Technical Memo

ECMWF

European Centre for Medium-Range Weather Forecasts

929

Forecast impact assessment of SMBA using the EDA method

Zaizhong Ma[1,2], Niels Bormann[2], Katie Lean[2], David Duncan[2], Ernesto Hugo Berbery[1] and Satya Kalluri[3]

[1]Cooperative Institute for Satellite Earth System Studies (CISESS)/Earth System Science Interdisciplinary Center (ESSIC), University of Maryland
[2]European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
[3]NOAA/NESDIS/LEO, Greenbelt, MD, USA

August 2025

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:

http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

European Centre for Medium Range Weather Forecasts

Shinfield Park, Reading, Berkshire RG2 9AX, England

Abstract

As part of NOAA's Near Earth Orbit Network (NEON) program, the Sounder for Microwave-Based Applications (SMBA) is a next-generation microwave instrument designed to enhance temperature and humidity sounding capabilities through new frequency coverage and improved instrument performance, including channels near 118 GHz and 229 GHz. This study uses the Ensemble of Data Assimilations (EDA) method within European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) to assess the potential forecast impact of SMBA observations prior to launch. Simulated radiances were generated using high-resolution model fields and radiative transfer modelling and then assimilated under all-sky conditions using both idealized and pragmatic observation error assumptions. The experiments focused on SMBA configurations in both the 13:30 and 17:30 Local Time of Ascending Node (LTAN) orbits. Results show that SMBA improves short-range forecast skill, particularly for temperature and wind fields, with the most significant impact observed when instruments are present in both orbits. The additional 118 and 229 GHz channels provide complementary benefits but cannot replace the critical role of the 50 GHz temperature-sounding band. The study highlights the importance of low-noise instrument performance and supports the strategic deployment of SMBA across multiple orbital planes to maximize the benefit to global numerical weather prediction.

Plain Language Summary

Microwave sounders on satellites help weather forecasters observe the Earth's atmosphere by measuring temperature and humidity from space. National Oceanic and Atmospheric Administration (NOAA) is developing a new microwave instrument called the Sounder for Microwave-Based Applications (SMBA) that is expected to offer better accuracy and coverage than current instruments. Before SMBA is launched, scientists at the European Centre for Medium-Range Weather Forecasts (ECMWF) used a technique called Ensemble of Data Assimilations (EDA) to simulate its data and study how much it could improve weather forecasts. The results show that SMBA is likely to reduce forecast uncertainty, especially when used alongside other existing satellite data. This study shows that the EDA method is a powerful way to assess the benefits of new weather instruments before they are even launched.

1 Introduction

Microwave sounding instruments are primarily deployed on polar-orbiting satellites in low-Earth orbit (LEO), providing critical observations for numerical weather prediction (NWP) systems (Bormann et al., 2013, 2019). These satellites typically operate in sun-synchronous orbits with varying local equator-crossing times, enabling broad temporal coverage of atmospheric conditions. Key operational microwave sounders in LEO include the Advanced Technology Microwave Sounder (ATMS) on the National Oceanic and Atmospheric Administration (NOAA) Joint Polar Satellite System (JPSS) series, the Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) on MetOp, and the MicroWave Humidity Sounder-2 (MWHS-2) on China's Fengyun-3 (FY-3) satellites. The World Meteorological Organization (WMO) Vision for the Global Observing System highlights the importance of maintaining a constellation of microwave sounders distributed across at least three complementary orbits shown in Figure 1: early morning (17:30 LTAN), mid-morning (21:30 LTAN), and afternoon (13:30 LTAN) (WMO, 2019). In recent years, NOAA satellites have covered the afternoon orbit (13:30 LTAN), whereas European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) MetOp satellites are covering the mid-morning orbit (21:30 LTAN).

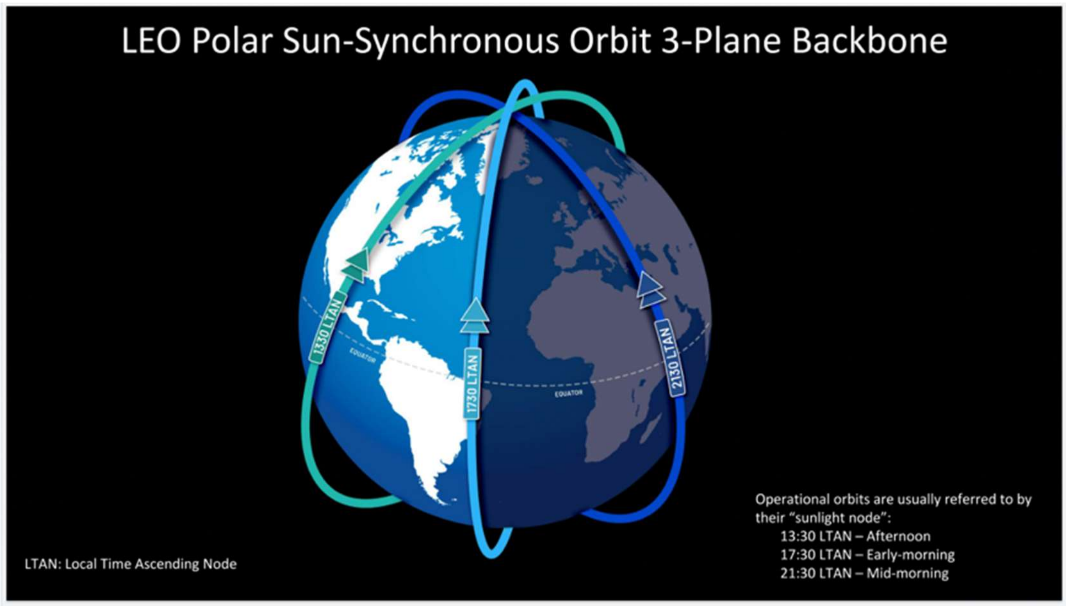


Figure 1: Three-plane backbone configuration of a sun-synchronous polar Low Earth Orbit (LEO) constellation. from https://govtribe.com/file/government-file/neon-program-overview-dot-pdf

NOAA has a longstanding commitment to operating environmental satellites in LEO, beginning with the Polar Operational Environmental Satellites (POES) program and continuing with the JPSS series. To ensure continuity and further advancement in LEO observations, NOAA has initiated the Near Earth Orbit Network (NEON) program. As part of NEON, the QuickSounder mission serves as a pathfinder, while the next-generation Sounder for Microwave-Based Applications (SMBA) is being developed to provide enhanced capabilities, including coverage in the 118 GHz and 229 GHz region not previously available with ATMS. It is planned to operate SMBA in both the afternoon and early-morning orbits, thereby complementing existing instruments such as Micro-Wave Humidity Sounder-2 (MWHS-2, Steele et al., 2023) on Fengyun-3E (FY-3E).

The Ensemble of Data Assimilations (EDA, Isaksen et al., 2010; Bonavita et al., 2016) method at the European Centre for Medium-Range Weather Forecasts (ECMWF) is a well-established tool for assessing the impact of new or future observing systems on Numerical Weather Prediction (NWP) (Bormann et al, 2023). Since its introduction in 2007, the EDA has been successfully applied to evaluate various observation types, including Doppler Wind Lidar from Aeolus (Tan et al., 2007; Healy et al., 2023), radio occultation data (Harnisch et al., 2013), and microwave sounders onboard small satellites (Lean et al., 2021, 2022, 2023, 2025). Most recently, the EDA was used to assess the potential forecast impact of a refurbished ATMS-like instrument operating in the early-morning orbit (e.g., 17:30 Local Time of Ascending Node (LTAN)) as part of NOAA's future microwave sounding missions (Ma et al., 2024). These studies have also explored the consistency of EDA impacts between real and simulated radiance observations. For example, comparisons of EDA results obtained with simulated ATMS data and those with real ATMS observations from the Suomi National Polar-orbiting Partnership (S-NPP) and NOAA-20 satellites revealed comparable impacts on ensemble spread, suggesting that the simulation framework provides realistic estimates of the actual impact.

As a continuation of this line of research, the present study evaluates the expected forecast impact of the SMBA instrument using EDA experiments that cover different channel usage and orbit configurations. The assessment examines how SMBA's new capabilities (in terms of noise performance, frequency bands, and covered orbits) affect forecast skill. By assimilating simulated SMBA data in multiple EDA scenarios, this study quantifies reductions in ensemble spread, which correlate to improvements in the forecast uncertainties, and investigates the added value of SMBA's broader frequency coverage and improved instrument performance compared to existing microwave observations.

The remainder of this paper is organized as follows. Section 2 reviews the EDA methodology and previous work on microwave sounder impact studies. Section 3 describes the SMBA instrument and its observational characteristics. Section 4 details the microwave (MW) all-sky data assimilation and observation error settings for SMBA. Section 5 presents the results of the SMBA forecast impact assessment, and Section 6 concludes with a discussion of the main findings and their implications for future satellite missions.

2 Overview of ECMWF EDA method for future mission impact studies

The EDA is an integral component of the Integrated Forecasting System (IFS) at ECMWF. Introduced operationally in 2010, the EDA provides a probabilistic estimate of analysis and short-range forecast uncertainty (Isaksen et al 2010). It achieves this by running multiple (typically 10 or more) parallel data assimilation cycles, each using perturbed observations, model parameters, and boundary conditions. These perturbations are designed to represent realistic sources of uncertainty, and the ensemble spread—defined as the standard deviation across ensemble members—serves as a diagnostic of the system's internal uncertainty.

The EDA framework enables a practical and system-consistent approach to evaluating the added value of proposed observations. Simulated data from the candidate instrument are assimilated alongside the current operational dataset. The impact of the new observations is assessed through changes in ensemble spread in key atmospheric variables such as geopotential height, temperature, humidity, and wind. A reduced spread indicates that the additional observations improve the constraint on the atmospheric state, thus enhancing analysis accuracy and short-range forecast skill.

Unlike traditional Observing System Simulation Experiments (OSSEs, Atlas et al., 2015; Ma et al., 2015), which require a "nature run" and full synthetic datasets, the EDA method allows for efficient and realistic impact assessment by leveraging the operational data assimilation framework and combining real and simulated data. This makes the EDA a powerful and cost-effective approach for pre-launch evaluation of satellite instrument performance and the value of proposed missions.

A typical EDA-based future mission impact study for MW radiances at ECMWF includes the following steps:

I. Simulated Observations: Synthetic radiance data are generated using high-resolution model analyses, radiative transfer modelling (e.g., RTTOV-SCATT), and perturbations that reflect the expected noise characteristics of the future observations.

II. All-Sky Assimilation: Microwave radiances are assimilated in all-sky conditions, incorporating both clear and cloudy scenes. Simulated observations are treated identically to real data, using the same observation operators, quality control, and error models.

III. Experimental Design: A control experiment ("BL" in this study) is run using the operational observing system, while one or more denial/addition experiments include the simulated data from the proposed instrument. Differences in ensemble spread at short forecast lead times (e.g., 12 hours) are used to isolate the impact on the analysis.

IV. Evaluation: The effect of the new observations is quantified by analysing spread differences in key variables. Diagnostics include vertical profiles, zonal means, and spatial maps to assess global and regional sensitivity.

Further details regarding the use of the EDA method and previous applications can be found in Healy et al (2024).

3 SMBA instrument characteristics and its observation simulation

3.1 Instrument characteristics

The Sounder for Microwave-Based Applications (SMBA) will be the primary payload on the NEON Series-1 satellite, part of NOAA's NEON program. NEON Series-1 is planned to be launched into sun-synchronous orbits with LTAN at 13:30 and 17:30.

Table 1. Notional sensor specifications for the NEON Program Microwave Sounder, as used in this EDA study. Entries in red describe new channels not previously available on ATMS, whereas other channels are based on ATMS heritage.

Channel Number	Center Frequency (GHz)	Center Frequency Stability (MHz)	Channel Bandwidth (GHz)	Calibration Accuracy (K)	Temperature Sensitivity NEDT@300K (K)
1	23.8	5	0.27	0.5	0.24
2	31.4	5	0.18	0.5	0.28
3	50.3	4	0.18	0.5	0.33
4	51.76	4	0.4	0.5	0.22
5	52.8	4	0.4	0.5	0.22
6	53.596 ± 0.115	3	0.17	0.5	0.24
7	54.4	2	0.4	0.5	0.22
8	54.94	3	0.4	0.5	0.22
9	55.5	3	0.33	0.5	0.30
10	57.290344	0.3	0.33	0.5	0.35
11	57.290344 ± 0.217	0.4	0.078	0.5	0.45
12	57.290344±0.3222± 0.048	0.9	0.036	0.5	0.50
13	57.290344 ± 0.322 ± 0.022	0.4	0.016	0.5	0.75
14	57.290344 ± 0.322 ± 0.010	0.4	0.008	0.5	1.00
15	57.290344±0.3222±0.0045	0.5	0.003	0.5	1.60
16	88.2	18	2	0.5	0.20
17	114.50	1	1	0.5	0.30
18	115.95	1	0.8	0.5	0.30
19	116.65	1	0.6	0.5	0.30
20	117.25	1	0.6	0.5	0.30
21	117.80	1	0.5	0.5	0.40
22	118.24	1	0.38	0.5	0.40
23	118.58	1	0.30	0.5	0.50
24	165.5	22	3	0.5	0.40
25	183.31 ± 7	14	2	0.4	0.26
26	183.31 ± 4.5	14	2	0.4	0.26
27	183.31 ± 3	16	1	0.4	0.36
28	183.31 ± 1.8	10	1	0.4	0.36
29	183.31 ± 1	9	0.5	0.4	0.50

30	229	22	2	0.5	0.36

SMBA is designed to acquire high-resolution atmospheric temperature, moisture, and pressure profiles by measuring radiances across the microwave spectrum, from approximately 23 GHz to 229 GHz. It is expected to operate in a polar orbit at an altitude of 824 km and provide a wide swath of about 2,530 km, sampled in 96 Earth views per scan.

Although SMBA is ultimately expected to function as a hyperspectral sounder, this study does not simulate hyperspectral observations. Instead, we adopt a configuration of 30 discrete channels, representing a practical implementation based on current design expectations. This configuration includes all ATMS-equivalent channels and adds seven channels centred near 118 GHz and one near 229 GHz—highlighted in red in Table 1. These additions are designed to enhance upper-tropospheric and lower-stratospheric temperature sounding and improve the detection of ice clouds and humidity in the upper troposphere.

All channel specifications used in this study are based on the 2023 edition of the Performance Requirements Document (PRD), provided by the NEON Program Configuration Management Office. These channel characteristics are used both in the radiative transfer simulations to simulate and assimilate the observations, as well as in the simulation of the noise performance as described later.

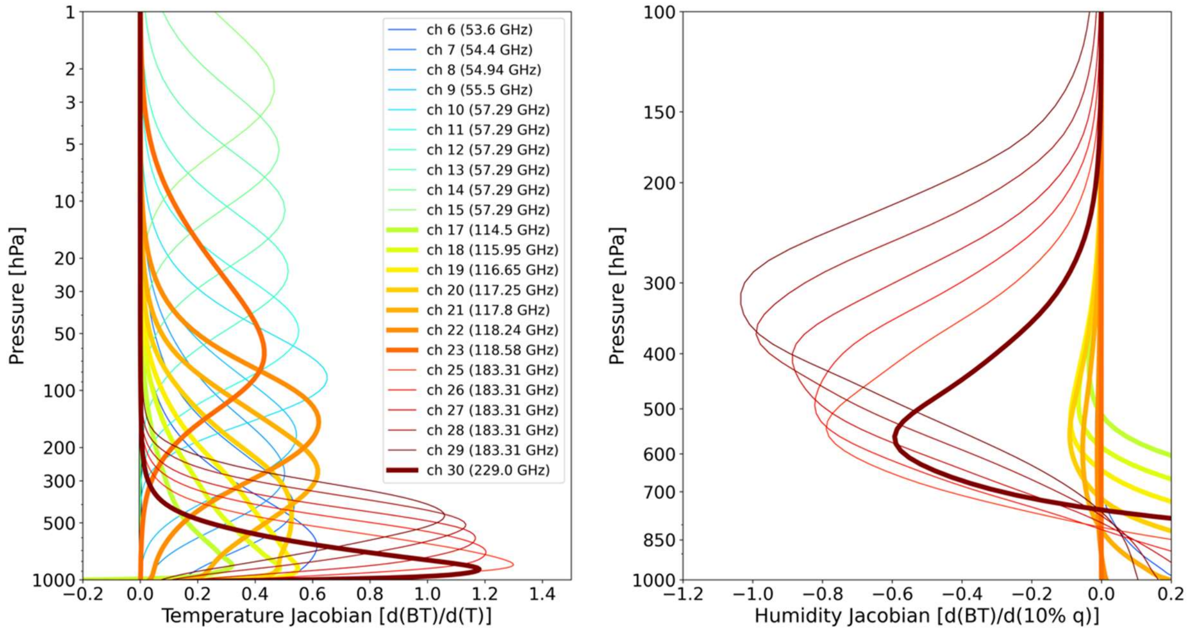


Figure 2: Temperature and humidity Jacobians for SMBA in clear-sky conditions, with new 118 GHz and 229 GHz channels. Values are based on an average over 5000 variable atmospheric profiles and normalized by the log of the model layer depth. For humidity, the Jacobians are based on perturbing the humidity profile by 10%.

Jacobians quantify how radiative fluxes respond to perturbations in atmospheric parameters and are essential for understanding the vertical sensitivity of remote sensing measurements. Specifically, temperature and humidity Jacobians indicate how changes in atmospheric temperature and water vapor at different altitudes influence the observed radiances. Figure 2 presents the near-nadir-viewing Jacobians for the key active SMBA channels in the ECMWF EDA system, highlighting their vertical sensitivity to atmospheric temperature and humidity in clear-sky conditions. Compared to ATMS, the new SMBA channels at 118 GHz and 229 GHz are illustrated with thicker curves. These Jacobians provide insight into the contribution of each channel to retrieving temperature and moisture profiles and demonstrate the enhanced vertical resolution and broader spectral coverage of SMBA compared to legacy instruments.

3.2 SMBA observation simulation

The simulation of SMBA observations follows the standard system described in Ma et al. (2024), originally adapted from the work of Lean et al. (2022, 2025) for evaluating potential future microwave sounding constellations. This simulation framework consists of three primary steps: (1) interpolating high-resolution atmospheric fields to simulated observation locations, (2) converting atmospheric profiles into brightness temperatures (BTs) using a radiative transfer model, and (3) adding random noise to reflect realistic instrument performance characteristics.

In this study, high-resolution ECMWF operational analyses at TCo1279 spectral resolution (approximately 9 km horizontal grid spacing, 137 vertical levels) are used to simulate the SMBA observations. The spatial and temporal sampling of the model fields is aligned with simulated SMBA scan patterns for both 13:30 and 17:30 LTAN orbits, with orbit geometries provided by EUMETSAT. The NEON Series-1 mission is planned to carry four SMBA instruments—two in 13:30 LTAN orbits and two in 17:30 LTAN orbits. To represent this configuration, four SMBA datasets are simulated using distinct orbit scenarios. The simulations are based on the geographical sampling expected from SMBA, with two satellites in each of the two orbital planes, 180 degrees apart.

Radiative transfer modelling is performed using the scattering package of the Radiative Transfer for TIROS Operational Vertical Sounder (RTTOV-SCATT) version 13.2, which incorporates scattering effects from hydrometeors and thus enables simulation under all-sky conditions (Saunders et al., 2020; Geer et al., 2021). This capability is essential for realistically representing the use of microwave data in operational NWP.

To emulate real instrument behaviour, random noise is added to the simulated BTs. Channel-specific Noise Equivalent Differential Temperature (NEDT) values are used, consistent with those defined in Table 1. These NEDT values are based on a 3×3 field-of-view averaging strategy, assuming ideal noise reduction. While the nominal NEDT values for SMBA are largely similar to those of ATMS, a key distinction is the treatment of 1/f noise. For ATMS, the presence of correlated (1/f) noise reduces the benefit of spatial averaging, leading to larger noise values for 3x3-averaged data than would be expected from white noise. For the present study, we investigate two scenarios for SMBA: 1) a “pragmatic” scenario which achieves a comparable performance to ATMS in terms of NEDT and 1/f noise, and 2) an “idealised” scenario in which we use the NEDT values specified in Table 1 and assume that SMBA can achieve the full theoretical noise reduction factor of 3 through 3x3 averaging. Different perturbations are applied to simulate SMBA observations in line with either the “idealised” or the “pragmatic” noise assumption. The perturbations applied follow a Gaussian distribution with no spatial or inter-channel error correlations. As in previous work, no attempt is made to model systematic errors for the simulated observations. The different scenarios are also reflected in the observation-error modelling, see Section 4.2.

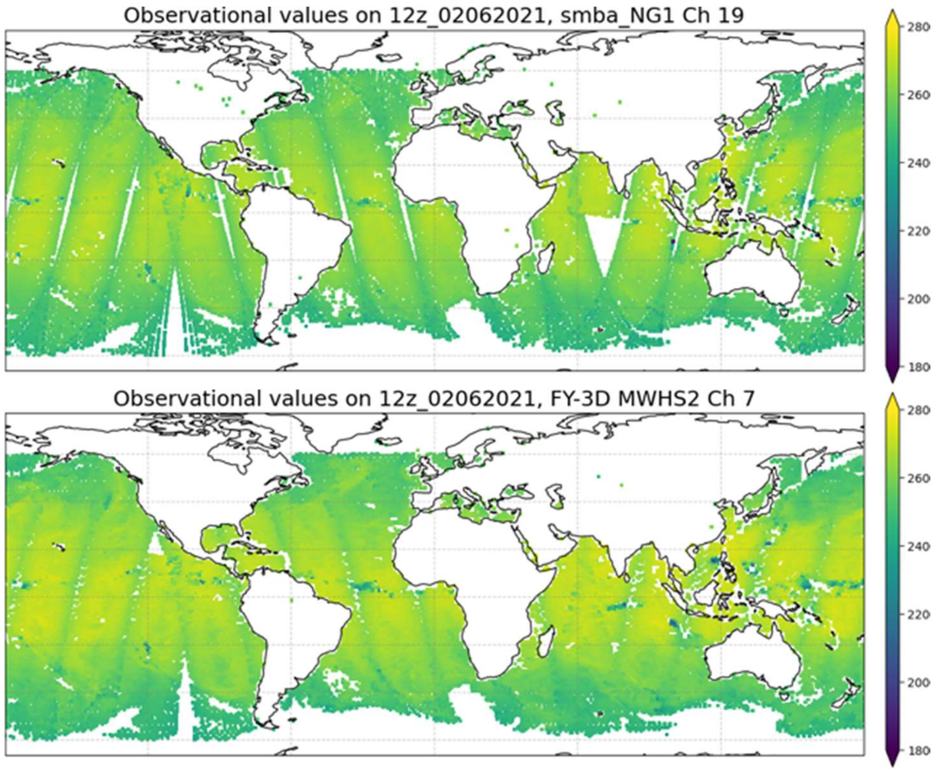


Figure 3: Assimilated data distribution maps for the new 116.65 GHz channel: simulated SMBA observations (top) and real observations from FY-3D MWHS-2 at 118.75 ± 2.5 GHz (bottom). Data are for a 12h period 09-21Z, 2 Jun 2021.

All channels were evaluated within the ECMWF Integrated Forecasting System (IFS) four-dimensional variational (4D-Var) data assimilation framework after completing the SMBA observation simulations. Particular attention was given to the newly introduced channels centred at 118 GHz and 229 GHz. The top panel of Figure 3 presents the simulated data for SMBA channel 19, one of the 118 GHz channels, on 12Z 2 June 2021. The data show good spatial consistency and are assimilated over oceanic regions within the IFS DA system. When compared with the corresponding channel 7 from the Fengyun-3D (FY-3D) MWHS-2, the spatial patterns are remarkably similar, lending confidence to the fidelity of the simulated observations. In contrast, Figure 4 displays simulated observations for the 229 GHz channel, which is entirely new and has no current equivalent in existing operational instruments, making it a novel addition to microwave sounding capabilities.

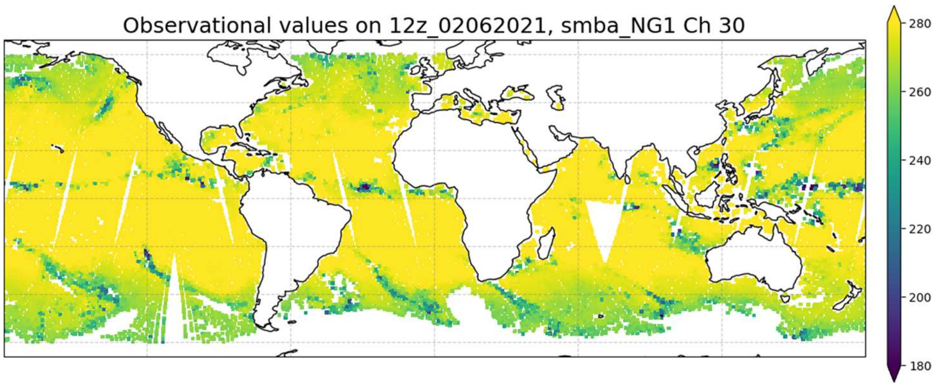


Figure 4: Assimilated data distribution maps for the new 229 GHz channel over ocean. Data are for a 12h period 09-21Z, 2 Jun 2021.

4 SMBA all-sky assimilation and observation errors

As part of NOAA's continuing effort to evaluate the impact of future microwave missions, we apply the ECMWF EDA method to assess the potential benefits of the SMBA instrument. These experiments follow the same EDA system configuration as described in Ma et al. (2024), which assessed an ATMS-like instrument in an early-morning orbit. The setup is based on ECMWF Cycle 48r1 and incorporates the all-sky assimilation for all microwave sensors.

The EDA configuration used here follows ECMWF's standard setup for operational development and future observing system assessments. It includes one unperturbed control member and ten perturbed ensemble members, each running at TCo399 horizontal resolution (~25 km) with 137 vertical levels. The inner loop minimizations are performed at resolutions TL95/TL159/TL255 (~210/125/80 km). The experiments span 1–30 June 2021, a period selected for its stable performance of key MW and other observing systems. After discarding the first week as spin-up to achieve representative levels of spread change, the remaining period is used to evaluate ensemble spread changes at T+12 h forecast range and TL255 resolution.

All-sky assimilation allows MW radiances to be used in clear, cloudy, and precipitating conditions, employing model-derived cloud fields in the observation operator (Geer et al., 2017). This method provides greater impact, particularly for humidity-sensitive channels, and is now standard for new MW instruments at ECMWF. While ATMS is currently still assimilated in clear-sky situations only in the operational ECMWF system (48r1), in this study, data from the "ATMS-like" channels at 50 GHz and 183 GHz in SMBA are also assimilated using a prototype all-sky configuration for consistency across MW instruments, as described in Ma et al. (2024).

4.1 Data selection for new SMBA channels

The new simulated SMBA channels at 118 GHz and 229 GHz, also follow the all-sky approach and are assimilated in the ECMWF system to improve temperature and humidity sounding, particularly in the upper troposphere and lower stratosphere. Compared to traditional temperature-sounding channels near 50–60 GHz (e.g., from ATMS), the 118 GHz channels have greater sensitivity to ice clouds, as reflected in colder brightness temperatures in deep convective regions. The 229 GHz window channels, meanwhile, provide improved sensitivity to cloud and precipitation features relative to lower-frequency window channels such as 89 GHz.

In this study, for the newly introduced channels near 118 GHz, the configuration of data selection follows that of the corresponding MWHS-2 channels (Steele et al., 2023), with identical settings applied in the EDA data assimilation system. The 229 GHz channel is assimilated only over sea. The details are in Table 2.

To ensure data quality and robust assimilation performance, the new SMBA 118 and 229 GHz channels are currently assimilated over ocean, while excluded over sea ice and snow-covered regions due to high surface emissivity variability and forward model uncertainty—consistent with the surface screening approaches in Geer et al. (2022). Over ocean, emissivity is dynamically estimated using the Fast microwave Emissivity Model (FASTEM-6; Kazumori and English 2015) in the Radiative Transfer for TOVS microwave scattering package (RTTOV-SCATT; Bauer et al. 2006, Saunders et al., 2020). Over land, a hybrid approach is applied—using a dynamic emissivity retrieval where available and a fixed emissivity atlas elsewhere. This treatment, adapted from Baordo and Geer (2016), enables broader land usage while managing representation errors. Additional land-based quality control (QC) filters observations with poorly characterized emissivity, large background-minus-observation departures, or unreliable model backgrounds under cloud-affected conditions. The geographical QC has also been reviewed to ensure consistency with practices used for equivalent ATMS and MWHS-2 channels, maintaining comparable observation usage across instruments.

Table 2: the configuration of data selection for the newly introduced channels from 118 GHz and 229 GHz in EDA system. Note: ✓ used; ✗ excluded.

SMBA new channels	Blacklist setup in EDA system			Equivalent Channel
	Over sea/water	Over land	Over sea-ice	
Ch17	✗	✗	✗	between MWHS-2 8 and 9
Ch18	✗	✗	✗	~MWHS-2 8
Ch19	✓	✗	✗	~MWHS-2 7
Ch20	✓	✓	✗	~MWHS-2 6
Ch21	✓	✓	✗	~MWHS-2 5
Ch22	✓	✓	✗	~MWHS-2 4
Ch23	✓	✓	✗	~MWHS-2 3
Ch30	✓	✗	✗	

To reduce the effect of neglected spatially correlated observation errors, a horizontal thinning strategy is applied to the simulated SMBA observations at all frequencies before assimilation. Observations are thinned to an approximate horizontal resolution of 125 km, in line with ECMWF's operational practice for microwave temperature sounders. Thinning is applied uniformly to all scenes, whether clear or cloud-affected, ensuring consistency within the all-sky assimilation framework.

4.2 Observation error modeling for SMBA

The specification of observation errors for SMBA channels in the EDA framework is critical to obtaining realistic estimates of forecast impact. Observation errors define the weight given to observations in the data assimilation system and are especially important for new instruments where direct tuning with real data is not yet possible. The assigned observation errors also determine the perturbations applied to observations in the EDA.

The observation error model used for SMBA channels follows the established all-sky approach as introduced in Geer and Bauer (2011). This assigns larger values in cloudy regions, to reflect larger representation error, and this is described as a function of a channel-specific cloud indicator. A symmetric approach is used for the cloud indicator, that is, it indicates the cloudiness in the observations as well as in the model fields. Key parameters of the model are the minimum (clear-sky) error and the maximum (cloud-saturated) error, as well as cloud indicator values that indicate up to which point the clear-sky error applies, and from which point onwards a saturated maximum error is applied. For channels with ATMS heritage, the cloud indicators used for SMBA follow Duncan et al. (2022) and Geer et al. (2014). For the new channels, we adopt the scattering index (SI), defined as the brightness temperature difference between channel 16 and channel 24, as a cloud indicator following Lawrence et al. (2018). Channel 16 has a centre frequency of 88.2 GHz, while channel 24 is centred at 165.5 GHz. In this study, clear-sky and cloudy observation errors for SMBA are defined based on a combination of theoretical expectations, empirical relationships, and short-term assimilation diagnostics using 4D-Var.

4.2.1 50 GHz, 118 GHz, and 183 GHz Bands

For the 50 and 183 GHz channels the observation errors were estimated as follows:

1) Clear-sky errors were calculated using the empirical formula from Lean et al. (2023), which relates the assigned observation error to the sample NEDT, representation error, and a tuning factor to account for unmodeled effects such as inter-channel error correlations. See the appendix for further details.

2) Cloudy errors were adopted directly from those assigned to equivalent ATMS (NOAA-20) channels in ECMWF operations. These errors are dominated by representation error and hence expected to be similar for SMBA.

To calculate the clear-sky errors for the 50 and 183 GHz channels from the empirical formula, we use NEDT values as given in Table 1, divided by 3 to account for the effect of 3x3 averaging. This assumes that the SMBA instrument noise is made up of white noise and hence shows an ideal noise reduction through spatial averaging. The resulting assigned clear-sky errors are approximately 20% lower than those for ATMS which exhibits a considerable contribution of 1/f noise. We will refer to this observation error setting as the "Idealised" observation errors, and it is in line with the perturbations applied to the simulated observations mentioned earlier.

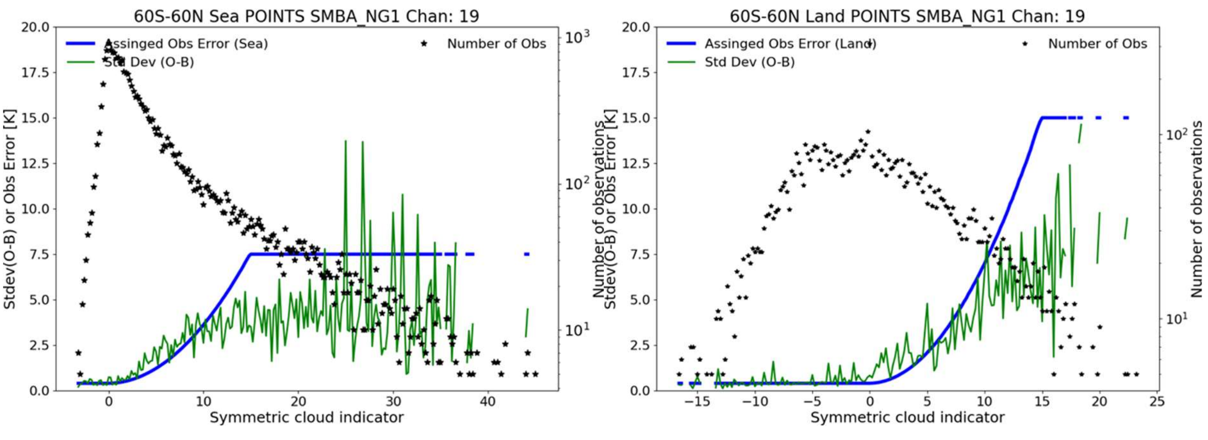


Figure 5: Standard deviation of first-guess departures from SMBA Channel 19 (118GHz) as a function of the symmetric cloud predictor (green line) along with the applied observation error (blue line) and the normalised number of observations in each bin (black dots). Data are for the period 07 June 2021, and from latitudes between 60^0 N-60^0S and over ocean surfaces only (left panel) and land surfaces only (right panel).

For the 118 GHz channels, which are newly introduced in SMBA and do not have a direct ATMS equivalent, the clear-sky errors were estimated using the same formula as for the 50 GHz channels, by respectively applying the formula for the channel with the most similar weighting function peak. This assumes that in clear-sky conditions any contributions from representation error are similar for the two spectral regions. Cloudy errors were adopted from equivalent MWHS-2 channels, as these provide the closest analogue currently assimilated in all-sky conditions.

To evaluate the appropriateness of the observation-error settings for the 118 GHz channels, Figure 5 shows examples of the standard deviation of observation-minus-background (O–B, green lines) from Channel 19 in 118 GHz as a function of symmetric cloud indicator over ocean and land. The values are taken from a TCO399 4D-Var experiment in which the simulated and perturbed SMBA observations have been added. The assigned observation errors are broadly consistent with the standard deviation of background departures as a function of the symmetric cloud indicator, in line with typical choices for real data.

4.2.2 Channel 30 (229 GHz): Sea-Only Usage

SMBA's Channel 30 (229 GHz) does not have a direct counterpart in existing operational microwave sounders assimilated at ECMWF and therefore required a more specialized treatment. This channel is used only over ocean surfaces in this study. To estimate appropriate observation errors, a short-term 4D-Var test was conducted to evaluate the consistency of assigned errors with background departure statistics.

Specifically, the standard deviation of O–B values was plotted against the cloud indicator (e.g., symmetric scattering index) to evaluate the validity of assumed clear and cloudy errors in Figure 6. The goal was to ensure that the assigned observation errors lie close to or slightly above the observed O–B standard deviations, consistent with operational practice. This diagnostic also helps prevent overestimation of SMBA's forecast impact by avoiding artificially low error values. As with other surface-sensitive channels, a conservative approach is often used in specifying cloudy observation errors to account for increased uncertainty due to cloud and surface effects. In our study, while the cloudy errors were set conservatively, they still remain reasonably tight to the observed standard deviations—especially over land—indicating that the error specification is appropriately balanced and not excessively cautious.

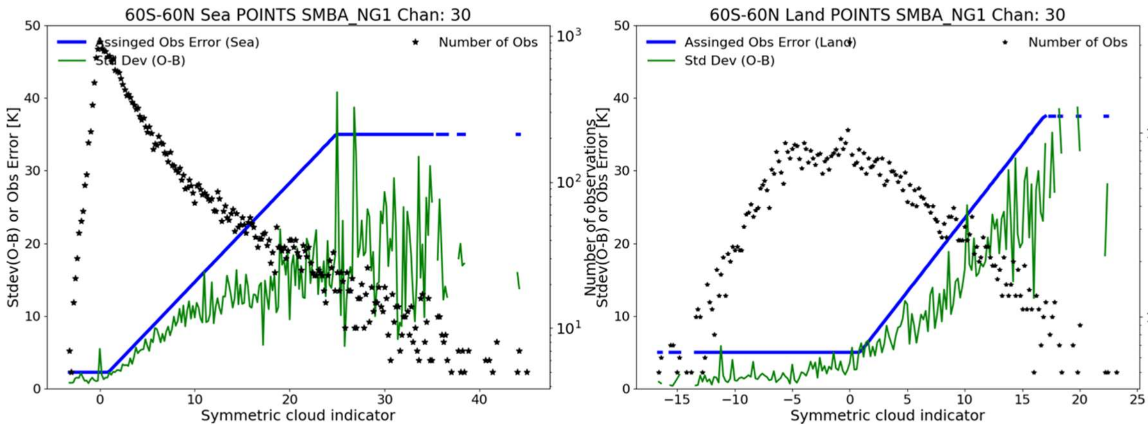


Figure 6: Same as Figure 5, but for Channel 30 (229 GHz).

4.2.3 Testing the sensitivity to the noise performance and observation error settings

To investigate the sensitivity of the EDA results to assumptions about instrument noise performance, we perform additional experiments in which we assume larger clear-sky observation errors. In this alternative observation error assignment, we use the same observation errors currently applied to NOAA-20 ATMS for the 50 and 183 GHz channels. This implicitly takes into account that the presence of 1/f noise would reduce the effectiveness of the noise reduction achieved from spatial averaging. For the other channels, we apply a 20% inflation to the empirically derived clear-sky errors. The value of 20% is a pragmatic and ad-hoc choice based on the experience with heritage channels from real ATMS observations. We will refer to this observation error setting as the "Pragmatic" setting, and the main assumptions underlying these two settings are outlined in Table 3. This setup helps evaluate how sensitive the forecast impact estimates are to the assumed noise characteristics of the SMBA instrument, particularly in the absence of real observational data.

Table 3. Assigned Observation Error Settings Used in the SMBA EDA Study.

Configuration	Description	Assumptions	Purpose
Idealised	Uses specified NEDT values in empirical formula (Lean et al., 2025)	Assumes ideal white-noise performance (no 1/f noise)	Represents best-case scenario with optimistic instrument characteristics
Pragmatic	Uses NOAA-20 ATMS values for 50 and 183 GHz; other channels = empirical formula × 1.2	Assumes performance similar to ATMS for heritage channels	Tests sensitivity to more conservative, realistic error assumptions

5 SMBA EDA impact studies

5.1 Baseline Observing System

As part of the ongoing EDA-based impact assessment of NOAA's future microwave missions, this study adopts the same baseline observing system as described in Ma et al. (2024). The configuration reflects the full global observing system used operationally at ECMWF in June 2021, but restricts passive MW sounding data to the mid-morning orbit covered by MetOp satellites. MW imagers (e.g., AMSR2, GMI) and window channels from the Special Sensor Microwave Imager/Sounder (SSMIS) are retained in this baseline. All other observations, such as radiosondes, aircraft, hyperspectral infrared sounders (AIRS, IASI, CrIS), GNSS radio occultation (GPSRO), atmospheric motion vectors (AMVs), geostationary radiances, and Doppler wind lidar data from Aeolus, are included. The baseline observing system reflects a somewhat pessimistic future scenario in which the old POES satellites have been decommissioned and the use of other MW sounding data is restricted.

5.2 Impact from SMBA in the 13:30 LTAN orbit and from 118 and 229 GHz

This subsection presents the results of EDA experiments designed to assess the forecast impact of assimilating simulated SMBA observations from the 13:30 LTAN orbit. A summary of the experimental scenarios is provided in Table 4. The experiments are designed to investigate the impact of the new frequency bands added to SMBA, as outlined further below. The idealised observation error setting (defined in Table 3) is applied to all SMBA channels.

To evaluate the vertical extent of the impact, Figure 7 shows changes in EDA spread for geopotential height, comparing one of the addition experiments against the baseline. Vertical profiles of spread reduction are presented separately for the Northern Hemisphere (latitudes > 20°N) and Southern Hemisphere (latitudes > 20°S), covering the analysis period from 8 to 30 June 2021. A reduction in ensemble spread indicates improved analysis and short-range forecast error characteristics. In the **BL+SMBA** scenario (purple line), which includes simulated SMBA data in the afternoon orbit, geopotential height spread is reduced by approximately 4% in the Northern Hemisphere and 6% in the Southern Hemisphere, highlighting the benefit of MW observations at this orbital slot.

Table 4: A detailed list of proposed scenarios in SMBA (only in 13:30 LTAN) EDA impact studies.
** See main text for a description of observations other than passive MW soundings. (BL=Baseline)*

Scenario Name	Observing system other than MW sounding	MW sounding in 21:30 LTAN	MW sounding in 13:30 LTAN	MW sounding in 17:30 LTAN	MW obs error setting
BL	Full*	Two MetOp	-	-	
BL+SMBA	Full*	Two MetOp	Two SMBA	-	Idealised values
BL+SMBA-50ghz	Full*	Two MetOp	Two SMBA, without 50 GHz	-	Idealised values
BL+SMBA-118GHz-229GHz	Full*	Two MetOp	Two SMBA, without 118 GHz & 229 GHz	-	Idealised values

To further explore the contribution of different frequency bands, two further experiments were conducted. The first (yellow line), referred to as **BL+SMBA-118GHz-229GHz**, removes the new 118 GHz and 229 GHz channels, retaining only the standard ATMS-like channels of SMBA at 50 and 183 GHz. The second (red line), **BL+SMBA-50GHz**, excludes the 50 GHz temperature-sounding channels from the full channel set, hence relying solely on the 118 GHz channels for temperature-sounding. As shown in Figure 7, the difference between the yellow and purple lines suggests that the addition of 118 and 229 GHz channels provides a modest improvement when combined with 50 and 183 GHz. However, the comparison between the purple and red lines clearly demonstrates that the 50 GHz temperature-sounding channels are essential—the 118 GHz channels alone do not provide sufficient information to replace them. This is likely due to the larger noise of these channels, plus their larger cloud sensitivity, resulting in a less “clean” temperature signal. These findings confirm the value of maintaining 50 GHz observations and suggest that the benefit of 118 GHz channels is complementary but not a substitute.

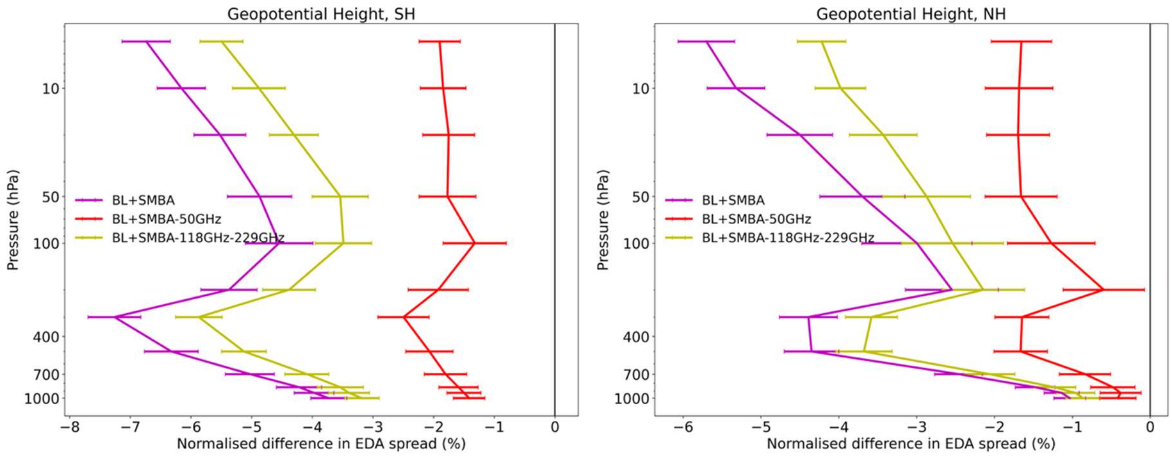
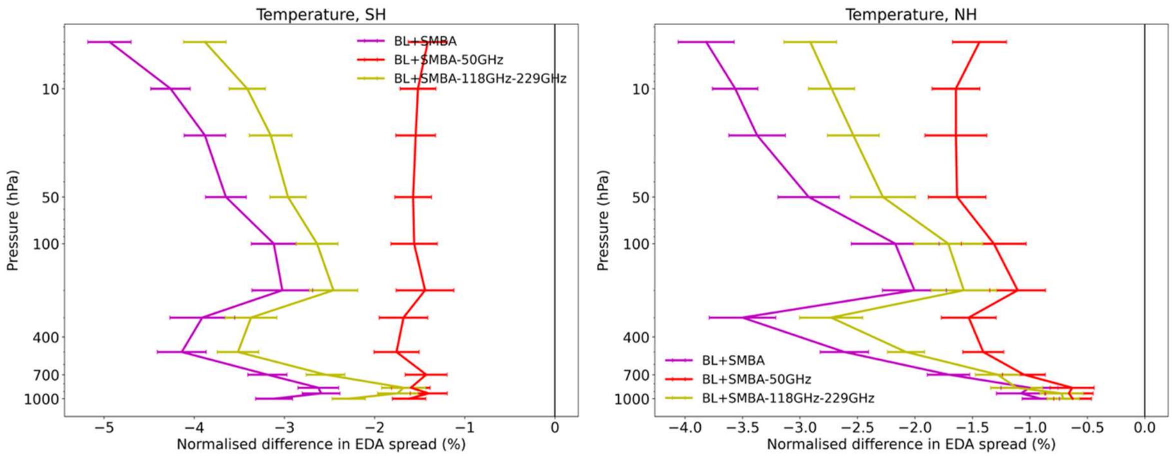


Figure 7: Vertical profiles of EDA spread reduction for geopotential height in the Southern Hemisphere (latitude > 20°S), and Northern Hemisphere (latitude > 20°N), The baseline observing system, which used as proxy for a future observing system without NOAA MW sounders, includes all non-MW observations used operationally at ECMWF in 2021, excluding passive MW data from China. Data are for the period 8-30 June 2021 and error bars indicate an estimate of 95% confidence. Negative values in EDA spread (x-axis) show positive improvement.

To provide a more comprehensive evaluation of SMBA's impact within the EDA framework, Figure 8 presents vertical profiles of ensemble spread changes for additional variables: temperature, U-component wind, and relative humidity. The results for temperature and wind are consistent with those for geopotential height, reinforcing that SMBA data reduce short-range forecast uncertainty in dynamical fields. In contrast, for relative humidity only modest reductions in spread are observed from the addition of the 118 GHz and 229 GHz channels compared to using only ATMS-like channels (purple vs yellow line). The importance of the 50 GHz temperature-sounding observations is also clear for these additional variables, as the SMBA impact is much reduced when the 50-GHz band is not present (red line).



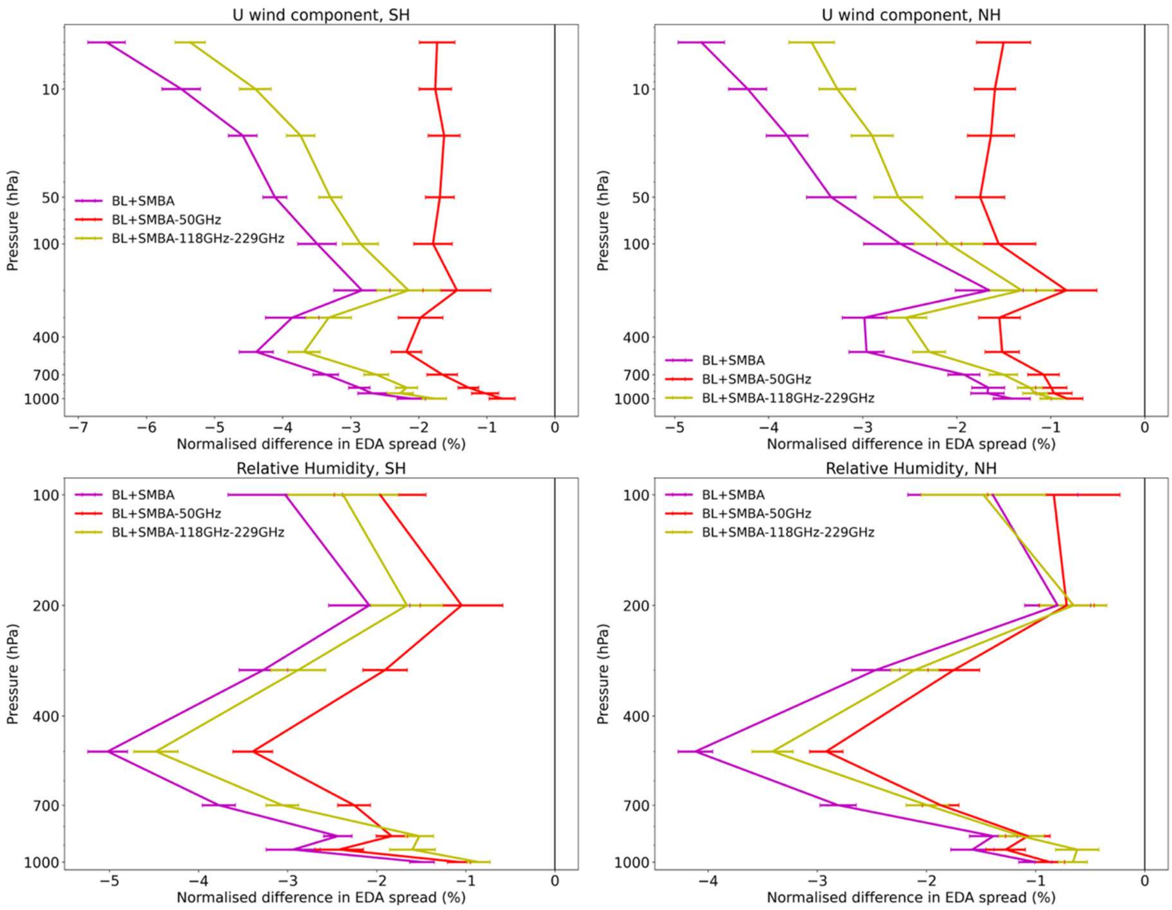


Figure 8: Same as Figure 7, but showing ensemble spread changes for Temperature and U-component wind in the Southern Hemisphere (latitude > 20°S), and Northern Hemisphere (latitude > 20°N), and for relative humidity in the tropics (±20° latitude). Relative humidity spread is displayed only up to 100 hPa, as humidity increments are not applied above the hygropause. Negative values in EDA spread (x-axis) show positive improvement.

5.3 SMBA EDA Impact Studies: Sensitivity to Observation Noise

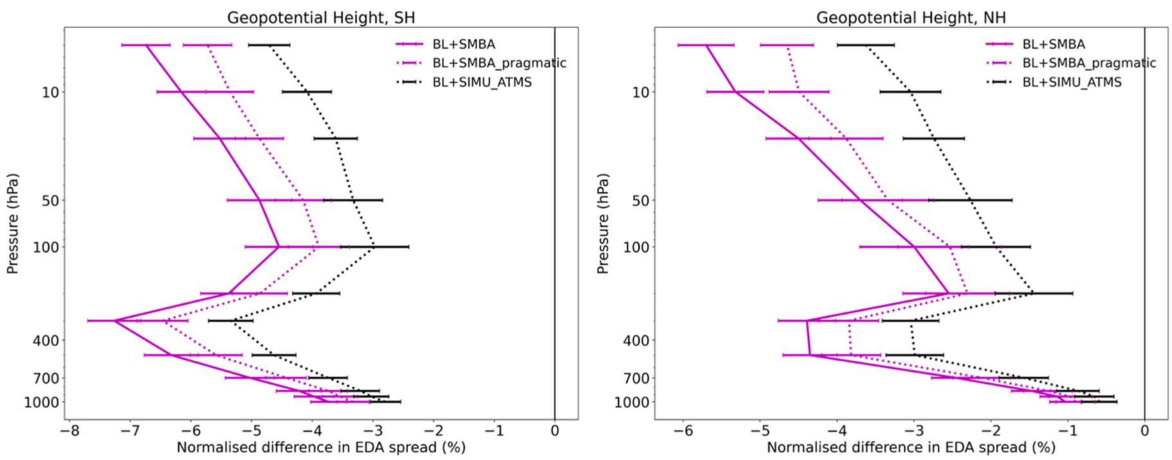
In addition to the impact assessments shown above, a set of EDA experiments was conducted to evaluate the sensitivity of SMBA impact to instrument noise characteristics. These experiments focus on SMBA data simulated for the afternoon orbit (13:30 LTAN), but assuming a different noise performance. The BL+SMBA scenario (as listed in Table 5) is the same configuration evaluated in the previous section 5.2 and is based on the idealised noise performance as in all previous experiments, assuming white-noise performance as described in 4.2.1. In contrast, BL+SMBA_pragmatic scenario applies pragmatic error values that reflect more conservative assumptions, in line with the achieved performance for NOAA-20 ATMS (as described in 4.2.3). For ATMS, the presence of 1/f noise means that 3x3 averaging is not as effective as expected for white noise (e.g., Weston and Bormann 2018), and this aspect is approximated here by assuming inflated noise values. Note that the perturbations applied for SMBA in the observation simulation as well as in the EDA still follow random Gaussian noise, and no attempt has been made to explicitly model 1/f noise contributions. The setup enables a direct comparison of forecast impact under optimistic and realistic noise conditions.

The results presented in Figure 9 demonstrate a clear sensitivity of the EDA spread reduction to the assumed instrument noise characteristics. The experiment using idealised errors (BL+SMBA) shows a noticeably greater reduction in ensemble spread compared to the pragmatic error configuration (BL+SMBA_pragmatic). These findings underscore the importance of achieving low-noise performance in the design and calibration of future microwave instruments, as the quality of the observations plays a critical role in determining their value for NWP.

To further address the question of how much additional impact SMBA may be expected in comparison to ATMS, we include in Figure 9 the results from BL+SIMU_ATMS scenario (black dashed curve), originally shown in Ma et al. (2024). This scenario was conducted using this simulated S-NPP and NOAA-20 ATMS data under consistent observational assumptions. A comparison with BL+SMBA_pragmatic (purple dashed curve) reveals that added channels at 118 GHz and 229 GHz in SMBA contribute noticeable additional benefits, clearly for geopotential height and temperature fields.

Table 5: Detailed list of proposed scenarios in the SMBA EDA impact study for evaluating noise sensitivity.

Scenario Name	Observing system other than MW sounding	MW sounding in 21:30 LTAN	MW sounding in 13:30 LTAN	MW sounding in 17:30 LTAN	MW obs error setting
BL	Full*	Two MetOp	-	-	
BL+SMBA	Full*	Two MetOp	Two SMBA	-	Idealised values
BL+SMBA_pragmatic	Full*	Two MetOp	Two SMBA	-	Pragmatic values
BL+SIMU_ATMS	Full*	Two MetOp	Two **Simulated ATMS**	-	Pragmatic values



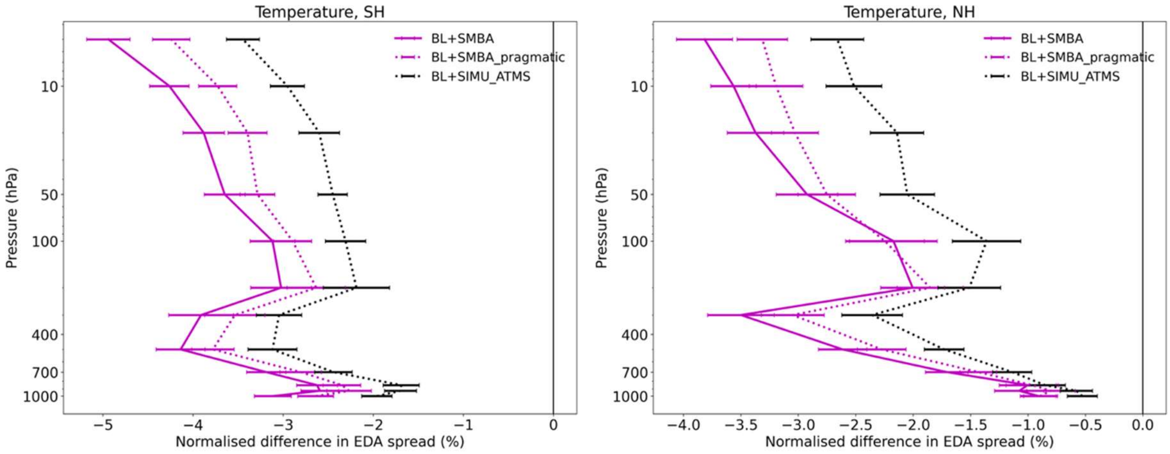


Figure 9: Same as Figure 7, but for geopotential height and Temperature in the Southern Hemisphere (latitude > 20°S). Negative values in EDA spread (x-axis) show positive improvement.

Overall, the results in this subsection suggest that the forecast improvement potential of SMBA depends strongly on the instrument's noise characteristics, with further gains achieved through the inclusion of the new spectral channels. These findings reinforce the dual importance of high instrument performance and expanded spectral coverage in the development of NOAA next-generation microwave sounders.

5.4 Impact from SMBA in the 13:30 and 17:30 LTAN orbits

This subsection presents results from additional EDA experiments designed to evaluate the forecast impact of SMBA observations in both the 13:30 and 17:30 LTAN orbits. By comparing ensemble spread reductions across various addition scenarios, we assess the incremental value of including SMBA observations in the early morning orbit as well as the afternoon one.

In alignment with NOAA's future MW mission plans, which aim to deploy two additional SMBA instruments in the early morning orbit, a dedicated EDA experiment was conducted to test the potential benefit of this configuration. All SMBA channels in these scenarios use the idealised observation error values defined in Table 3. A detailed summary of the evaluated scenarios is provided in Table 6.

Table 6: A detailed list of proposed scenarios in SMBA EDA impact studies. MW observation error settings are with ***Idealised values****. *See main text for a description of observations other than passive MW sounding.*

Scenario Name	Observing system other than MW sounding	MW sounding in 21:30 LTAN	MW sounding in 13:30 LTAN	MW sounding in 17:30 LTAN	MW obs error setting
BL	Full*	Two MetOp	-	-	
BL+SMBA	Full*	Two MetOp	Two SMBA	-	Idealised values
BL+SMBA+2EM_orbits	Full*	Two MetOp	Two SMBA	Two SMBA	Idealised values

The results, illustrated in Figure 10, show a clear benefit from the addition of SMBA data in the early morning orbit, especially for geopotential height and temperature fields. These improvements are evident across both hemispheres in all vertical levels. When SMBA instruments are deployed in both the afternoon and early morning orbits, the largest forecast impact is observed, highlighting the value of a multi-orbit configuration for enhancing global coverage and improving the quality of initial conditions in NWP systems. The findings are in line with the real-data experience that the continued addition of further MW sounding data leads to further benefits (e.g., Duncan et al. 2021). Consistent with previous work, the incremental benefit from adding SMBA instruments reduces somewhat with the number of MW sounders present: adding two SMBA instruments in the early morning orbit on top of two SMBA instruments in the afternoon orbit (blue vs purple line) gives a smaller impact than the benefit of adding two SMBA instruments in the afternoon orbit in the first place (purple line).

These findings confirm that the inclusion of SMBA observations in the 17:30 LTAN orbit complements existing afternoon data and provides additional constraint to the analysis system, especially in data-sparse regions. The results support the strategic deployment of SMBA instruments across multiple orbits to maximize forecast benefit. The findings regarding the benefit of coverage from the early-morning orbit are also consistent with real-data experience with the Chinese FY-3E satellite, as well as the findings in Ma et al (2024).

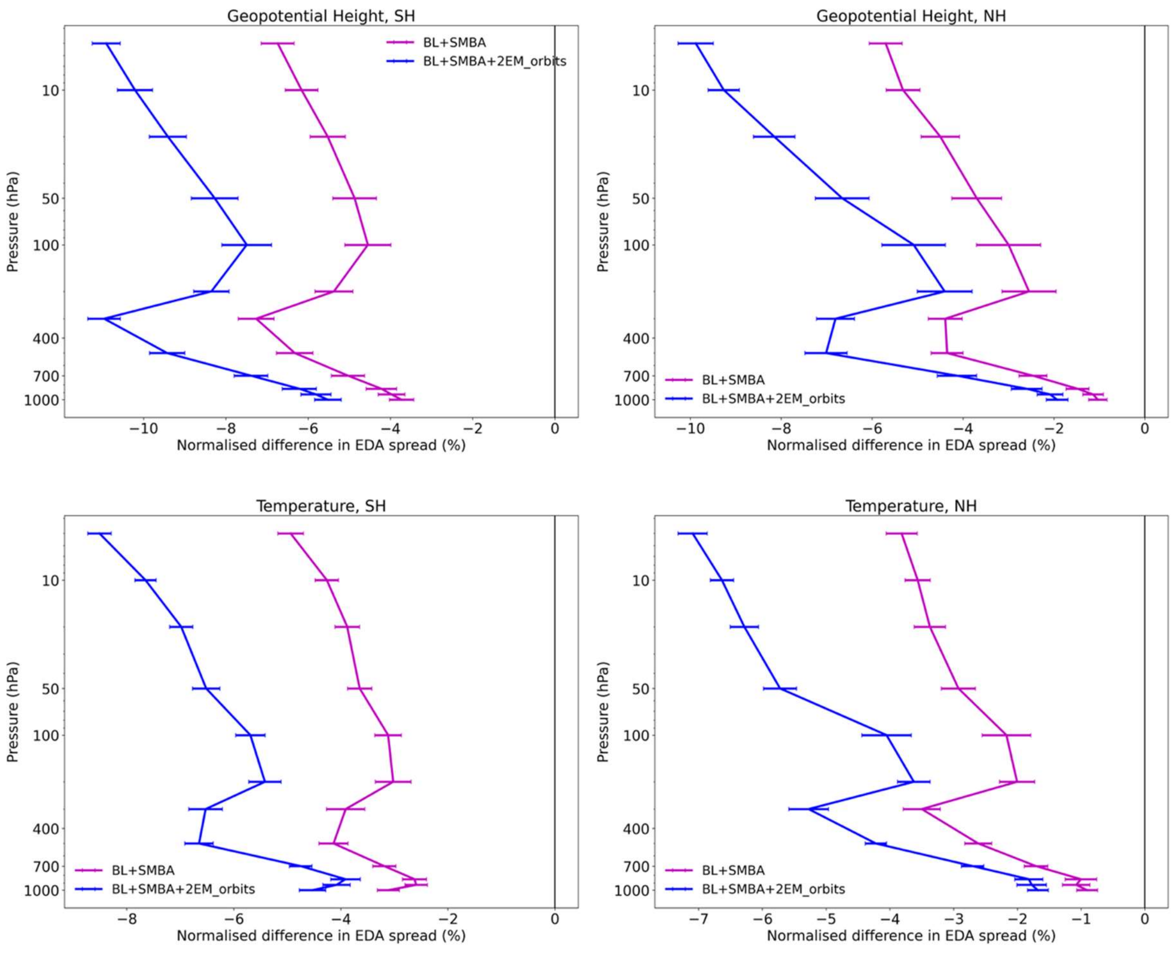


Figure 10: Same as Figure 7, but for geopotential height and temperature in the Southern Hemisphere (latitude > 20°S). Negative values in EDA spread (x-axis) show positive improvement.

6 Conclusion

As part of NOAA's next-generation NEON program, SMBA introduces additional channels at 118 GHz and 229 GHz, enhancing the capabilities of the current ATMS instrument family. These new frequencies are designed to improve temperature and humidity profiling by offering greater vertical resolution and sensitivity. Evaluating their potential impact on NWP systems prior to launch is an essential step in mission planning.

In this study, we applied the well-established EDA method at ECMWF to assess the forecast impact of SMBA. This work builds on previous EDA-based studies, including evaluations of a refurbished ATMS instrument in the 17:30 LTAN early-morning orbit. We maintained consistency with prior work by using the same EDA configuration—ECMWF's Integrated Forecasting System Cycle 48r1—and the same experimental period, from 1 to 30 June 2021, incorporating all-sky microwave radiance assimilation. The EDA framework was extended to evaluate 30 channels, including seven at 118 GHz and one at 229 GHz, in addition to ATMS-like frequencies.

Prior to running the experiments, significant effort was dedicated to defining appropriate observation error characteristics, particularly for the new 118 GHz and 229 GHz channels. We conducted a series of scenarios to isolate the impact of specific frequency bands and orbital configurations, along with a dedicated noise sensitivity study to evaluate the influence of assumed instrument performance.

Key findings from this study include:

- Adding the 118 and 229 GHz channels to the 50 and 183 GHz ATMS channels in SMBA yields modest improvements over the current ATMS for temperature and wind fields.
- The 50 GHz channels remain essential; the 118 GHz channels cannot fully replace them for core temperature sounding. Replacing the 50GHz channels with 118 GHz channels show large degradation in all model outputs.
- Results show strong sensitivity to assumed instrument noise, highlighting the importance of achieving low-noise performance.
- The greatest forecast impact occurs when SMBA data are assimilated in both afternoon and early-morning orbits, supporting a multi-orbit strategy for maximizing global NWP benefit.

A key outcome of this study is the demonstrated sensitivity of forecast impact to instrument noise assumptions. Achieving low-noise performance is crucial to unlocking the full value of SMBA observations. The combination of 13:30 and 17:30 LTAN coverage yields the strongest impact, emphasizing the importance of orbit configuration in future mission planning. While the 118 and 229 GHz channels contribute meaningfully, they are best viewed as complementary enhancements, not substitutes for the foundational 50 GHz temperature-sounding channels. The latter finding is also relevant in the context of MW sounding instruments on CubeSats or small satellites. A set of temperature-sounding channels in the 50-GHz band is more challenging to accommodate on a CubeSat and there is currently hence a trend to use 118 GHz channels instead. However, our results suggest that this design choice may lead to a substantial reduction in forecast impact compared to satellites that include 50 GHz channels.

Some caveats of the present study are worth highlighting, to put into context the substantial benefits (above 5% spread reduction) found from four SMBA instruments in the 13:30 and 17:30 LTAN orbits. Firstly, the results were obtained with a limited baseline observing system in which the MetOp satellites in the mid-morning orbit provide the only cross-track passive MW sounders. The baseline is designed to highlight the crucial role of SMBA instruments in the three-orbit backbone system established by the Coordination Group for Meteorological Satellites (CGMS). It reflects a situation in which no POES satellites are available, no Chinese MW sounders are used, and back-bone MW sounding from the JPSS satellites is to be replaced by SMBA. In a future observing system, with contributions from additional MW sounding instruments from, for instance, the Arctic Weather Satellite (AWS), the FY-3 series, and potentially EUMETSAT Polar System – Sterna (EPS-Sterna), or with hyperspectral infrared instruments from geostationary satellites, the relative benefit of even a high-performing SMBA constellation would likely appear smaller. Secondly, the results shown here reflect the current use of the overall observing system in the ECMWF data assimilation system. Further developments in the data assimilation system or the use of observations may affect the impact of individual observing systems, and hence lead to different relative impacts. Nevertheless, the current study provides our most realistic estimate of the expected impact of SMBA under the conditions investigated, suggesting very significant advancements in the forecast impact compared to ATMS.

7 Acknowledgements

This study was supported by NOAA grants NA24NESX432C0001 and NA19NES4320002 (Cooperative Institute for Satellite Earth System Studies (CISESS)) at the University of Maryland/ESSIC. Thanks to Joerg Ackermann for generating SMBA scan simulations in this study. Thanks to Emma Turner for providing the SMBA coefficients and its Jacobian input files. Thanks to Tony McNally for reviewing the manuscript.

8 Appendix: Estimation of SMBA clear sky observation errors

The clear-sky observation errors for SMBA were estimated using the specified NEDT values listed in Table 1, following the empirical approach developed by Lean et al. (2023). In the all-sky observation error model, each channel requires two key inputs: the minimum (clear-sky) error and the maximum (cloud-saturated) error. While the maximum error values under cloudy conditions are adopted directly from values used for real satellite data—since representation error dominates and instrument noise is negligible—clear-sky errors are adjusted to reflect the specific noise performance of the SMBA instrument.

Table 7: Values of tuneable parameters (scaling factor α and "representation error" σ_r) to compute the clear sky observation error from the NEDT values for active channels (from 50-, 118- and 183-GHz) shown in Table 1. Statistics are based on considering departures from the ECMWF system over two seasons (13-31 May and 12-31 Oct 2021).

SMBA active channel	Equivalent Channel	Sea		Land	
		α	σ_r	α	σ_r
Ch6	ATMS 6	1.15	0.14	1.15	0.27
Ch7	ATMS 7	1.15	0.08	1.15	0.13
Ch8	ATMS 8	1.15	0.08	1.15	0.08

Ch9	ATMS 9	1.15	0.08	1.15	0.08
Ch10	ATMS 10	1.15	0.09	1.15	0.08
Ch11	ATMS 11	1.15	0.09	1.15	0.08
Ch12	ATMS 12	1.15	0.09	1.15	0.08
Ch13	ATMS 13	1.15	0.09	1.15	0.08
Ch14	ATMS 14	1.15	0.09	1.15	0.08
Ch15	ATMS 15	1.15	0.09	1.15	0.08
Ch19	TROPICS 4, ~MWHS-2 7	1.15	0.14	1.15	0.14
Ch20	TROPICS 5, ~MWHS-2 6	1.15	0.14	1.15	0.14
Ch21	TROPICS 6, ~MWHS-2 5	1.15	0.08	1.15	0.08
Ch22	TROPICS 7, ~MWHS-2 4	1.15	0.08	1.15	0.08
Ch23	TROPICS 8, ~MWHS-2 3	1.15	0.09	1.15	0.08
Ch25	ATMS 18	1.3	1.4	1.3	1.45
Ch26	ATMS 19	1.3	1.4	1.3	1.45
Ch27	ATMS 20	1.25	1.5	1.3	1.35
Ch28	ATMS 21	1.25	1.5	1.3	1.35
Ch29	ATMS 22	1.1	1.5	1.3	1.35

To estimate the clear-sky observation error $\sigma_{o,clr}$ for each channel, we apply the following relationship:

$$\sigma_{o,clr} = \alpha\sqrt{\sigma_{NEDT}^2 + \sigma_r^2}$$

where: σ_{NEDT} is the sample instrument noise, σ_r is the estimated representation error, and α is a scaling factor accounting for other neglected effects such as inter-channel error correlations.

This approach assumes that instrument noise and representation error are uncorrelated, and that their combined effect can be approximated through this quadratic sum. The parameters σ_r and α are derived from real data by analysing standard deviations of background departures across multiple operational sensors with differing noise characteristics.

Separate sets of parameters were used for land and sea surfaces, and the resulting values are summarized in Table 7. These are based on the values given in Lean et al. (2023) for channels 6-10 and 25-29. For channels 11-15, the same values are adopted as for channel 10, whereas values for channel 19-23 are taken from the channel 6-9 peaking at a similar altitude. The resulting $\sigma_{o,clr}$ values are used in the all-sky assimilation system as the clear-sky component of the observation error model for SMBA, enabling consistent and realistic error specification aligned with ECMWF operational practices.

9 References

Atlas, R.; Hoffman, R.; Ma, Z.; Emmitt, G.; Wood, S.; Greco, S.; Tucker, S.; Bucci, L.; Annane, B.; Hardesty, R.M.; et al., 2015: Observing System Simulation Experiments (OSSEs) to Evaluate the Potential Impact of an Optical Autocovariance Wind Lidar (OAWL) on Numerical Weather Prediction. J. Atmos. Ocean. Technol. 32, 1593–1613.

Baordo, F. and Geer, A.J., 2016: Assimilation of SSMIS humidity-sounding channels in all-sky conditions over land using a dynamic emissivity retrieval. Quart. J. Roy. Meteor. Soc., 142(700), 2854–2866, doi:10.1002/qj.2873, URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.2873.

Bauer, P., E. Moreau, F. Chevallier and U. O'Keeffe, 2006: Multiple- scattering microwave radiative transfer for data assimilation applications. Quart. J. Roy. Meteor. Soc., 132, 1259–1281, https://doi.org/10.1256/qj.05.153.

Bonavita, M., E. Hólm, L. Isaksen and M. Fisher, 2016: The evolution of the ECMWF hybrid data assimilation system. *Q. J. R. Meteorol. Soc.*,142, 287-303, doi:10.1002/qj.265

Bormann, N., A. Fouilloux, W. Bell, 2013: Evaluation and assimilation of ATMS data in the ECMWF system. J. Geophys. Res., 118(23), https://doi.org/10.1002/2013JD020325

Bormann, N., H. Lawrence, J. Farnan, 2019: Global observing system experiments in the ECMWF assimilation system. ECMWF Technical Memorandum 839, 24pp, https://www.ecmwf.int/node/18859, doi: 10.21957/sr184iyz.

Bormann, N., Healy, S., Lean, K. & Lonitz, K., 2023: Predicting the forecast impact of potential future observing systems. ECMWF Newsletter, 174, 12–17.

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, 3703–3718. doi: 10.1002/qj.4149

Duncan, D.I., N. Bormann, A.J. Geer and P. Weston, 2022: Assimilation of AMSU-A in All-Sky Conditions. Mon. Wea. Rev., 150, 1023–1041, https://doi.org/10.1175/MWR-D-21-0273.1.

Geer, A.J. and Bauer, P., 2011: Observation errors in all-sky data assimilation. Q.J.R. Meteorol. Soc., 137: 2024-2037. https://doi.org/10.1002/qj.830

Geer, A.J., F. Baordo, N. Bormann, S.J. English, 2014: All-sky assimilation of microwave humidity sounders. ECMWF Technical Memorandum 741, 57pp. https://doi.org/10.21957/obosmx154

Geer, A.J., F. Baordo, N. Bormann, P. Chambon, S.J. English, M. Kazumori, H. Lawrence, P. Lean, K. Lonitz, C. and Lupu, 2017: The growing impact of satellite observations sensitive to humidity, cloud and precipitation. Q J R Meteorol Soc, 143: 3189-3206. doi: 10.1002/qj.3172

Geer, A.J., Lonitz, K., Duncan, D.I. and Bormann, N., 2022: Improved surface treatment for all-sky microwave observations. Technical Report 894, ECMWF Tech. Memo., Shinfield Park, Reading, doi:10.21957/zi7q6hau, URL https://www.ecmwf.int/node/20337.

Harnisch, F., S.B. Healy, P. Bauer, S.J. English, 2013: Scaling of GNSS Radio Occultation Impact with Observation Number Using an Ensemble of Data Assimilations. Mon Wea Rev, 141, 4395–4413. doi: 10.1175/MWR-D-13-00098.1.

Healy, S.B., Lean, K., Semane, N., Bormann, N., 2023: Task 2: Doppler Wind Lidar EDA Impact Assessment. EUMETSATContract EUM/CO/22/4600002673/SDM Final Report, ECMWF, Reading, UK.

Healy, S.B., N. Bormann, A. Geer, E. Hólm, B. Ingleby, K. Lean, K. Lonitz and C. Lupu, 2024: Methods for assessing the impact of current and future components of the global observing system. ECMWF Technical Memorandum 916, doi: 10.21957/2f240fe55f

Isaksen, L, Bonavita, M, Buizza, R, Fisher, M, Haseler, J, Leutbecher, M, Raynaud, L, 2010: Ensemble of data assimilations at ECMWF. ECMWF Technical Memorandum 636, https://www.ecmwf.int/node/10125, doi: 10.21957/obke4k60, 48pp

Kazumori, M., English, S.J., 2015. Use of the ocean surface wind direction signal in microwave radiance assimilation. QJRMS 141, 1354–1375. URL: https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.2445, doi:10.1002/qj.2445.

Lawrence, H., Bormann, N., Geer, A.J., Lu, Q. and English, S.J., 2018: Evaluation and assimilation of the microwave sounder MWHS-2 onboard FY-3C in the ECMWF numerical weather prediction system. IEEE T. Geosci. Remote Sens., 56(6), 3333–3349, doi:10.1109/TGRS.2018.2798292, URL https://doi.org/10.1109/TGRS.2018.2798292.

Lean, K., N. Bormann, S.B. Healy, 2021b: Developing a flexible system to simulate and assimilate small satellite data. ESA Contract Report for 4000130590/20/NL/IA, 18pp, https://www.ecmwf.int/node/20303, doi: 10.21957/kjmxyh9xy

Lean, K., N. Bormann, S.B. Healy, S. English, 2022: Final Report: Study to assess earth observation with small satellite and their prospects for future global numerical weather prediction. ESA Contract Report for 4000130590/20/NL/IA, 40pp, https://doi.org/10.21957/kp7z1sn1n

Lean, K., N. Bormann, S.B. Healy, 2023: Evaluation of initial future EPS-Sterna constellations with 50 and 183 GHz. EUMETSAT contract report for EUM/CO/22/4600002673/SDM, 34pp, https://doi.org/10.21957/0a695fcc39

Lean, K., N. Bormann, S.B. Healy, S. English, D. Schüttemeyer and M. Drusch, 2025: Assessing forecast benefits of future constellations of microwave sounders on small satellites using an ensemble of data assimilations. Q J R Meteorol Soc, 151(768), e4939. https://doi.org/10.1002/qj.4939

Ma, Z., L P. Riishøjgaard, M. Masutani, J.S. Woollen and G.D. Emmitt, 2015: Impact of Different Satellite Wind Lidar Telescope Configurations on NCEP GFS Forecast Skill in Observing System Simulation Experiments. *J. Atmos. Oceanic Technol.*, **32**, 478–495, https://doi.org/10.1175/JTECH-D-14-00057.1.

Ma, Z., N. Bormann, K. Lean, D. Duncan, E. Berbery and S. Kalluri, 2024: Forecast impact assessment of a potential ATMS instrument in the early-morning orbit using the EDA method. *ECMWF Technical Memorandum*, 925, https://doi.org/10.21957/59eb3a9b44

Saunders, R., Hocking, J., Turner, E., Havemann, S., Geer, A., Lupu, C., Vidot, J., Chambon, P., Köpken- Watts, C., Scheck, L., Stiller, O., Stumpf, C., Borbas, E., 2020: RTTOV-13 science and validation report. EUMETSAT NWP SAF, version 1.0 URL: https://nwp-saf.eumetsat.int/site/software/rttov/documentation/.

Steele, L, N. Bormann, D. Duncan, 2023: Assimilating FY-3E MWHS-2 observations, and assessing all-sky humidity sounder thinning scales. EUMETSAT/ECMWF Fellowship Programme Research Report 62, 31pp, https://doi.org/10.21957/f42a9d9542

Tan, D.G.H., E. Andersson, M. Fisher and L. Isaksen, 2007: Observing-system impact assessment using a data assimilation ensemble technique: Application to the ADM-Aeolus wind profiling mission. Q J R Meteorol Soc, 133, 381–390.

Weston, P. and N. Bormann, 2018: Enhancements to the assimilation of ATMS at ECMWF: Observation error update and addition of NOAA-20. EUMETSAT/ECMWF Fellowship Programme Research Report No 48, 28pp, https://www.ecmwf.int/en/elibrary/80916-enhancements-assimilation-atms-ecmwf-observation-error-update-and-addition-noaa

WMO (2019): *Vision for the WMO Integrated Global Observing System in 2040*. WMO-No. 1243, World Meteorological Organization, Geneva, Switzerland. https://library.wmo.int/records/item/57028-vision-for-the-wmo-integrated-global-observing-system-in-2040