Progress toward global operational utilization of the Tomorrow.io Microwave Sounder with the Joint Effort for Data Assimilation (#488)

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Abstract (edited)

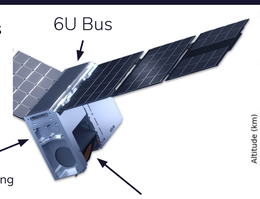
Passive microwave (PMW) sounders in Low Earth Orbit (LEO) garner some of the largest observational impacts on daily weather forecasts from operational centers. The Tomorrow.io Microwave Sounder (TMS) is the next generation of NASA's Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS). Driven by cost, latency, coverage, and the aging public fleet of PMW sounders, the TMS constellation of up to 18 6U Bus satellites will provide global revisit rates on the order of 30 minutes.

We conduct an Observing System Experiment (OSE) through 30 days of continual cycling with real TMS data. The expected TMS impacts are evaluated in a prototype system that is modeled after the NOAA's Global Data Assimilation System (GDAS). The prototype is based in GFSv16, with some modifications to account for our limited compute resources and and the still-in-development FV3-JEDI ecosystem. Forecasts and Data Assimilation (DA) are evaluated on a C768-L127 mesh of the Unified Forecast System Finite-Volume Cubed-Sphere (FV3-UFS) atmospheric model. We simulate observations with the Joint Effort for Data assimilation Integration (JEDI) Unified Forward Operator (UFO) and the Community Radiative Transfer Model (CRTM). The experiment period is throughout November 2024, only 3 months after the first TMS launch. We apply 3D ensemble variational data assimilation (3DEnVar) using 30-member C192-L127 6-h forecasts, cold-started from the NOAA's Global Ensemble Forecast System (GEFS) initial conditions. Fixed localization length scales of 1300 km in the horizontal and 0.5 log-p in the vertical are applied with the Background error on an Unstructured Mesh Package (BUMP). We use modern all-sky assimilation techniques for TMS. We plan to publicly share all of the quality control, observation error configurations, and CRTM coefficient lookup tables with the community.

Relative to our **CNTRL** prototype system, assimilating one TMS instrument (**add-1TMS**) achieves globally averaged RMSE of 2-3% in temperature, water vapor, and winds at most pressure layers. TMS impacts are generally positive, with the largest improvements in the southern extratropics. We expect the impact to be improved when using 4DEnVar, and possibly muted when assimilating additional observations that are missing from **CNTRL**, as compared to GDAS. We will assess the forecast impacts of subsequent TMS launches in the coming months. These assimilation methodologies are promising, and can be conveyed to end-users in the form of JEDI observer yaml configurations.

Tomorrow.io Microwave Sounder (TMS)

Calibration sources
1. Deep Space direct view
2. Noise diode superimposed on Deep Space
3. Internal Calibration Target (ICT)



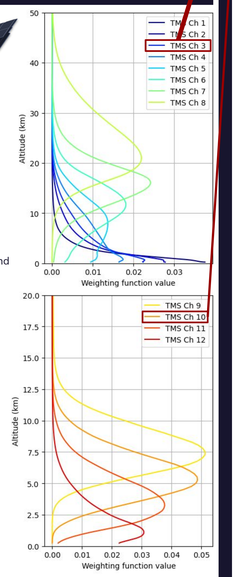
- Pyramidal RF absorbing material
- Characterized by 4 thermistors
- Complements noise diodes; characterizes noise diode drift

TMS Payload
- 12 channels
- **Digital spectrometer (ASIC)** for F-band
- Direct detect W-band and G-band
- Detectors rotate with antenna; constant polarization angle
- Pre-launch noise diode characterization

Channel	TMS Center Freq. (GHz)	TMS Bandwidth per sideband (GHz)	TMS NEDT Pre-launch Estimate (K)
1 (W)	91.65	2	0.38
2 (F1)	118.75±3.5	1	0.75
3 (F2)	118.75±2.625	0.75	0.87
4 (F3)	118.75±1.875	0.75	0.73
5 (F4)	118.75±1.25	0.5	0.78
6 (F5)	118.75±0.75	0.5	0.77
7 (F6)	118.75±0.375	0.25	1.00
8 (F7)	118.75±0.125	0.25	0.96
9 (G1)	184.41	2	0.54
10 (G2)	186.51	2	0.57
11 (G3)	190.31	2	0.65
12 (G4)	204.8	2	0.63

O_2 line used by MWTS-2, SMBA

H_2O line used by ATMS, MHS, MWHS-2



TMS OSE Design

Continual 6-hourly global atmosphere-only cycling
Surface analyses are interpolated from GDAS GRIB2 output
Analysis range: **2024-11-01T00Z** to **2024-12-01T00Z**

	DA	IAU	Mesh	ENS	SATWIND, GNSSRO, ADPUPA, SFCSHP, Conv. Ps	AIRCFT	ATMS (2)	ATMS (5)	MHS (3)	Hyper-Spectral IR (4)	GEO IR (4)	OZONE
CNTRL	3DEnVar	NONE	C768-L127	30-mem C192	X			X	X			
GDAS	Hybrid 4DEnVar	4D	C768-L127	80-mem C384	X	X	X	X	X	X	X	X

add-1TMS | same as **CNTRL** with assimilation of TMS-S02 (sun-sync orbit)

NOTE: GDAS provided as reference only; integration of remaining instruments is ongoing work.

I. Obs. Error Tuning

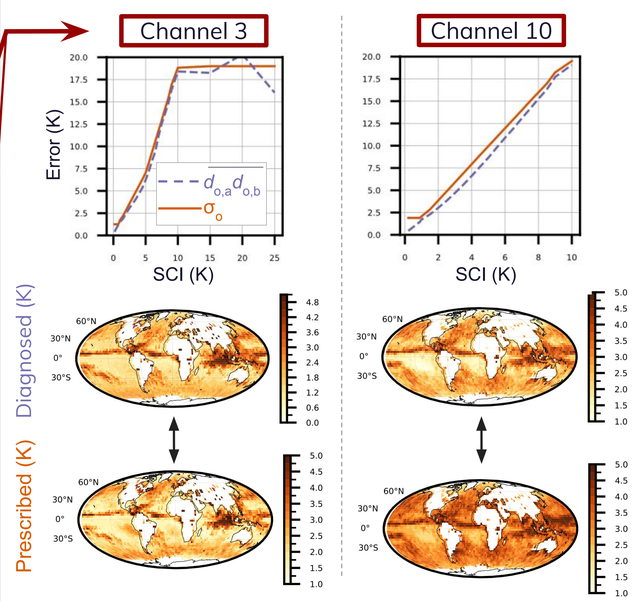
We prescribe piecewise 1-D error fits versus the Okamoto et al. (2014) Symmetric Cloud Impact (SCI) predictor, where

OCI = $|y\text{-}h_{clear}(x)|$
MCI = $|h(x)\text{-}h_{clear}(x)|$
SCI = (OCI + MCI) / 2

$\overline{d_{o,a}d_{o,b}}$ Desroziers et al. (2005) **diagnosed** error, where $d = y - h(x)$

σ_o Our **prescribed** all-sky error

Error tuning procedure:
1. Estimate σ_o from STD(y-$h(x)$) evaluated from 40 cycles of **CNTRL** 6-h forecasts
2. Tune σ_o from several 10-d spinup sensitivity experiments that include VarBC (final values shown below)

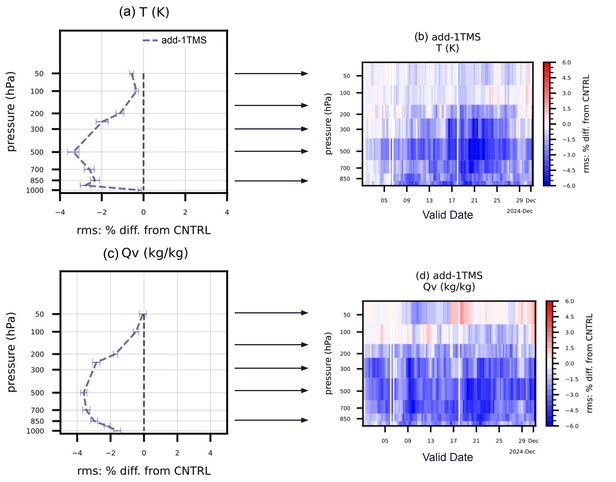


Spatial patterns of **diagnosed** and **prescribed** errors match well, with minor exceptions; we found similar correspondence versus channel difference "scattering indices" (not shown) that are traditionally used as PMW all-sky error predictors, and for the other 10 channels. Statistics are calculated after QC.

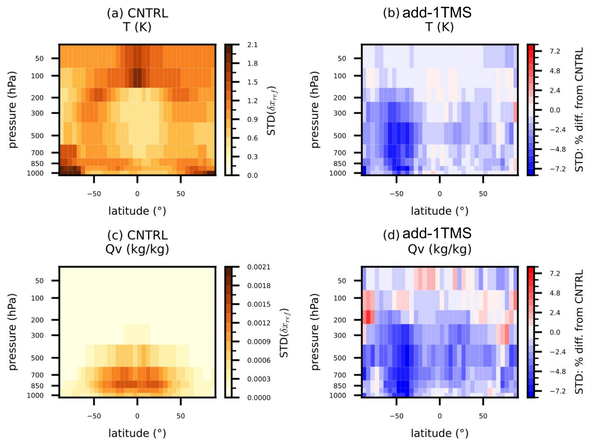
Valid period: 2024-11-01T00Z to 2024-12-01T00Z

III. 6-h Forecast Verification

We verify background forecasts against GDAS GRIB2 analyses, transformed to the C768 mesh.



- BLUE (negative diff.) indicates **add-1TMS** improvement relative to **CNTRL**, while RED (positive diff.) indicates degradation. Error bars: bootstrapped 95% conf. interval.
- TMS achieves immediate improvements to T and Qv, which then spreads down through the atmos. via NWP forecasts. Wind fields have commensurate improvements due to EnVar correlations (available upon request).

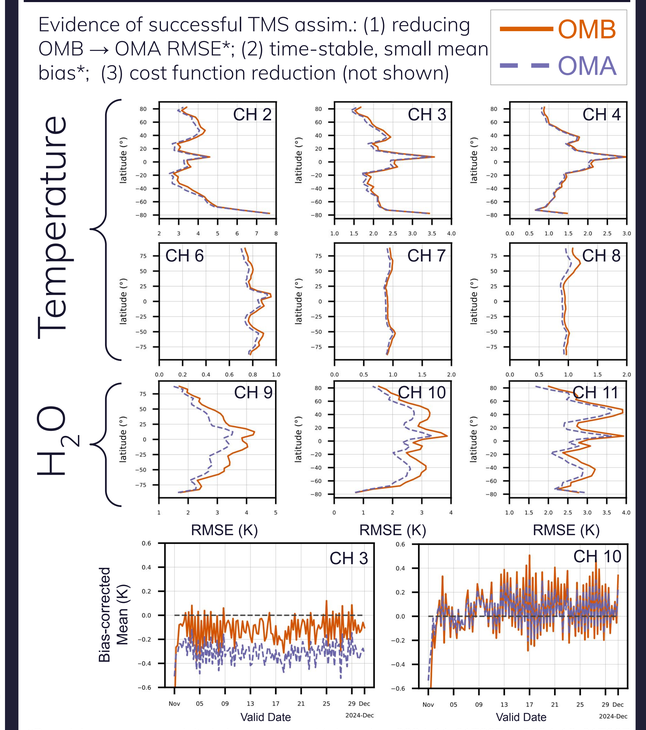


- **add-1TMS** surface impacts are primarily over the southern oceans, because that region has the biggest increase to observation counts relative to **CNTRL**. Others report similar outsized SH impacts from PMW sounders (e.g., Duncan et al., 2021). Both NH and SH impacts are statistically significant.
- As we move up through the atmosphere, improvements extend further north… why?
  - Closer to peaks of TMS channels 5-11, which are easier to model correctly; plus, only ch. 6-9 are assimilated over land, of which there is more in NH
  - In-situ obs. are more sparse than at the surface

Valid period: 2024-11-01T06Z to 2024-12-01T06Z

II. TMS OMB/OMA Validation

Evidence of successful TMS assim.: (1) reducing OMB → OMA RMSE*; (2) time-stable, small mean bias*; (3) cost function reduction (not shown)



*Remaining channels exhibit similar behavior Valid period: 2024-11-01T00Z to 2024-12-01T00Z

IV. Perspectives and Future Outlook

- Our TMS assimilation configurations are transferable to all JEDI+CRTM users (e.g., USAF, NOAA, NASA, U.S. Navy, JCSDA, NCAR), and the methodology is easily adapted for others.
- Missing data (e.g., ATMS) in **CNTRL** exaggerates the incremental impact of assimilating 1 TMS operationally today; from another POV, TMS is a small fraction of the cost of ATMS and may provide significant overlapping information content at similar quality (see Munchak+Nelson talk J1A.3). With numerous launches, we can also cover observation gaps in the current NOAA / NASA / EUMETSAT LEO constellations.
- 4D DA *will* be needed to reap the full benefit of the large quantity of data available in the whole TMS constellation
- We tried the SABER-implemented GSI BEC in 3DVar and Hybrid 3DEnVar variants of **CNTRL**, but found exclusively negative impacts regardless of hybrid weights. Looking for input.
- DA costs are quite large both for memory and storage, which requires additional optimization, both within our workflow and especially in the core JEDI codes.

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Related talks (Mon. 13 Jan.):
- 9:00 AM | J. Munchak and E. Nelson: J1A.3 - The Tomorrow.io Microwave Sounder Constellation: Pre-launch Performance Assessment and Early On-Orbit Results
- 5:15 PM | B. Taylor, et al.: 4A.4 – Accelerating the Transition of Satellite Precipitation Retrievals from Research to Operations Using Modern Software Engineering and MLOps Best Practices

Panel Discussion and Q&A with TMS experts
Advancing Weather Prediction Through Microwave Sounding Technology
10:30 AM Wed. 15 Jan.
Jen Splaingard, SVP of Space & Sensors, Tomorrow.io
Joe Munchak, Principal Atmospheric Data Scientist, Tomorrow.io
Bill Blackwell, Laboratory Fellow, MIT Lincoln Laboratory
Kelly Peters, VP of Marketing, Tomorrow.io

References and Related Literature

Blackwell W.J., Braun S, Bennartz R, et al. (2018): An overview of the TROPICS NASA Earth Venture Mission. Q J R Meteorol Soc., 144 (Suppl. 1): 16–26. https://doi.org/10.1002/qj.3290

Okamoto, K., McNally, A.P. and Bell, W. (2014), Progress towards the assimilation of all-sky infrared radiances: an evaluation of cloud effects. Q.J.R. Meteorol. Soc., 140: 1603-1614. https://doi.org/10.1002/qj.2242

Duncan, D.I., Bormann, N. & Hólm, E.V. (2021) On the addition of microwave sounders and numerical weather prediction skill. Q J R Meteorol Soc, 147(740, 3703–3718. https://doi.org/10.1002/qj.4149

Cannon, F., Pfreundschuh, S., Taylor, B., et al. (2024). Deep Learning for Multi-Satellite Precipitation Retrievals: Impact of Tomorrow.io's Microwave Sounders. ESS Open Archive. https://doi.org/10.22541/essoar.173430371.11882843/v1