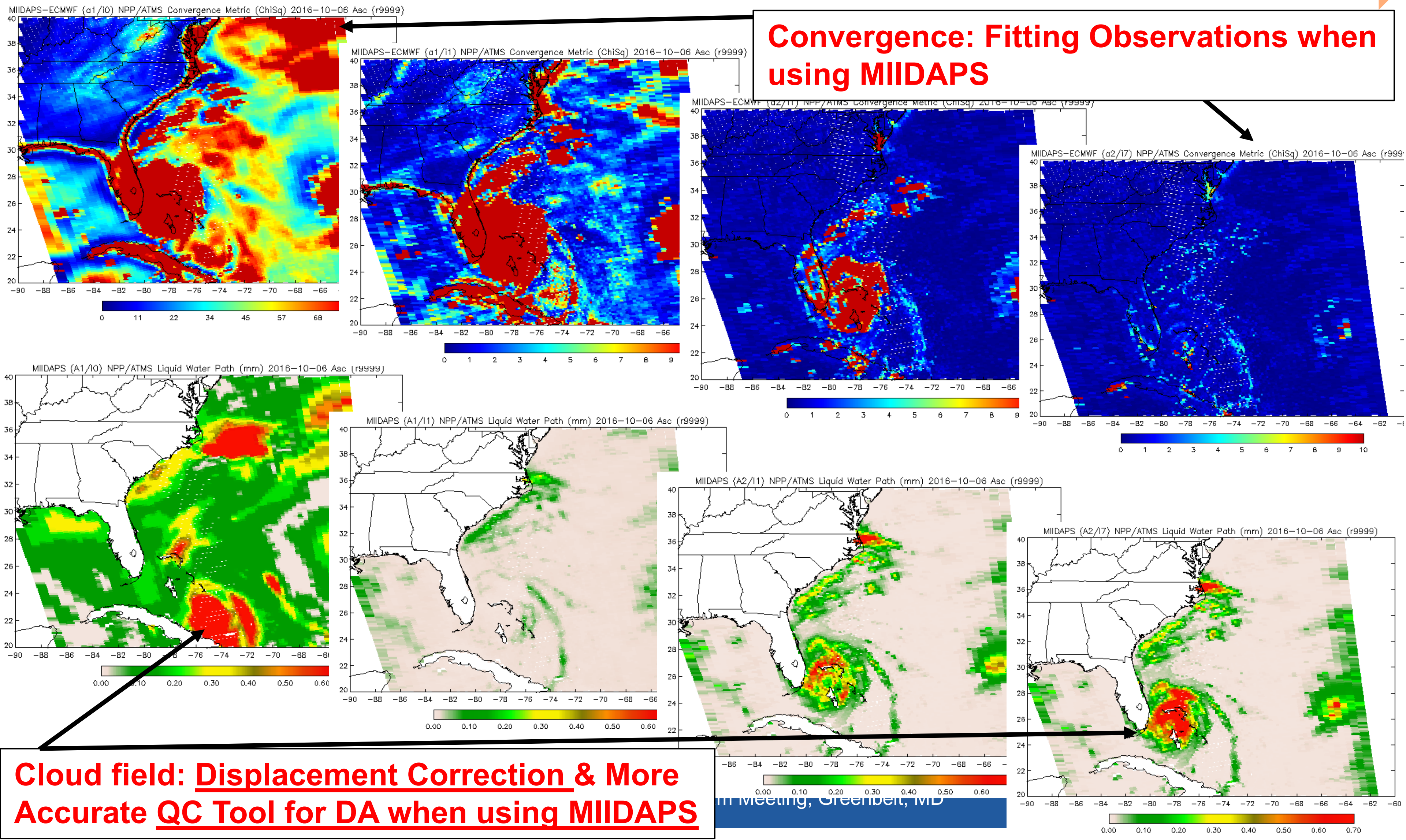
Performance at observation locations



- **Background Adjustment provides displacement correction in analysis.**

Generating & Displacement Correction of Hydrometeors in Analysis (Case Hurricane Matthew, Oct 2016, SNPP/ATMS)

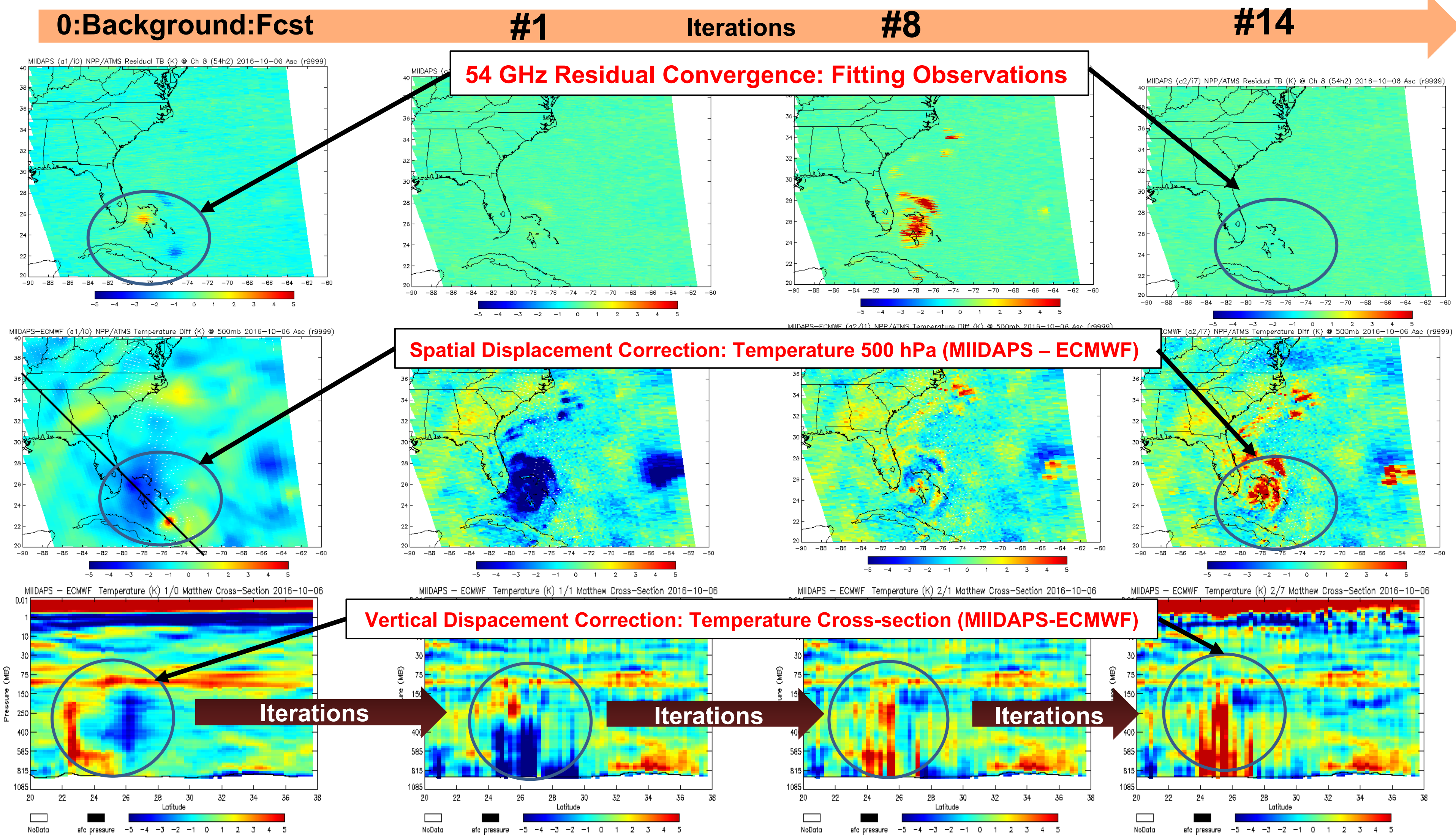
0:Background:Fcst — #1 — Iterations — #8 — #14



Convergence: Fitting Observations when using MIIDAPS

Cloud field: Displacement Correction & More Accurate QC Tool for DA when using MIIDAPS

Temperature Vertical and Horizontal Displacements Correction



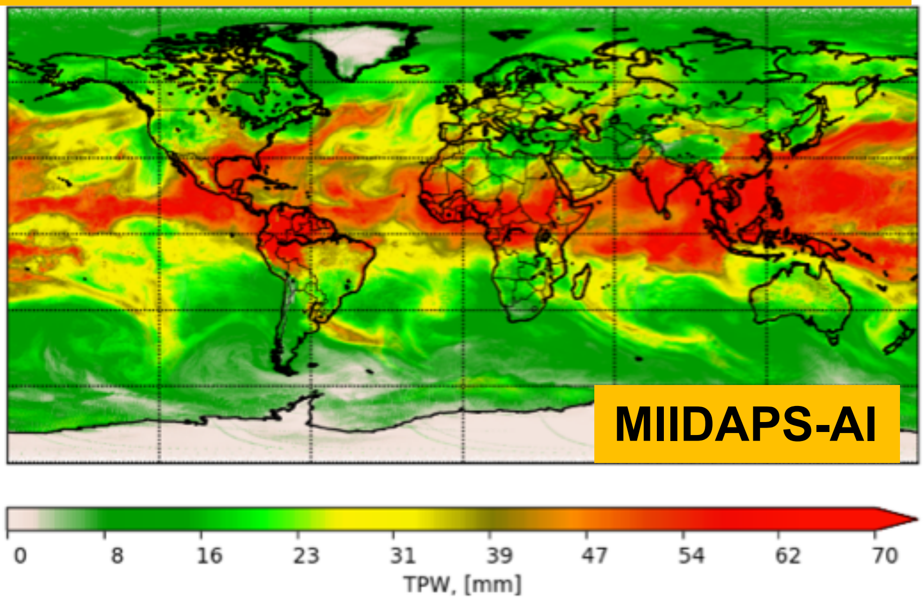
Findings

- MIIDAPS, when applied as standalone retrieval algorithm for both IR and MW sensors, retrieves sounding along with surface and hydrometeors data
- MIIDAPS has been applied (but not optimally tuned) to a large number of sensors.
- Quality of these retrievals depends on the sensors and the information content
- MIIDAPS (like MiRS) adopts a coupled inversion system, where measurements are inverted simultaneously, to provide geophysical data
- MIIDAPS, when applied as a Data Assimilation Preprocessing system, offers a way to correct spatial and vertical displacements in NWP analyses, for (1) cloud, (2) moisture, and (3) temperature, making them useful for Nowcasting
- Convergence Metric offers a powerful QC tool: In DA preprocessing mode, MIIDAPS also offers a universal QC tool to detect rain, ice, cloud, etc
- MIIDAPS major challenge: time cost. CRTM is significantly slow, especially in cloudy/rainy conditions (effort is on going to speed it up)

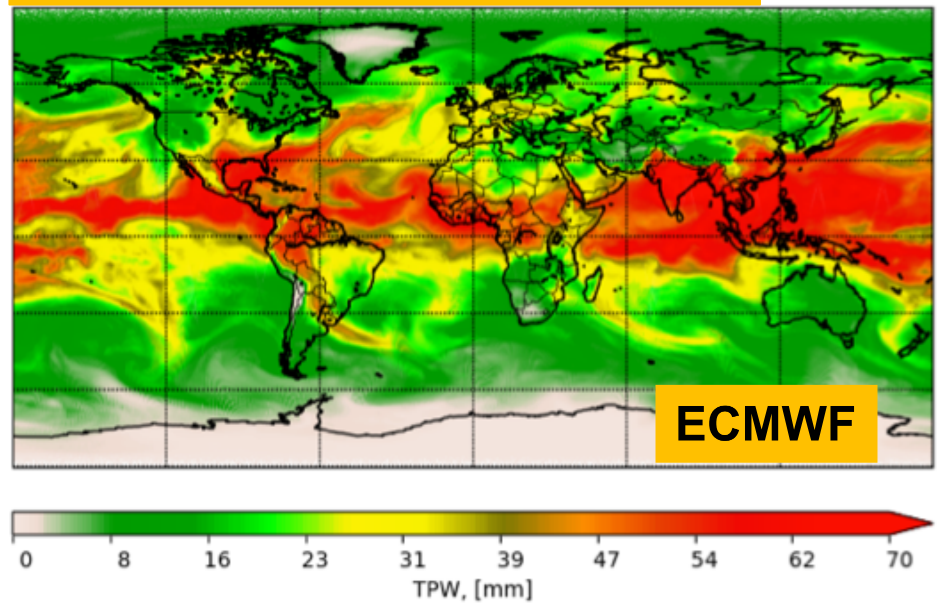
MIIDAPS-AI:

Exploring Artificial Intelligence for Remote Sensing/Data Assimilation/Fusion Applications

MIIDAPS-AI outputs (TPW) Using SNPP/ATMS Real Data



Reference source of TPW: ECMWF Analysis



- Comparison of AI-Based (left) and Reference field (right)
- Uses Google tensorFlow tool.
- AI algorithms uses real SNPP/ATMS data as inputs
- 40,000 points used train model using 2 epochs, each with 6000 iterations.
- Using the NR dataset (indep. from ECMWF) fro training

	AI-Based MIIDAPS	MIIDAPS (similar to oper. System)
Processing Time (Approx) for a full day data. Excluding I/O	**~5 seconds**	**~ 2 hours**

Several approaches being/will be tested:

(1) Direct Inversion of data Using an Deep-Learning AI algorithm

(2) Retain Variational Inversion but Use an AI-based RT/Jacobian Forward Operator

Content

Summary & Conclusion

- MIIDAPS: community software (freely available) with dual use: (1) standalone inversion and/or (2) DA pre-processing system
- It leverages CRTM for radiance and Jacobians computations
- Applicability to MW and IR sensors as long as they are handled by CRTM: sounders/imagers, x-track/conical, Polar/Geo
- Main advantage: Consistency+cost effectivess+agility, Drawback: Time cost
- Handling cloud/rainy data in MIIDAPS by varying hydromet. in state vector.
- Handling surface-sensitive channels by varying emissivity
- Products Assessment suggests approach provides very reasonable results. *Massive amount of validation is needed to finalize this (tens of sensors, tens of products for each)*
- Displacement corrections & Universal QC major benefit of MIIDAPS in NWP
- MIIDAPS as entry point to leveraging Remote Sensing in NWP applications.
- Current Use of MIIDAPS in Data Fusion System for Nowcasting applications