NATIONAL WEATHER SERVICE

Building a Weather-Ready Nation

3D Real Time Mesoscale Analysis (RTMA)

July 13, 2022

Presenter: Manuel Pondeca, IMSG @ EMC/NCEP/NWS/NOAA

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Outline

- 3DRTMA development plan
- 3DRTMAv1 Configuration
- Current work
  - Observation Quality Control
  - Background error covariance modeling
  - Dynamic Downscaling
  - RTMA Quality Assessment
- Future Work
  - Analysis Uncertainty Estimate
  - 15-min Background Field Improvement
  - The use of visibility VEIA data

The 3D-RTMA System

- **Description:** A high-spatial (**≤ 2.5km**) resolution rapidly updating (**≤ 15min**) 3D-analysis system intended to support nowcasting, situational awareness, and aviation operations. Will replace operational 2D-RTMA.

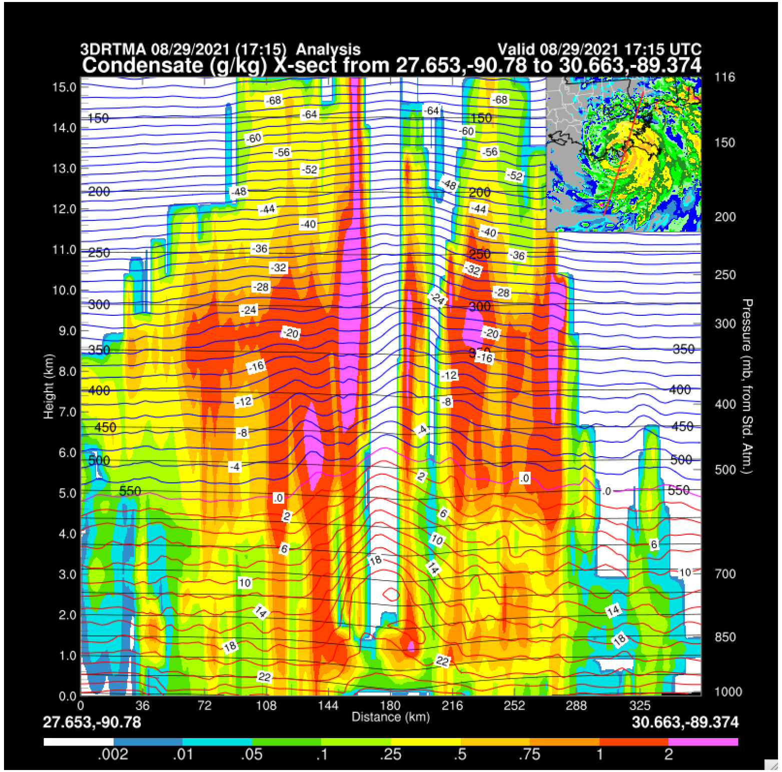
- **Companion system: 3D Unrestricted Mesoscale Analysis (3D-URMA)**
  - It's a delayed 3D-RTMA. Runs 6 hours later to use late arriving observations. Can use computationally more demanding algorithms. Will replace operational 2D-URMA as the Analysis of Record: Use for forecast verification and calibration in NBM.

- **Integrated in UFS-R2O SRW/CAM Project:** Joint work by EMC/NCEP & GSL/ESRL. Initiated in 2018 as JTTI project.
  - Collaborators/Stakeholders: NCEP Centers, NWS Regions, WFOs, MDL, FAA
  - Input from the Analysis & Nowcast Branch (AFS11) on forecaster requirements regarding Products & Quality.

- Provides full-column representation of standard atmospheric fields such as temperature, water vapor, and wind, as well as hydrometeors (i.e., clouds, precipitation of all forms), and eventually aerosols.
- To include land-surface diagnostics (e.g., soil moisture, snow state from multi-level land surface fields) and convective (e.g., hail size, supercell rotation tracks) fields.
- 2D fields that are intrinsically a function of 3D space (PBL height, precipitable water, ceiling, etc.) are diagnosed from the 3DRTMA fields, yielding full physical consistency through use of a very accurate high resolution model background.
- Experimental system runnig since 2018

3DRTMA Example

(Hurricane Ida)



3DURMA Example

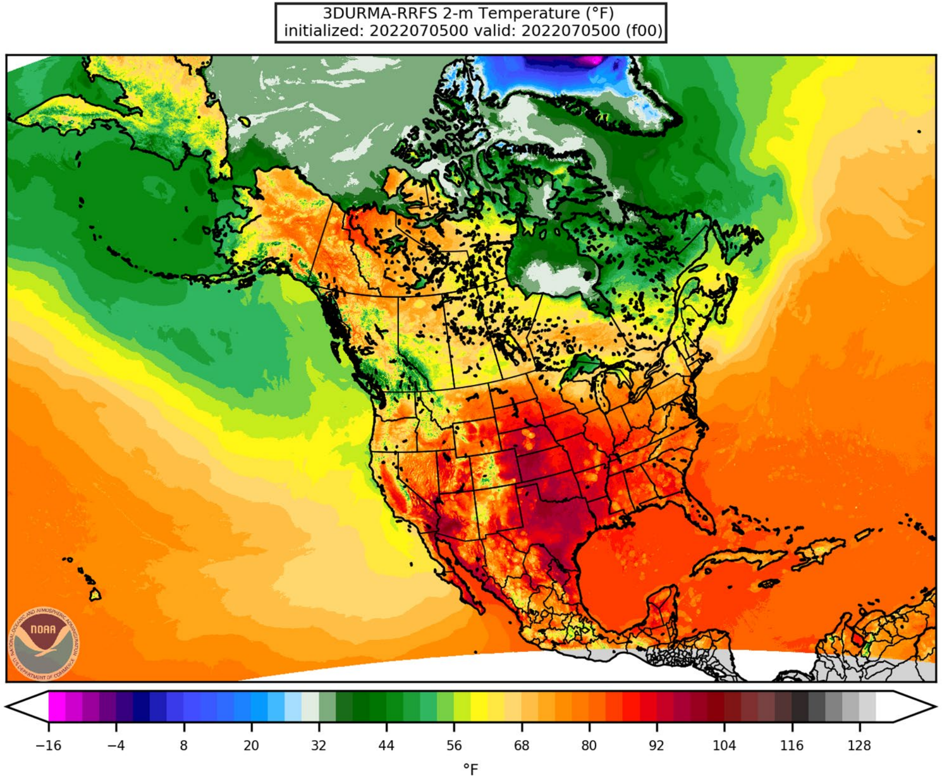


Table of Category 5 Storm Prediction Center (SPC) fields added to the Unified Parallel Processor (UPP) for the HWT 2021 SFE. Many are already standard products while other are novel (those derived from the calculation of the effective layer)

1	DESCRIPTION	UNITS	NAME	PRIORITY	GRIB2 TABLE	SYMBOL	TABLE #	Dependent fields	UPP ID	status	GRIB2 label in UPP	note
2												
3	Most Unstable CAPE (MUCAPE)	J kg-1	MUCP	5	4.2-0-7	CAPE	6		584	complete	CAPE:255-0 mb above ground	existing field
4	Most Unstable CIN	J kg-1	MUCN	5	4.2-0-7	CIN	7		585	complete	CIN:255-0 mb above ground	existing field
5	Most Unstable Lifted Index	J kg-1	MULI	5	4.2-0-7	4LFTX	11		31???	complete		existing field
6	Storm relative helicity sfc to 1 km	m2 s-2	SRH1	5	4.2-0-7	HLCY	8		162	complete	HLCY:1000-0 m above ground	existing field
7	Storm relative helicity sfc to 3 km	m2 s-2	SRH3	5	4.2-0-7	HLCY	8		162	complete	HLCY:3000-0 m above ground	existing field
8	Downdraft CAPE	J kg-1	DNCP	5	4.2-0-7	DCAPE	203		954	complete		existing field
9	Effective surface height	m	EFSH	5	4.2-0-3	EFSH	222	MU CAPE & Z		complete		commited to UPP Repository 03/07/2021
10	Effective surface helicity	m2 s-2	E3KH	5	4.2-0-7	E3KH	207	MU CAPE & HLCY		complete		committed to UPP Repository 03/30/2021
11	100 mb mean mixed CAPE	J kg-1	M1CP	5	4.2-0-7	CAPE	6			complete	CAPE:180-0 mb above ground	existing field
12	100 mb mean mixed CIN	J kg-1	M1CN	5	4.2-0-7	CIN	7			complete	CIN:180-0 mb above ground	existing field
13	100 mb mean mixed Lifted Index	J kg-1	M1LI	5	4.2-0-7	4LFTX	11		31??	complete		existing field
14	Equilibrium Level Temperature	C	MELT	5	4.2-0-0	ELMELT	205	MU CAPE & T		complete		commited to UPP Repository 03/07/2021
15	Sig Tornado parameter with CIN-Effective Layer	numeric	STPC	5	4.2-0-19? 4.2-0-7	STPC	200			complete		committed to UPP Repository 03/30/2021
16	Sig Hail parameter	numeric	SIGH	5	4.2-0-19? 4.2-0-7	SIGH	201			complete		committed to UPP Repository 03/30/2021
17	Inflow based (ESFC) to (50%) EL shear magnitude	kt	ESHR	5	4.2-0-2	ESHR	233	MU CAPE U & V		complete		commited to UPP Repository 03/07/2021
18	U inflow based to 50% EL shear vector	kt	UESH	5	4.2-0-2	UESH	234	MU CAPE & U	:1	complete		commited to UPP Repository 03/07/2021
19	V inflow based to 50% EL shear vector	kt	VESH	5	4.2-0-2	VESH	235	MU CAPE & V		complete		commited to UPP Repository 03/07/2021
20	U Bunkers Effective right motion	kt	UEID	5	4.2-0-2	UEID	236	MU CAPE & U		complete		committed to UPP Repository 03/30/2021
21	V Bunkers Effective right motion	kt	VEID	5	4.2-0-2	VEID	237	MU CAPE & V		complete		committed to UPP Repository 03/30/2021
22	Sfc based LCL height	m	SLCH	5	4.5	LCL	5			complete		existing field
23	100 mb mean mixed LCL height	m	MMLH	5	4.5	LCL	5			complete		existing field
24	100 mb mean mixed 3 km agl CAPE	J kg-1	M3KC	5	4.2-0-7	CAPE	6			complete		existing field
25	Supercell Composite Parameter-Effective Layer	numeric	SCCP	5	4.2-0-7	SCCP	210	?		complete		committed to UPP Repository 03/30/2021
26	Sig Tornado parameter-Fixed Layer	numeric	SIGT	5	4.2-0-19	STPC	200			complete		committed to UPP Repository 03/30/2021
27	Mixed Layer (100 mb) virtual LFC	numeric	MLFC	5	4.2-0-7 4.5	MLFC	14			complete		committed to UPP Repository 03/30/2021
28	100 mb mean mixing ratio	g kg-1	M1MX	5	4.2-0-1	MIXR	2			complete		existing field

A list of targets in the 3DRTMA Roadmap (Draft)

(10-year vision for system development consistent with GSL strategic plan and EMC 10 years strategy draft plan)

- **Observations**

  Improve QC and processing
  Add new observations (eg. web cameras, uncrewed aerial systems)

- **Improve efficiency of background covariance modeling**

  Develop highly scalable Multigrid Beta Filter (MGBF)

- **Improve estimate of the gridded analysis uncertainty**

  Lanczos method and MGBF + ML/AI

- **Improve background and analysis downscaling**

  Dynamic downscaling and ML/AI based application

- **Integrate analysis of aerosols**

  For air quality and smoke

- **Expand to coupled system**

  Land surface analysis

  Ocean current and wave height analyses consistent with 10-m winds

- **Continuous in-core capability**

  Very rapidly updating analysis (eg. 5 min)

  On demand over focus area (eg. wild fire event)

- **Unified visualization capability for 3DRTMA and RRFS**

  Common platform shared by GSL and EMC

  Efficient analysis and forecast evaluation

- **Observation impact and Quality Monitoring System**

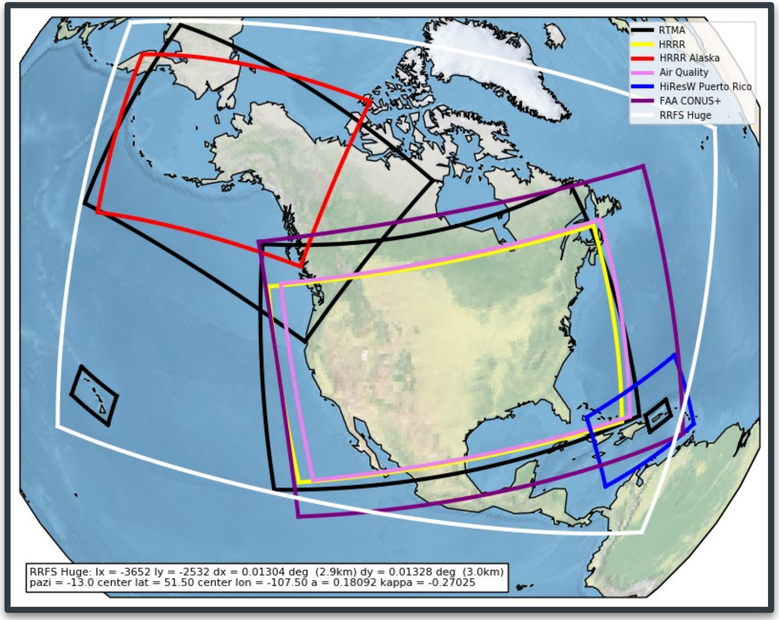
  Based on adjoint techniques

Target Configuration for 3DRTMAv1

(to be implemented in Q4FY24)

- Use RRFS domain (Covers CONUS, AK ,Hi, & PR NDFD grids)
- 3.0 km or 2.5-km resolution (TBD)
- RRFS bckg for the atmosphere
- GFS/wave bckg for significant wave height
- Hybrid En3DVar DA scheme using the RRFS ensemble
- GSI (but possibly JEDI)
- Non-Variational cloud analysis

  (see Terra Ladwig's talk)
- Separate system for Guam



3 km RRFS domain (white outline). Black outlines are current RTMA/URMA domains (Guam not shown)

Observation Quality Control

Improved observation QC in RTMA/URMA is an established requirement in CaRDS 18-028 and CaRDS 20-036 . Need for more automated and scientifically based QC procedures.

Automated QC package for sfc and aircraft observations integrated into 3DRTMA to reduce reliance on fixed reject/accept lists that can only be updated with system upgrades :

- uses SQL databases
  - reject lists based on RMSE and Stuck instrument checks
  - accept lists for mesonet wind observations based on RMSE checks
  - novel bias-correction algorithm for mesonet winds based on application of a Kalman-Buci filter (under testing)
    - Will increase % of mesonet obs assimilated. Currenly only ~40%

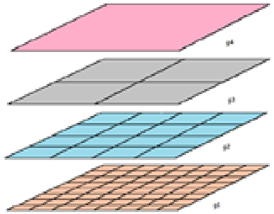
Background Error Covariance Modeling

Organization of calculation – generalized solution

The multigrid method (Brandt 1977, 1997; Hackbusch 2013), usually used for solving of elliptic problems, is based on the idea that the solutions derived at lower and higher resolutions can be combined in an overall more efficient numerical scheme.

In our case, we apply the multigrid by simultaneously calculating quasi-Gaussian approximations by the beta filter over all grid generations, and then combine them together by giving appropriate scale weights to contributions from various grids.

One critical element for the success of such a multigrid scheme is simplicity; therefore, our multigrid scheme is constructed in such a way that:



- Each grid in MG structure has a half of resolution of the previous
- Each grid operates on a quarter of processors of the previous

IMSG

Use radial and line beta filters
In future: AI/ML to estimate scale weights

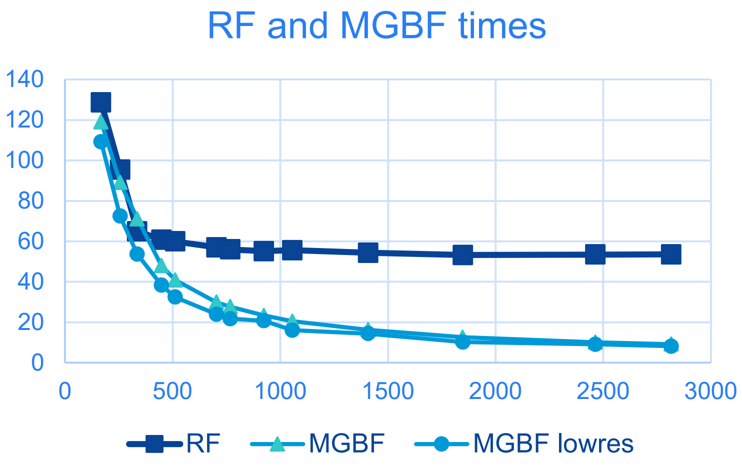
15-min high resolution 3DRTMA requires high computational efficiency.

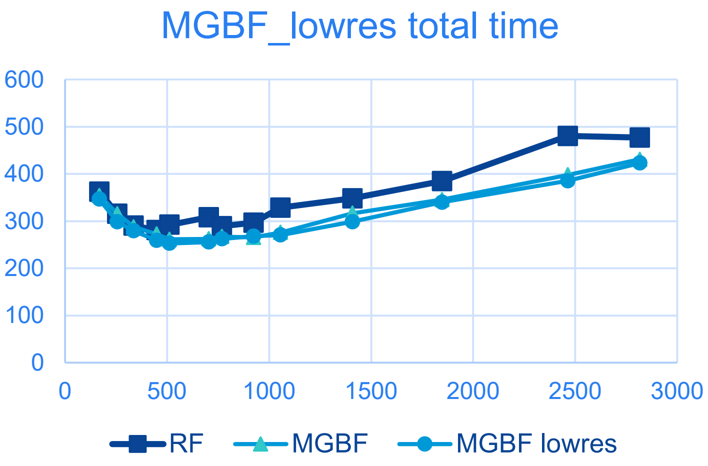
Significant speed up of the analysis can be achieved by optimizing the background error covariance implementation.

Recursive filters used in GSI are very difficult to parallelize because they represent sequential operators.

Introduce beta filters applied within multigrid structure

Tests in GSI



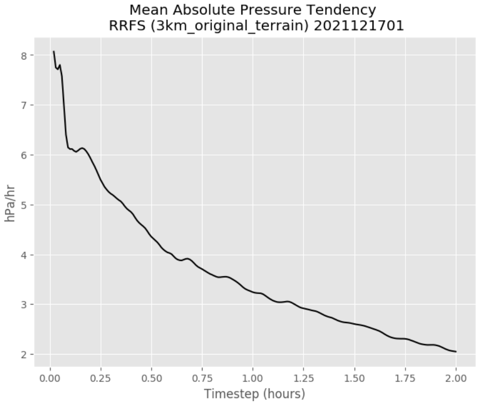


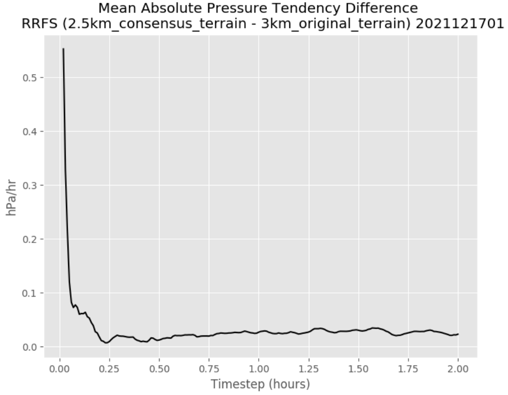
Isotropic version of MGB line filter is about 3 times faster than RF and scales better. Running filter grid at some 10 % lower horizontal resolution helps, though not substantially. (Rancic, 2022, *ResActESM*)

Yet, that alone is not sufficient to push down execution time of GSI beyond ~ 500-700 PEs.
Clearly, too much all-to-all calls and communication with discs. (Rancic, 2022, *ResActESM)*

Dynamic Downscaling

Results with HRRR IC





RRFS to provide the bckg fields. It runs a 3km resolution
RTMA dissemination is on NDFD grids: 2.5km (CONUS, HI, GU), 3km (AK), 1.25km (PR)

Explore two options for the analysis:
Option 1: Run 3km analysis
➔High order interpolation to NDFD grids
Option 2: Downscaling of RRFS to 2.5 km
➔Run 2.5km analysis
➔High order interpolation to NDFD grids
Both options associated with some loss of optimality of the variational solution.

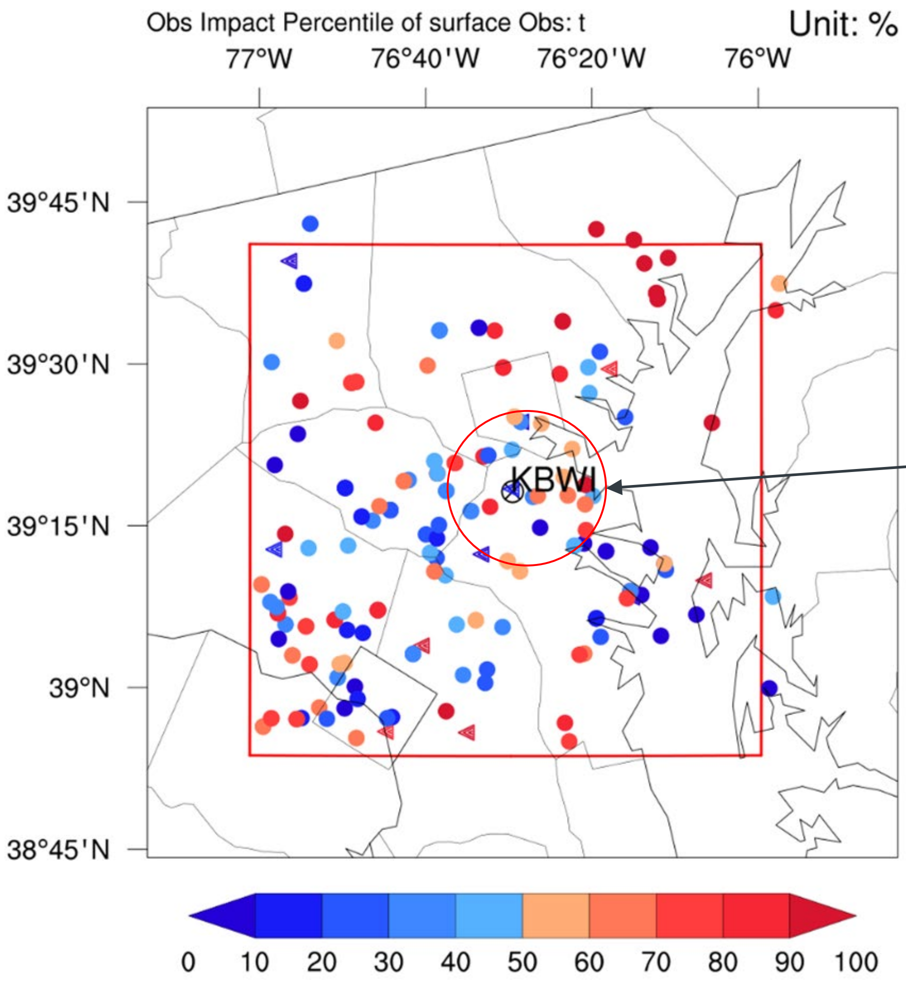
Less errors if analysis is run at resolution closest to that of the dissemination grid. Explore Dynamic downscaling! Produces 3D consistency in the bckg fields. Also potential to improve representation of bckg 10-m winds over complex terrain.

Successful test run with HRRR IC on FV3LAM model (~243 seconds of wall-clock time for 2 h on 2.5 km grid; ~ 195 seconds for 3.0 km run)
Recently, successful testing with RRFS IC on RRFS domain

RTMA Quality Assessment Project

- **Funded by the FAA**
- **EMC supplying RTMA weather report list to FAA at more than 400 airport locations. Currently 2mT values only**
  - Used in lieu of missing METAR reports at aeroport sites
- **Project aimed at:**
  - Assessing the feasibility to extend the RTMA weather report list to other parameters (psfc, 10m-wind, C&V, 2m-dew point)
  - Developing real-time monitoring system based on adjoint observation impact computation for 3DRTMA (Baker 2000; Baker and Daley 2000; Zhu and Gelaro 2008; Tyndall and Horel 2013; Todling 2013.)
    - Collaboration with Ricardo Todling (NASA)

Recycled from 3DRTMA slides for 2022 AMS Annual Mtg



- The percentile ranks of the ob impacts show the relative contributions from each ob.
- The percentile rank for the METAR T-ob (blue left-pointing triangle marker) at airport KBWI is about 10~20%; There are several nearby T-obs with larger percentiles ranks values (60~70%).
- For this case, if the METAR ob at KBWI were missing, the RTMA analysis would probably have been a feasible replacement
- The final assessment is to be based on statistics of the observation impacts, O-G, and O-A.

Recycled from 3DRTMA slides for 2022 AMS Annual Mtg

Upcoming work

Analysis Uncertainty Estimate

Gridded estimate of the analysis uncertainty for each analyzed parameter is an established requirement of the RTMA project

Enhancement to the Lanczos estimate (in use in operational RTMA)

- ❑ Add the day-to-day variability of the analysis error through the ensemble component of the hybrid En3DVar algorithm of the 3DRTMA. Tune the ensemble spread as needed and assess sensitivity of the analysis error.
- ❑ Use the randomization method or a second Lanczos solver to estimate the background error variance to account for the balance matrices coupling the analysis variables.
- ❑ Use cross-validation based estimates of the analysis error to validate and improve the estimate of the amplitude of the Lanczos analysis error.

Use of the new Multigrid/Beta filter to characterize the analysis error

The combination of ‘machine learning’ (ML) based on an artificial ‘neural network’ (NN), and the new MGBF provides the opportunity to quantify analysis error in a novel approximate way that takes fully into account the local density and quality (or ‘precision’) of the measurements as well as the form of the covariance expressed by the MGBF model.

Recycled from 3DRTMA slides for 2022 AMS Annual Mtg

Improvement of background fields

- Outstanding issue with 15-min 3D-RTMA: Increased degradation of the quality of the background fields at 15 min, 30 min, and 45 min compared to the top of hour (00 min).
  - Stems from the error growth in the model integration that provides the background fields, which is initiated from the top of the previous hour.
- We suggest the development of a novel AI/ML procedure, which will combine the model forecast at later hours with an AI replica of a very short-range forecast starting from the previous analysis time.

Assimilation of VEIA (Visibility Estimation through Image Analytics) data

- The Federal Aviation Administration (FAA) maintains a network of high quality web cameras throughout the state of Alaska
  - *Can these web camera observations be used in the RTMA system's analysis of horizontal visibility?*

FAA funded project recently, carried out by EMC & MIT/LL

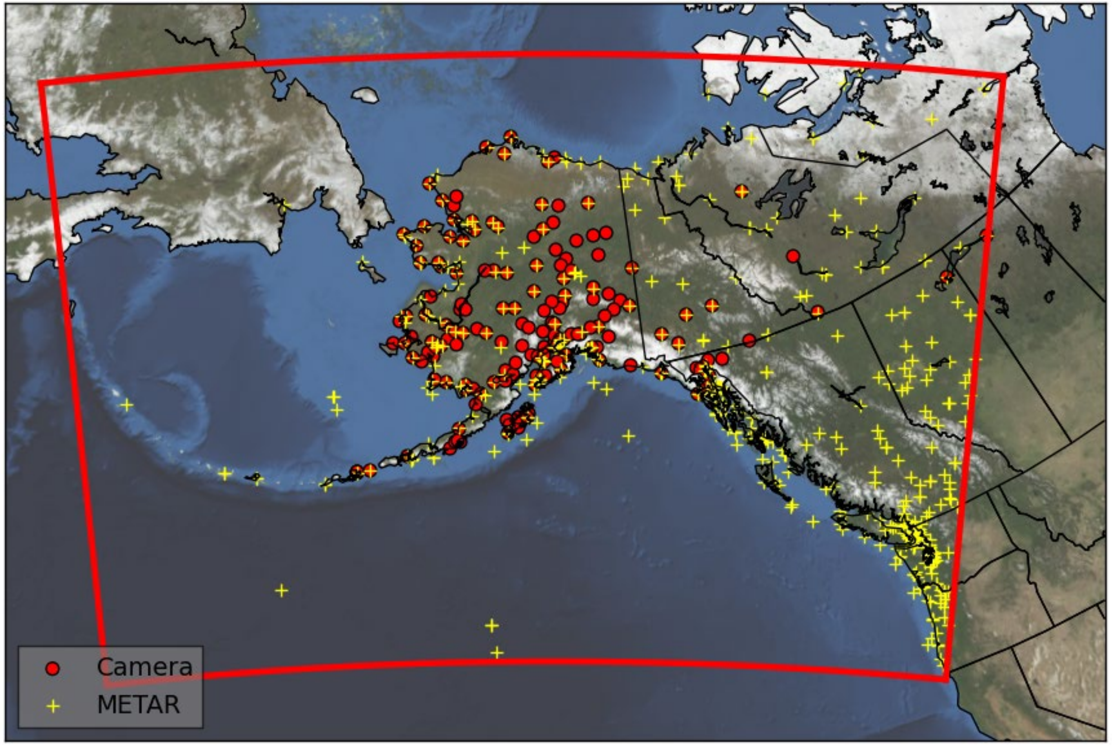
FAA WeatherCams Alaska Network

- Visibility is estimated from imagery at camera sites via an edge-detection algorithm
  Calibration is done using cameras co-located with METARs
- Two *general* options for assimilation
  1. Develop a forward operator for the camera data
  2. Assimilate retrievals

  We chose option 2 for assimilation in 2DRTMA for simplicity

  Consider option 1 in future in the context of 3DRTMA

METAR and Web Camera Observation Locations



Adapted from Carley etal. Presentation at the 2022 AMS Annual Mtg

Conclusions and Discussion

(from FAA project to assess impact of VEIA data assimilation in 2DRTMA. Work conducted by EMC & MIT/LL)

- **Can these web camera observations be used in the RTMA system's analysis of horizontal visibility? _Yes._**
  - Improves the RTMA at the most restrictive, and impactful, categories of LIFR and IFR.
    - Can fill gaps in present network
  - However - a slight degradation was noted at MVFR and VFR categories.
- **Limitations**
  - Sufficient sunlight is needed for cameras to work → Northern Hemisphere Winter is a challenge.
  - Cameras must be sited well and of sufficient quality, not all cameras will work!
    - Things like traffic cameras point at roads, thus features may often only be within several hundred meters - insufficient for visibility estimates.
- **Future work:**
  - **Test new (2021) VEIA translation function, → better MVFR and VFR performance**
  - **Potential implications for other high quality camera networks**

Contact: jacob.carley@noaa.gov

Carley, J. R., M. Matthews, M. T. Morris, M. S. F. V. De Pondeca, J. Colavito, and R. Yang, 2021: Variational assimilation of web camera-derived estimates of visibility for Alaska aviation. *Experimental Results*, **2**, e14. https://doi.org/10.1017/exp.2020.66

FAA Disclaimer: This material is based upon work supported by the Federal Aviation Administration under Air Force Contract No. FA8702–15-D-0001 and Federal Aviation Administration Contract No. DTFACT-17-X-80002. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Federal Aviation Administration.

Adapted from Carley etal. Presentation at the 2022 AMS Annual Mtg

Thank you!

Questions ?

BACKUP SLIDES

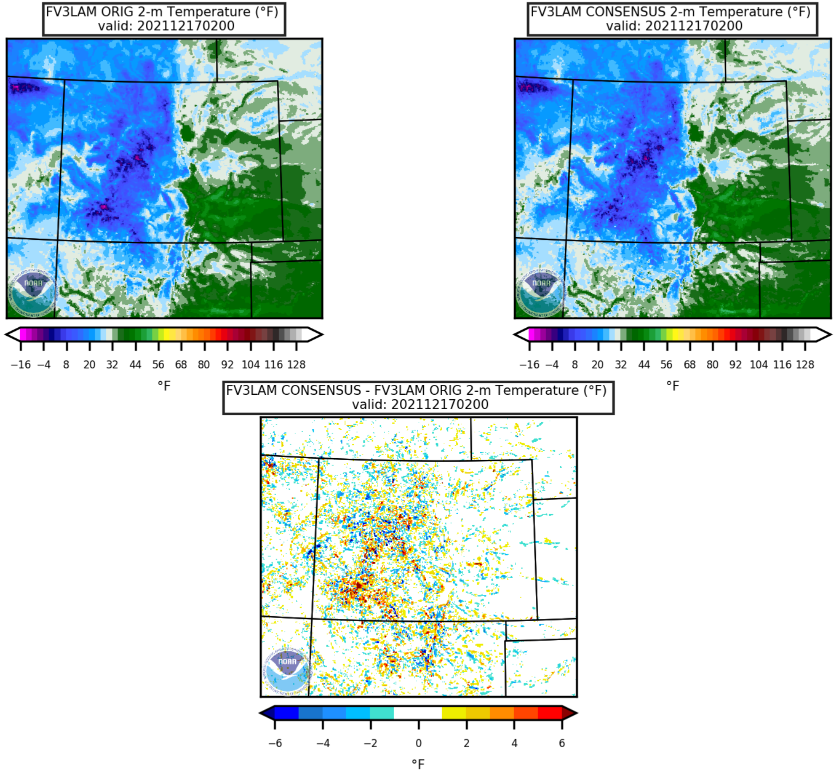
A few words regarding the C&V Analysis in 3DRTMA

- Currently diagnosed from standalone non-variational cloud analysis package.
  - Full physical consistency with analyzed 3D fields

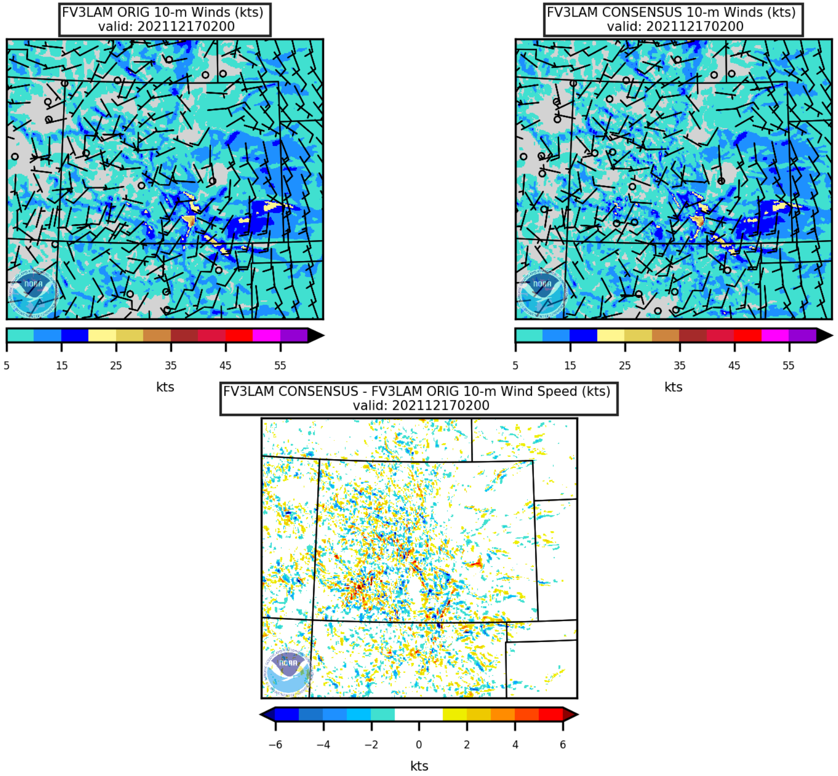
- Possible alternate method: GSI has built-in capability for direct analysis of ceiling height, lowest cloud base height, and total cloud amount (as done in 2DRTMA).
  - Consider enforcing physical consistency with 3D fields through weak constraint terms and matrix relations added to cost function.
  - Keeps the analysis variational

Dynamic Downscaling

2-m T (1-hr fcst)



10-m Winds (1-hr fcst)



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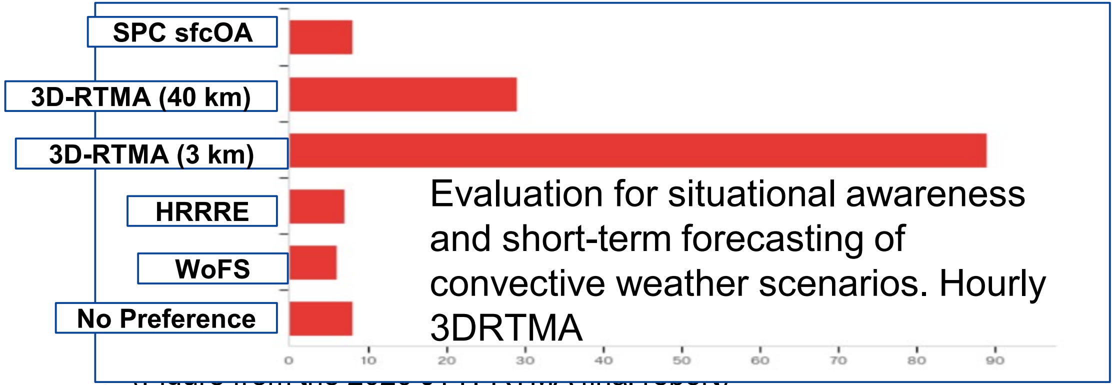
Evaluation Results

In 2018, GSL and EMC began to run a prototype 15-min 3D version of RTMA based on a modified HRRR GSI analysis setup for CONUS and AK (3-km resolution)

- **Analysis approach:** Hybrid Ensemble/3DVar (EnVar)
- Use GSI with GDAS and HRRDAS ensembles
- Standalone cloud analysis package (see J14.2 - Cloud Analysis Studies in the Rapid Refresh Forecast System (RRFS) and the Real-Time Mesoscale Analysis (RTMA), Craig Hartsough, 26th IOAS-AOLS Conf., Thu., Jan. 27, 11:00 CST)
- Observations: Same as used in HRRR DA: Conventional from prepbufr file, 15-min processed lighting data, 15-min processed NASA cloud data, 15-min processed NSSL Mosaic Radar Data

Ratings from HWT 2019 SFE



Evaluation for situational awareness and short-term forecasting of convective weather scenarios. Hourly 3DRTMA

HWT 2020 SFE

- Compared two hourly 3DRTMA systems: GSI with GDAS vs HRRRDAS ensemble for bckg error covariance:
- Both performed well for situational awareness in short-term convective forecasting.
- Value in Convection Allowing DA

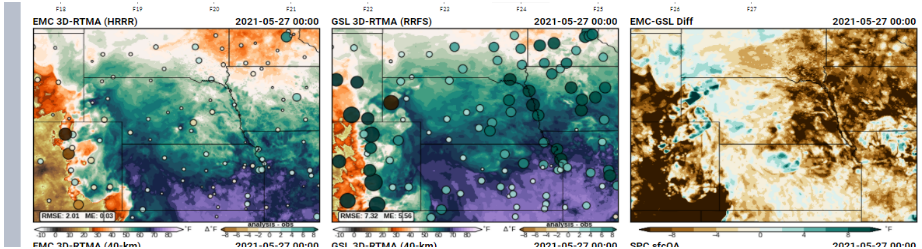
RRFS-3DRTMA

Development started in 2021. Preliminary version of RRFS-3DRTMA subjectively evaluated at SFE 2021 for situational awareness & short term forecasting of convective weather scenarios

FROM SPC & NSSL's "SPFE 2021 Preliminary Findings and Results" Report

- CTRL: HRRR-3DRTMA / EXP: RRFS-3DRTMA
- Hourly analyses + GDAS ensemble for both systems
- Looked at 2mT, 2mTd, SB/ML/MUCAPE

2m-Td analysis valid at 0000UTC 27 May 2021



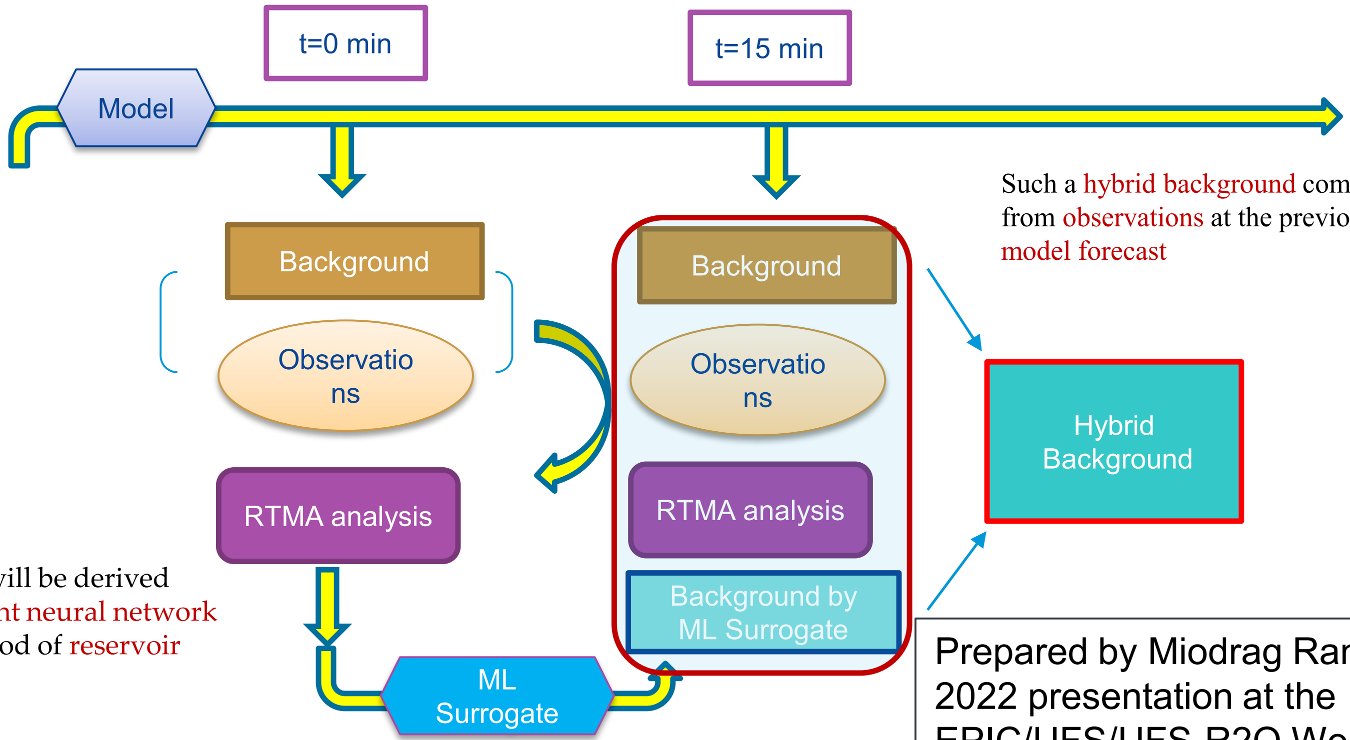
Left: HRRR-3DRTMA, middle: RRFS-3DRTMA,
Right: difference (HRRR-RFFS)
Dots represent A-O at METAR sites.

Takeaway:

Work needed! RRFS-3DRTMA rated as "much worse to "slightly worse" than the CTRL! Issues in composite reflectivity field (too much convection) and 2m Td field (too moist).

BUT, there was an important difference between the two systems: RRFS-3DRTMA did not contain all the components of the cloud analysis package present in the HRRR-3DRTMA! Looking forward to SFE 2022.

We came with a method in which we combine the model background with the background derived running a ML surrogate from the previous time interval, which includes knowledge of data from previous time

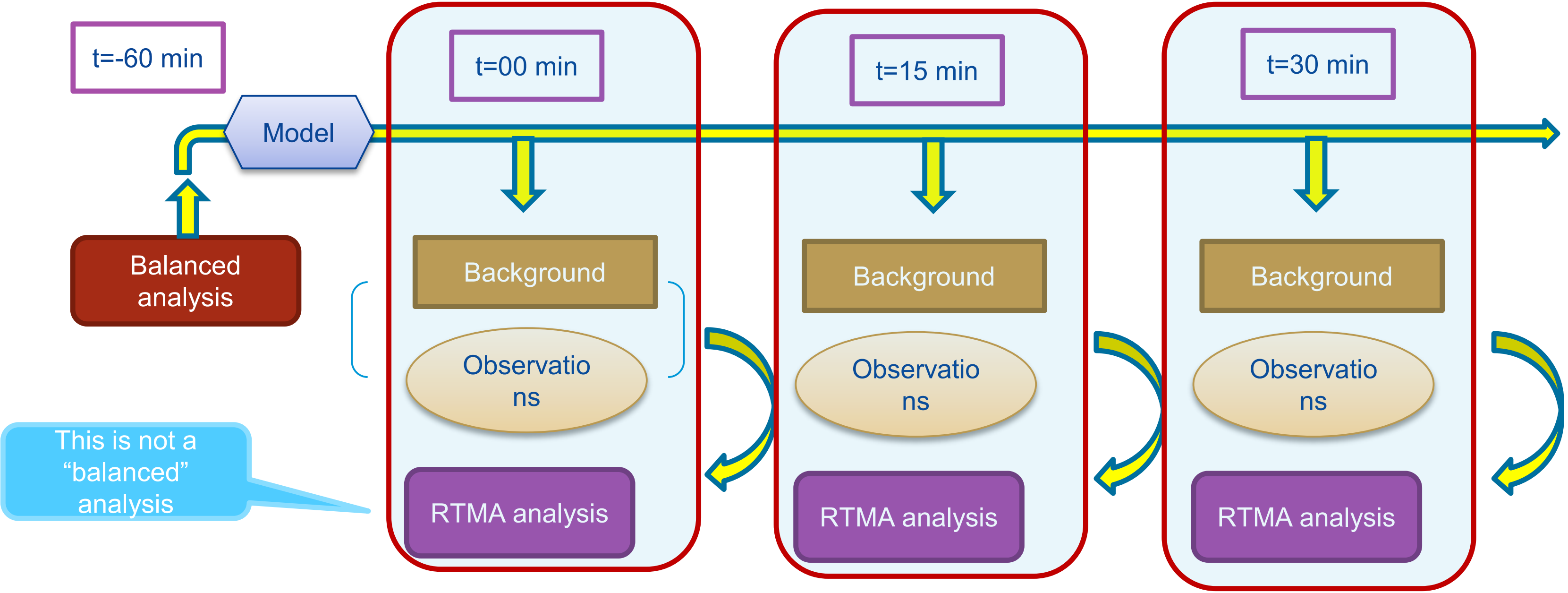


Such a hybrid background combines information from observations at the previous time and model forecast

ML surrogate will be derived using a recurrent neural network (NN) or a method of reservoir computing

Prepared by Miodrag Rancic for his July 2022 presentation at the EPIC/UFS/UFS-R2O Workshop

Application of AI for improving the background field in RTMA



Model starts its run from a balanced analysis at -60 min, and its forecasts at 0, 15, 30, and 45 min are used as the background at these times. RTMA analyses at 0, 15, 30 and 45 min are produced using these backgrounds and observations at (and around) these times. Problem is that backgrounds degrade with time, because they do not take advantage of analyses and data from the previous analysis times.

Prepared by Miodrag Rancic for his July 2022 presentation at the EPIC/UFS/UFS-R2O Workshop

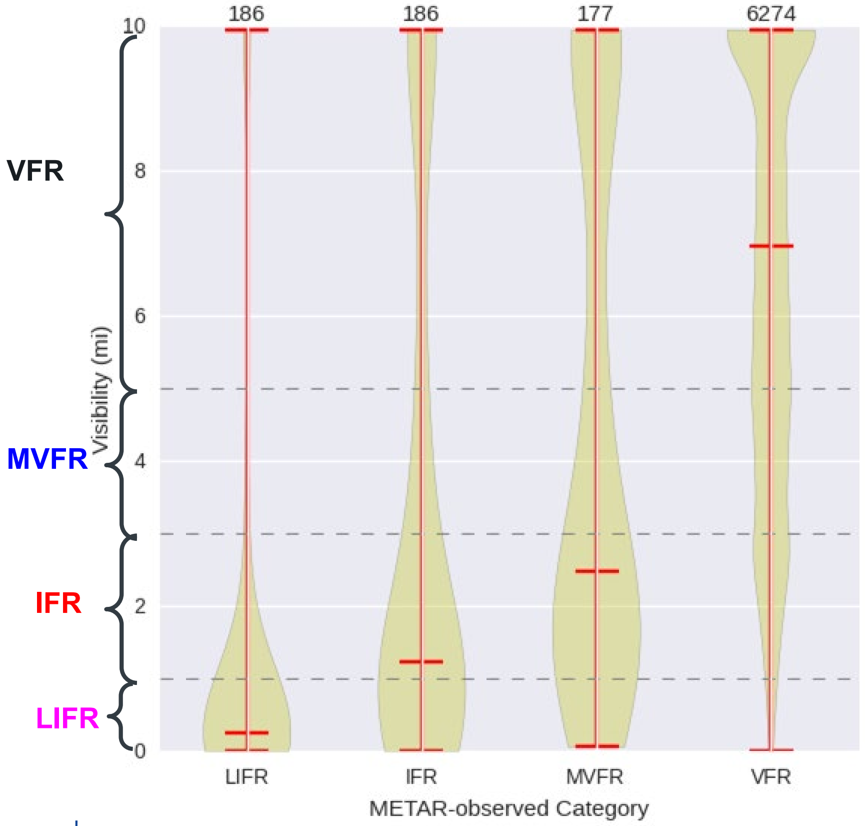
From AFS conduced field survey/ slide from 2020 Field Briefing on AFS11 RTMA/URMA Survey Results

Q10) The first version of the three-dimensional RTMA/URMA is planned to be released in 2023. Which of the following parameters from specifically the 3-D RTMA/URMA would help you most in operations?

Help Most in Operations		
Parameter	**All**	**WR**
Severe Weather Derived Parameters (e.g., CAPE and Helicity)	67.4%	55.6%
Aviation Weather Derived Parameters (e.g., Probability of IFR/VFR and Turbulence)	61.0%	63.9%
Fire Weather Derived Parameters (e.g., Mixing Height and Trans Wind)	57.6%	77.8%
Vertical Temperature and Moisture Profiles	58.7%	44.4%
Freezing-Level Height	47.1%	55.6%
Upper-Level Temperature and Moisture	29.7%	19.4%
Upper-Level Winds	29.7%	25.0%
Other	11.6%	8.3%

How well do camera estimates align with METAR observations?

- **LIFR**
  - Corresponds well with METAR-observed conditions
- **IFR**
  - Wider distribution than LIFR
  - Larger range of camera-derived visibilities relative to METAR
- **MVFR**
  - Bimodal
  - Highest densities at 2 miles and 10 miles
- **VFR**
  - Most commonly observed event
  - Peak in density at 10 miles with a long tail toward 1 mile
  - Generally consistent with camera estimates
    - Long tail indicative of considerable variability



RTMA → Analysis Results

Three sets of experiments were conducted:

1. **<u>GES</u>: Without data assimilation (i.e. first guess)**
2. **<u>CONTROL:</u> Only assimilates traditional METAR observations**
3. **<u>CAMERA:</u> Assimilates both METAR and the new camera-derived observations**

Impacts are depicted via performance diagram (*right* →), where analyses are measured against METAR observations:

- **<u>LIFR and IFR:</u>**
  - POD is increased, Bias is improved, and CSI is higher in **CAMERA** relative to **CONTROL**
  - FOH is slightly decreased in **CAMERA** (i.e. more false alarms)
- **<u>MVFR and VFR:</u>**
  - A slight degradation is noted in **CAMERA** relative to the **CONTROL**
  - Camera-derived estimates have difficulty with less restrictive categories