

RESEARCH ARTICLE

Estimating the potential impact of the *EPS-Sterna* satellite constellation in regional numerical weather prediction

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Abstract

The European Space Agency (ESA) launched the *Arctic Weather Satellite (AWS)* into a sun-synchronous low Earth orbit in August 2024. The purpose of the launch is to demonstrate the feasibility of new low-cost satellite technology in provision of continuous microwave sounding data for the use in numerical weather prediction (NWP) and nowcasting applications. *AWS* is intended as a predecessor of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) *Polar System–Sterna (EPS-Sterna)*, which is a small-satellite microwave-sounding constellation that EUMETSAT envisions as one of its future operational programmes. Planned to operate from 2029 to the 2040s, *EPS-Sterna* would maintain a constellation of six satellites in orbits complementary to the baseline polar satellites of EUMETSAT, the National Oceanic and Atmospheric Administration (NOAA), and the Chinese Meteorological Administration (CMA). We present an estimate of the potential forecast impact that can be expected from the assimilation of *EPS-Sterna* microwave radiance data into regional NWP systems at high northern latitudes. The estimate is based on running state-of-the-art limited-area NWP systems and quantifying the impact obtained from the heritage microwave sounders of EUMETSAT, NOAA, and CMA. The results indicate that the expected forecast impact will be greater in winter than in summer and that the greatest benefit will be in the forecast of humidity-related parameters near the surface. In terms of the reduction in root-mean-squared forecast error, the impact expectation at short-range forecast lead times (up to 24 hours) is up to 5%–10% in humidity and cloudiness and up to 1%–2% in temperature.

KEYWORDS

4D-Var, *Arctic Weather Satellite*, *EPS-Sterna*, microwave sounding, NWP, regional modelling

1 | INTRODUCTION

Satellite-based measurements of radiance (brightness temperature) at microwave frequencies are among

the most influential observations in both global and regional applications of numerical weather prediction (NWP) (e.g., Chambon *et al.*, 2023; Eyre *et al.*, 2022; Randriamampianina *et al.*, 2021; Samrat *et al.*, 2025).

Typically, these kinds of data are assimilated into NWP systems using variational methods that rely on fast yet accurate quantitative modelling of radiative transfer. The meteorological information provided by space-based microwave sounders originates from sampling upwelling radiation at selected frequency intervals in the 53–57 and 183-GHz spectral regions, that is, near the main absorption lines of oxygen and water vapour, respectively. At present, such measurement data are provided by less than a dozen operational satellites flying in polar low Earth orbits and being maintained by space organizations such as the National Oceanic and Atmospheric Administration (NOAA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the Chinese Meteorological Administration (CMA).

Thanks to the long-standing effort of the Coordination Group for Meteorological Satellites (CGMS), a mutual agreement is in place between the European and American data providers, such that each is responsible for continued maintenance and production of meteorological data from one specific sun-synchronous orbital plane. As expressed in terms of the local time of descending node (LTDN), the satellites in the 1:30 AM and 9:30 AM orbits are being maintained by NOAA and EUMETSAT, respectively. Relatively recently, CMA launched one of their polar orbiters (*Fengyun-3E*) into a complementary 5:30 AM LTDN orbit. These three orbital planes constitute a configuration that CGMS has identified as a “baseline” for atmospheric sounding from low Earth polar orbit.

In principle, the three complementary sun-synchronous orbital planes are sufficient to guarantee provision of measurement data at any location at repeat cycles no longer than four hours. Nevertheless, it would be desirable to shorten the repeat cycles further for the benefit of a wide range of users of weather data. However, the design, build, and maintenance of a full-scale state-of-the-art meteorological satellite are very considerable efforts that incur significant financial costs. These considerations have led the space agencies to consider cheaper alternatives, such as designing constellations of small and lightweight satellites that each come with a relatively short expected lifetime and carry only a single or limited number of payloads. An early example of such a concept is the *Time-Resolved Observations of Precipitation structure and storm intensity with a Constellation of Small-sats (TROPICS)* constellation that has been operated by the National Aeronautics and Space Administration (NASA) from 2023 onwards (Blackwell *et al.*, 2018). The *TROPICS* satellites fly in low-inclination orbits and provide support for the monitoring of tropical cyclone development.

The *EUMETSAT Polar System (EPS)* is a series of three *Metop* satellites that have provided operational data continuously since 2006. The follow-up mission, that is, the

EUMETSAT Polar System Second Generation (EPS-SG), is scheduled for an operational lifetime spanning from 2025 to 2046. While these satellites will continue to occupy the 9:30 AM LTDN orbit, EUMETSAT is additionally envisioning a complementary mission called *EPS-Sterna* in order to serve the demand of more frequent updates at mid- to high latitudes. The design of *EPS-Sterna* consists of a constellation of six low-cost satellites placed in three distinct orbital planes that are complementary to the CGMS baseline configuration. The payload of the *EPS-Sterna* satellites will consist of a microwave sounder that measures the upwelling radiation in the 53–57, 183-, and 325-GHz spectral regions. While the target is to make the *EPS-Sterna* constellation operational from 2029 onwards, the first satellite of this type (the *Arctic Weather Satellite, AWS*) has already been launched into the 10:30 AM LTDN orbit as a demonstrator mission in August 2024 (Eriksson *et al.*, 2025).

The AWS sounder includes 19 spectral channels. The window channels centred at 50.3, 52.8, 89, and 165.5 GHz have counterparts in the measurement spectra of heritage sounders, including the Advanced Microwave Sounding Unit–A (AMSU-A), Advanced Technology Microwave Sounder (ATMS), Microwave Humidity Sounder (MHS), and MicroWave Humidity Sounder–2 (MWHS-2). In the 53–57 GHz spectral range, AWS has five channels that match the frequencies of the tropospheric and lower-stratospheric temperature-sounding channels of AMSU-A and ATMS. Similarly, in the 176–183 GHz range, there are five AWS channels that correspond broadly to the humidity-sounding channels of ATMS, MHS, and MWHS-2. The sounding channels at 325 GHz are sensitive to tropospheric humidity and have no correspondence with earlier microwave sounders. There is an additional new channel at the central frequency of 53.246 GHz. The noise performance of AWS is comparable with that of AMSU-A (Duncan *et al.*, 2025).

It is tempting to attempt to estimate how much the *EPS-Sterna* constellation might contribute to the reduction of forecast error in NWP. The expected constellation impact has previously been evaluated in the framework of Observing-System Simulation Experiments (OSSEs). In their global OSSE at Meteo-France, Rivoire *et al.* (2024) quantified the hypothetical impact expectation assuming an *EPS-Sterna*-like constellation of six satellites in three orbital planes. According to their results, the short-range forecast impact in the northern (southern) hemisphere would correspond approximately to 70% (150%) of the impact that is presently obtained from the assimilation of data from one *Metop* satellite. Guedj *et al.* (2023) also produced an OSSE with focus specifically on regional NWP in the Arctic and demonstrated expected reductions of 3%–6% in the short-range forecast errors of mid-tropospheric

humidity, temperature, and wind. Recent work of Lean *et al.* (2025) complements these OSSE-based studies by employing an Ensemble of Data Assimilations (EDA) based method and producing estimates of the short-range forecast impact of various hypothetical small satellite constellations. The EDA spread reductions attributed to constellations of 8–20 small satellites were found to be broadly comparable with those obtained from a combination of four currently operating full-scale microwave-sounding satellites in the 1:30 AM and 9:30 AM LTDR orbits. In summary, all of these studies suggest measurable and positive forecast impact from the *EPS-Sterna* constellation, even when adding the new data on top of diverse use of satellite and ground-based meteorological observations in advanced data assimilation systems.

This article aims to complement the studies of Guedj *et al.* (2023) and Rivoire *et al.* (2024) by presenting an estimate of the future *EPS-Sterna* constellation impact in regional NWP applications in the north. This estimate is derived by extrapolating from a series of data assimilation experiments that evaluate the impact of real measurement data collected from earlier microwave sounders placed in multiple orbital planes. The work has been conducted in the context of a research project coordinated by the Swedish Meteorological and Hydrological Institute (SMHI), relying on funding received from the European Space Agency (ESA). While the project is set up to facilitate a quick implementation of the AWS microwave sounder data assimilation in the operational regional NWP systems of the Nordic countries, evaluation of the constellation impact is one of the other goals of the project. Initially, the evaluation was based solely on the heritage satellite data from NOAA, EUMETSAT, and CMA, and in the latter half of the project it is being refined on the basis of real-world assimilation impact obtained from in-orbit measurement data from the AWS microwave sounder.

The state-of-the-art limited-area NWP systems employed here are instances of the High Resolution Limited Area Model (HIRLAM)–Aire Limitée Adaptation dynamique Développement InterNational (ALADIN) Research on Mesoscale Operational NWP in Europe–Application of Research to Operations in Mesoscale (HARMONIE–AROME) reference architecture (Bengtsson *et al.*, 2017; Gleeson *et al.*, 2024). This reference architecture is provided by the international HIRLAM programme and it builds on a strong heritage of long-continued multinational co-operation of not only the countries participating in the HIRLAM programme, but additionally those having been part of the ALADIN consortium too. The HARMONIE–AROME reference architectures are closely connected with operational systems such as those run by the AROME–Arctic and Meteorological Co-Operation on Operational NWP

(MetCoOp) groups (Müller *et al.*, 2017a, 2017b). Consequently, the numerical experiments presented in this work are close to the operational regional NWP systems currently in use in the Nordic and Baltic countries. There is a lot of experience from the use of satellite-based radiance data in variational data assimilation systems at the governmental institutes of these countries (Eresmaa, 2024; Lindskog *et al.*, 2021; Randriamampianina *et al.*, 2011; Schönach *et al.*, 2025).

In the following, the article proceeds first to describe the characteristics of the variational data assimilation as implemented in the HARMONIE–AROME reference system (Section 2). This is followed by a review of the experience gathered over recent years from the use of microwave radiance data at the MetCoOp and AROME–Arctic operational groups (Section 3). The numerical data assimilation experiments conducted in this work are described in Section 4, and the results from these are presented with discussion in Section 5. Section 6 provides a brief summary and highlights the most important conclusions of the study.

2 | DATA ASSIMILATION IN THE HARMONIE–AROME REFERENCE

There is support for the use of a wide range of observation types in the analysis of upper-air meteorological fields in the HARMONIE–AROME reference system. While all operational instances continue to apply three-dimensional variational assimilation (3D-Var) for the time being, certain pre-operational suites are being run with four-dimensional variational assimilation (4D-Var) instead. This section discusses the relevant aspects of the operational and pre-operational implementations of 3D-Var and 4D-Var methods as they appear in the HARMONIE–AROME context.

2.1 | The operational systems based on the HARMONIE–AROME reference

The HARMONIE–AROME reference architectures provide the basis for most of the operational regional NWP systems that are being run in the Netherlands, Ireland, Spain, and all of the Nordic and Baltic countries. At the time of writing, the most recent quality-assured HARMONIE–AROME reference architecture is version 46h1 (Gleeson *et al.*, 2024). Most of the operational suites are currently built upon the previous quality-assured reference, that is, 43h2.

There are two notable operational groupings that each share the production, maintenance, and short-term

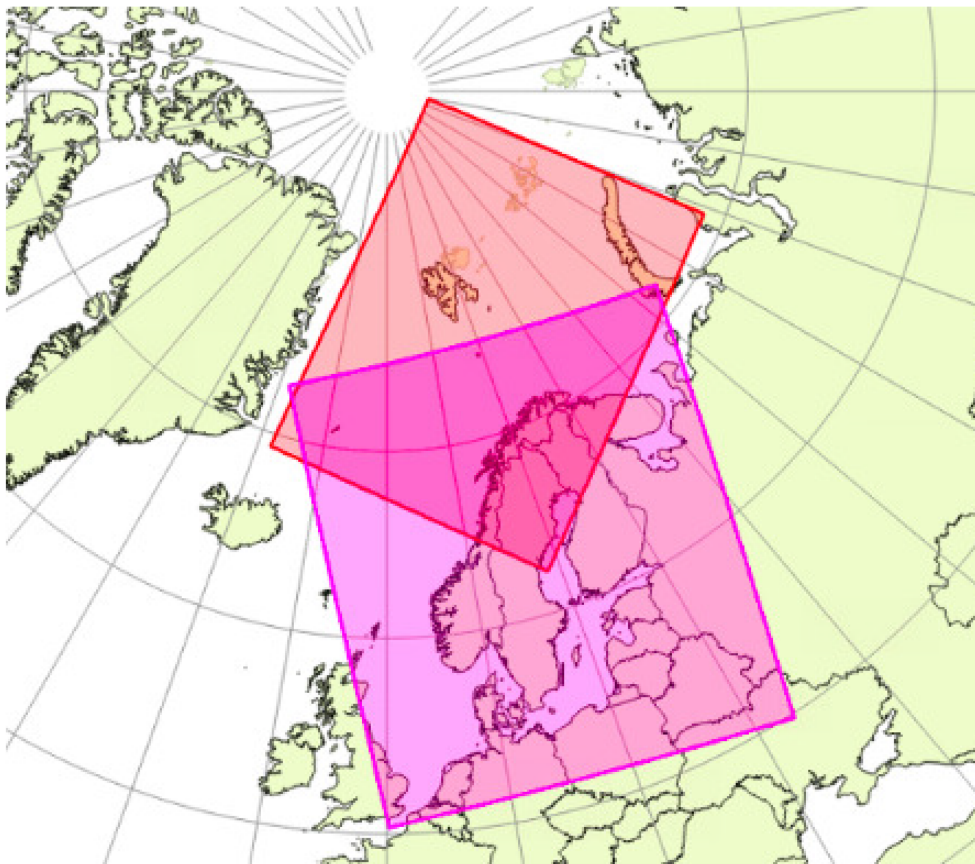


FIGURE 1 Horizontal extents of the computing domains at the AROME-Arctic (red) and MetCoOp (purple) operational groups.

development between four or five nations. One is a joint effort of Estonia, Finland, Latvia, Norway, and Sweden and is called MetCoOp (Müller *et al.*, 2017b). The other comprises the meteorological offices of the Netherlands, Ireland, Denmark, and Iceland and is called United Weather Centres-West (UWC-W: Gleeson *et al.*, 2024). There are additional operational setups maintained by single countries, such as those run by the Spanish Meteorological Institute (AEMET) and the Norwegian effort in an Arctic domain (AROME-Arctic: Müller *et al.*, 2017a).

The experiments conducted in this work are based on the operational setups of the MetCoOp and AROME-Arctic groups. Both apply 2.5-km grid spacing in the horizontal and 65 hybrid model levels, and the model top is at 10-hPa pressure. The horizontal extent of the computing domains is shown in Figure 1. The lateral boundary forcing is retrieved from global forecasts of the European Centre for Medium-range Weather Forecasts (ECMWF). The time integration of the numerical forecast is out to the 66-h lead at 75-s time steps.

2.1.1 | The operational use of observations

The background field for the analysis is taken from each run's own short-range forecast from an earlier analysis

cycle. By default, this cycling is set up at three-hour intervals and the time window of the observations used in the 3D-Var analysis spans from 90 min before to 90 min after the nominal analysis time. The background-error statistics are constant in time and are derived from samples of ensemble forecasts that represent all seasons and, as a whole, cover approximately two to three months of data.

The operational use of observations includes the assimilation of several conventional and remotely sensed data types. The conventional data types include surface synoptic observations, ships, drifting buoys, aircraft meteorological data relay, and radiosonde reports. Regarding the use of remotely sensed data, the operational suites assimilate infrared and microwave sounder radiance data in clear-sky conditions, as well as scatterometer-based wind data, from polar-orbiting satellites. Additionally, the suites make use of other remotely sensed data types such as ground-based weather radar measurements of reflectivity and Doppler wind. While there has been recent work on the potential of radiances from geostationary satellites at MetCoOp (Schönach *et al.*, 2025), the use of satellite data at high latitudes in Europe still relies almost uniquely on instruments from polar orbiters. This makes regional NWP at these latitudes particularly sensitive to the availability and repeat cycles of polar-orbiting satellite data.

2.2 | HARMONIE–AROME 4D-Var

The operational use of 4D-Var has been a major goal in the long-term development of HARMONIE–AROME for several years. The existing pre-operational suites already demonstrate technical maturity that is sufficient for routine use in daily production runs, but evaluations of meteorological performance have so far provided only inconclusive evidence of skill benefit compared with the operational 3D-Var suites (Barkmeijer *et al.*, 2021). In the context of satellite data assimilation, 4D-Var is an attractive development, since it improves the treatment of observations taken at asynoptic times and allows radiance data to influence the wind field directly through the tracing effect (Geer *et al.*, 2017).

In the HARMONIE–AROME 4D-Var, the three-hour time window consists of 20-minute time slots (except for the first and last time slots that are 10 minutes each) and opens two hours before the nominal analysis time. The observation cutoff is set to the closing of the time window, that is, at one hour past the analysis time. The setup includes a screening run and two trajectory runs that are computed at the full 2.5-km horizontal resolution. The trajectory runs are preceded by minimization runs at 15- and 7.5-km resolution in the first and second loop, respectively.

3 | THE OPERATIONAL EXPERIENCE FROM THE ASSIMILATION OF MICROWAVE SOUNDER DATA

Since the late 1970s, there has been a continuous time series of microwave sounding from polar orbit. In this section, we review the recent experience of using microwave sounder data at the MetCoOp and AROME–Arctic operational groups.

The MetCoOp and AROME–Arctic groups hold extensive experience from operational use of radiance data from AMSU-A, ATMS, MHS, and MWHS-2 (Lindskog *et al.*, 2021). Until recently, there has been near-real-time access to these instruments' measurement data from several polar-orbiting satellites. In 2024–2025, the operational data flow included the NOAA-18, NOAA-19, NOAA-20, NOAA-21, Suomi-NPP, Metop-B, Metop-C, Fengyun-3D, and Fengyun-3E satellites. Most of the microwave sounders on these satellites include the sounding capability for both temperature (in the 53–57 GHz spectral region) and humidity (in the 183-GHz region). However, this is not the case in NOAA-18 (which lacks a functioning humidity sounder). Furthermore, the Nordic operational groups do not assimilate the 53–57 GHz data from FengYun-3D or FengYun-3E (although such data

is available in the measurement spectra of MicroWave Temperature Sounders -2 and -3). Also, while MWHS-2 includes temperature-sounding channels in the 118 GHz spectral region, these are not assimilated in the operational systems at present.

All of these satellites are in sun-synchronous high-inclination low Earth orbits (LEO) and they pass over any given location in the low and midlatitudes twice per day. At high latitudes, the overpasses are more frequent. The recent evolution of the associated orbital planes is as follows.

1. *Metop-B* and *Metop-C* are in stable and maintained 09:30 AM LTDN orbits. Both of these satellites have been operational for longer than six years.
2. *Suomi-NPP*, *NOAA-20*, and *NOAA-21* are in stable and maintained 01:30 AM LTDN orbits. They have been operational since 2011, 2017, and 2023, respectively, and continue to provide useful data.
3. *Fengyun-3E* is in a stable and maintained 05:30 AM LTDN orbit. The operational monitoring of *Fengyun-3E* was started in September 2023.
4. *NOAA-18* was decommissioned in June 2025. Over the past decade, its orbit was drifting at an approximate rate of 20 minutes per year. In early 2025, the LTDN was 10:30 AM.
5. *NOAA-19* was decommissioned in June 2025. Over the past decade, its orbit was drifting at an approximate rate of 54 minutes per year. In early 2025, the LTDN was 09:50 AM.
6. *Fengyun-3D* was originally launched into the 01:30 AM LTDN orbit, but in recent times the orbit has been evolving (though slowly). The current rate of change is approximately 15 minutes per year. In early 2025, the LTDN was 03:00 AM.

The use of the microwave sounder channels in the MetCoOp and AROME–Arctic groups is summarized in Table 1. Because of the relatively low model top at the 10-hPa pressure level, only two stratospheric-peaking channels are assimilated from AMSU-A and ATMS. The use of the tropospheric-sensitive channels for temperature and humidity sounding is as complete as possible, given the known failures and excessive noise levels on certain individual channels in some sounders. The assimilation applies the following specific settings on microwave sounder data.

1. The tropospheric temperature-sounding channels are considered cloud-affected and therefore rejected if the observed brightness temperature at 52.8 GHz deviates from its background equivalent by more than 0.7 K. Similarly, the humidity-sounding channels are rejected

TABLE 1 The operational use of microwave sounder channels at MetCoOp and AROME–Arctic.

Satellite	Temperature sounding	Humidity sounding
NOAA-18	AMSU-A: 5, 6, 7	n/a
NOAA-19	AMSU-A: 5, 6, 9	MHS: 4, 5
Metop-B	AMSU-A: 5, 6, 7, 9	MHS: 3, 4, 5
Metop-C	AMSU-A: 5, 6, 7, 8, 9	MHS: 3, 4, 5
Suomi-NPP	ATMS: 6, 7, 8, 9, 10	ATMS: 18, 19, 20, 21, 22
NOAA-20	ATMS: 6, 7, 8, 9, 10	ATMS: 18, 19, 20, 21, 22
NOAA-21	ATMS: 6, 7, 8, 9, 10	ATMS: 18, 19, 20, 21, 22
Fengyun-3D	n/a	MWHS-2: 11, 12, 13, 14, 15
Fengyun-3E	n/a	MWHS-2: 11, 12, 13, 14, 15

if the observation at either 89 or 165 GHz deviates from the background equivalent by more than 5.0 K.

- The low-peaking channels (channel 5 in AMSU-A, channels 6 and 18 in ATMS, channel 5 in MHS, and channel 15 in MWHS-2) benefit from the dynamic estimation of surface emissivity as described in Guedj *et al.* (2010) and Bormann *et al.* (2017).
- All channels are assimilated over land, sea, and sea ice, but there are channel-specific restrictions in place over areas of high orography and near coastlines.
- The data are subjected to horizontal thinning, such that the average distance between the closest neighbours of the same observation type is 60 km.
- The assigned observation-error standard deviations are in the range 0.16–0.23 K for AMSU-A, 0.23–0.27 K for the temperature-sounding channels of ATMS, and 1.8–2.0 K for the humidity-sounding channels of ATMS, MHS, and MWHS-2. The same observation errors are applied for all satellites.
- ATMS data are averaged (superobbed) in each group of 3×3 fields of view to reduce instrument noise. Other microwave sounders are not subjected to superobbing.

4 | EXPERIMENT FRAMEWORK

This section outlines the experiment runs conducted to quantify and characterize the impact of microwave sounders in HARMONIE–AROME suites at high northern latitudes.

As far as is reasonable, the experiment runs presented here mimic the operational use of microwave sounder radiances in the MetCoOp and AROME–Arctic groups. The most notable deviation from this principle is that the analysis of upper-air meteorological fields is conducted using 4D-Var (instead of 3D-Var as in operations). Given the ongoing developments in the HARMONIE–AROME research context, there is a fair chance that the actual use of the *EPS-Sterna* satellite data from 2029 onwards will indeed be with operational 4D-Var. Moreover, the use of 4D-Var is appropriate, since it allows efficient use of potentially many satellite overpasses during each three-hour assimilation time window. Another notable deviation from operational setups is that the experiments here are conducted only in deterministic mode and thus the impact on probabilistic forecasting will not be evaluated.

All experiment runs apply three-hour cycling, that is, produce an analysis and forecast every three hours and use the three-hour forecast from the previous run as the background at the subsequent analysis time. Four times a day, that is, at the main analysis times (0000, 0600, 1200, 1800 UTC), the forecast is run out to the 36-h lead time. At the intermediate analysis times, the forecast runs are limited to the three-hour lead time.

4.1 | Setup of the experiments

We will base the estimation of the *EPS-Sterna* constellation impact on the impact that we get from the existing microwave sounders in state-of-the-art HARMONIE–AROME systems. Given that there is not much correspondence between the currently populated orbits and the proposed *EPS-Sterna* constellation, our chosen approach is first to quantify the impact in the present and then, by making certain (more or less justified) assumptions, to extrapolate from the demonstrated impact to the expected *EPS-Sterna* constellation impact. The impact at present is quantified by evaluating the forecasting system performance changes when introducing additional satellites one by one on top of a one-satellite baseline run.

4.1.1 | Scenarios

On the one hand, the procedure to estimate the *EPS-Sterna* constellation impact includes a “single-orbit” scenario, where each addition to the data usage comes from the same orbital plane that is already covered by the one-satellite baseline run. On the other hand, the procedure additionally includes a “complementary orbits”

scenario, where the assimilated data are chosen from orbital planes that are not yet included in the earlier runs.

Considering the evolution of the orbit characteristics of the meteorological satellites over the past five years, one can go from one to up to three satellites in each scenario. In the single-orbit scenario, this requires making extensive use of the 01:30 AM LTDN orbit and choosing either *Fengyun-3D* or *NOAA-21* to complement the use of *Suomi-NPP* and *NOAA-20*. In the complementary orbits scenario, the polar orbiters in the maintained orbits at 01:30 and 09:30 AM LTDN are obvious choices for two of the three satellites, and the third satellite could be either *Fengyun-3E* or *NOAA-19*. Since the majority of the experiments discussed here were actually run in 2023 and the operational experience from *Fengyun-3E* was very limited at the time, we have chosen to rely on *NOAA-19*. To maximize the separation of *NOAA-19* with respect to both the 01:30 and 09:30 AM LTDN orbits, the experiment dates will cover time periods back in 2020–2021, when the LTDN of *NOAA-19* was in the range 05:30–06:30 AM.

4.1.2 | The use of satellites

The use of satellites in each of the experiment runs is as follows.

1. The one-satellite baseline run assimilates data from the MWS-2 instrument on *Fengyun-3D*. Following the operational settings, this implies only assimilating the humidity-sounding channels in the 183-GHz spectral region.
2. In the single-orbit scenario, there is a two-satellite run that adds the ATMS instrument of *NOAA-20* on top of the baseline run. Additionally, there is a three-satellite run that adds the ATMS instruments from both *NOAA-20* and *Suomi-NPP*.
3. In the complementary orbits scenario, there is a two-satellite run that adds the AMSU-A and MHS instruments of *Metop-B* on top of the baseline run. Additionally, there is a three-satellite run that adds those from both *Metop-B* and *NOAA-19*.

It is worth noting that, even though the one-satellite baseline run only includes sounding capability for humidity, all subsequent runs provide capability for sounding of both temperature and humidity. Hence, the use of additional sounders in the two scenarios is consistent and the intercomparison of forecasting system performance in the two scenarios will be fair. Because of individual channel malfunctions, there are slight differences in the numbers of assimilated channels from *Metop-B* and *NOAA-19*.

4.1.3 | The experiment dates

The evaluation will run through two separate six-week time periods that represent boreal winter and summer seasons. Each evaluation period is preceded by a two-week warming-up period, during which no active assimilation of microwave radiances is performed. The purpose of the warming-up period is to let the coefficients of the variational bias correction (VarBC) adjust to a balanced state, such that the use of the data can be considered to be close to optimal right from the start of the evaluation period. Here, we consider six weeks to be a reasonable compromise between obtaining a sufficiently large sample for statistically robust verification on the one hand and preventing the computational cost from becoming excessive on the other.

The six-week evaluation periods extend from December 28, 2020–February 7, 2021 in the boreal winter and from June 29–August 9, 2020 in the boreal summer. Initially, full sets of five experiment runs are produced over the winter period with the MetCoOp settings and over the summer period with the AROME–Arctic settings. At a later stage of the study, the initial set of experiment runs is complemented by additional runs that use the MetCoOp settings in summer and the AROME–Arctic settings in winter. These additional runs do not include the full set of five experiments, but only the one-satellite baseline run and the three-satellite run of the complementary orbits scenario.

5 | RESULTS

In this section, results from the impact evaluation are presented and interpreted. Given the known difficulties in applying analysis-based verification methods at short forecast lead times (Geer *et al.*, 2010), the evaluation here relies almost exclusively on forecast verification against in situ measurements taken at synoptic ground stations and radiosondes. Furthermore, because of the characteristics of the observing-station network and particularly the sparseness of verifying data inside the AROME–Arctic domain, we will put the main emphasis on the results obtained when using the MetCoOp settings. The latter part of the section discusses the implications regarding the expected *EPS-Sterna* constellation impact.

5.1 | Forecast verification

The verification scores are first examined in the form of scorecard representations to get an overview of which forecast parameters show the clearest impact. In subsequent

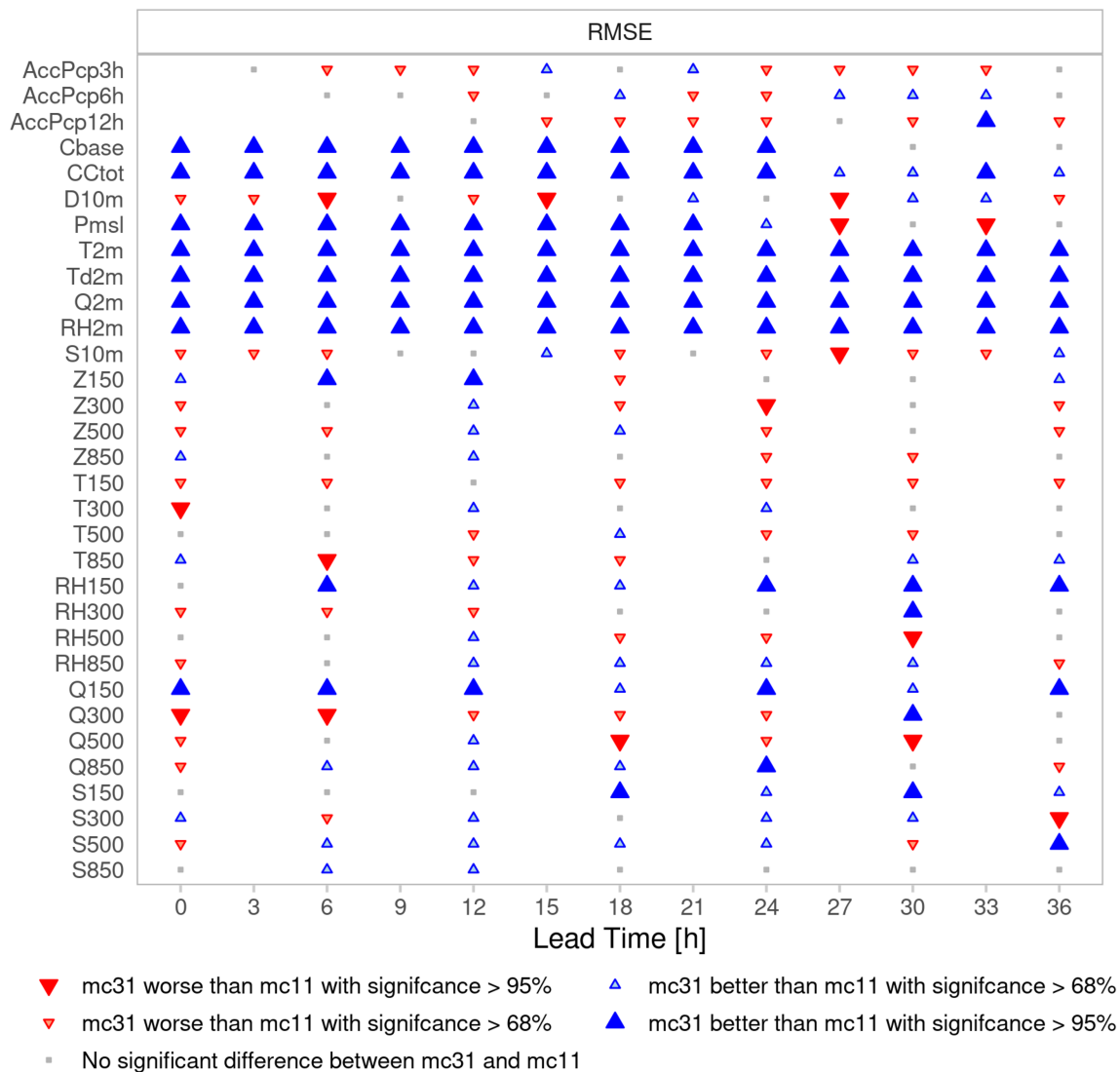


FIGURE 2 Scorecard representation of the impact of introducing two microwave-sounding satellites in the single-orbit scenario when using the MetCoOp settings in winter. Blue (red) triangles indicate positive (negative) impact from the additional satellite data. The large triangles indicate an impact that is statistically significant at 95% confidence level. The verification metric is the root-mean-squared error (RMSE) computed against observations taken at synoptic surface and radiosonde stations.

steps, the impact is quantified and the examination is extended to the progressive accumulation of the impact when introducing the satellites one by one. The seasonal variation of the impact is also considered.

5.1.1 | Scorecard representation

Figures 2–5 are scorecard representations of the microwave radiance impact in the three-satellite runs. In each case, the impact shown originates from the use of two additional satellites on top of the one-satellite baseline run. Blue and red triangles, respectively, indicate a decrease and an increase in the root-mean-squared forecast error (RMSE), that is, a positive and a negative

impact. The large triangles highlight impacts that are statistically significant at the 95% confidence level. The x-axis shows the forecast lead times from 0 to 36 h. Various forecast parameters, as explained in Table 2, are shown on the y-axis. Figures 2 and 3 show the verification scores for the MetCoOp runs in winter and Figures 4 and 5 show those for the AROME–Arctic runs in summer.

In the single-orbit scenario and using the MetCoOp settings in winter (Figure 2), there is a statistically significant positive impact in the forecast of mean sea-level pressure, near-surface temperature and humidity, cloud-base height, and total cloud cover. In all these parameters, the significant positive impact extends to at least the 21-h lead time. However, the impact on near-surface wind direction and speed, as well as that on precipitation

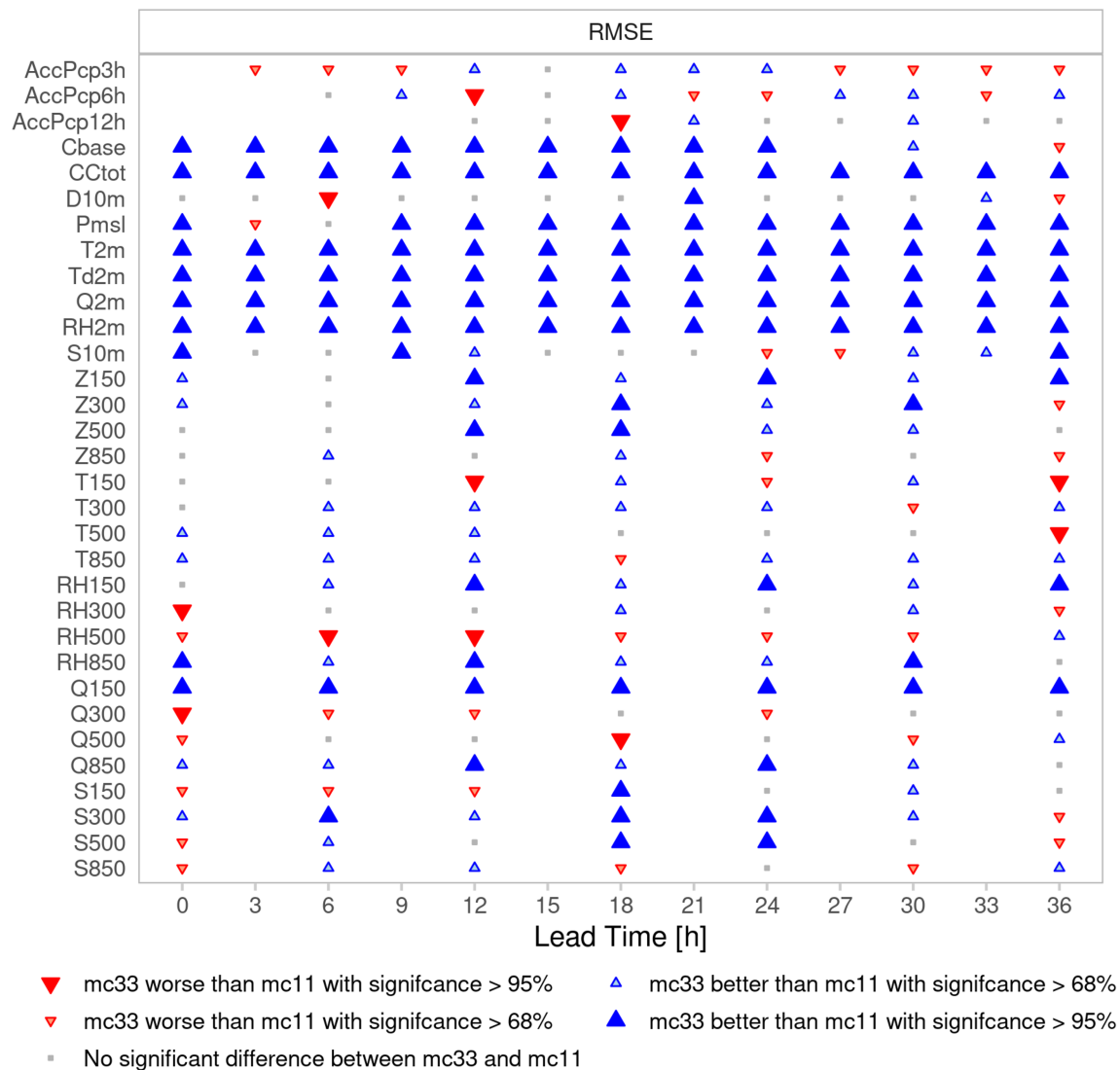


FIGURE 3 As Figure 2, but for introducing two satellites in the complementary orbits scenario.

accumulations, is mostly non-significant and even on the negative side at some lead times. Similarly, the verification of upper-air parameters against radiosonde data shows only isolated or statistically non-significant impacts. The isolated indications of a significant impact point towards a negative rather than a positive impact in most cases.

The overall impact appears more pronounced in the complementary orbits scenario (Figure 3). Again, the impact on mean sea-level pressure, near-surface temperature and humidity, and cloud-related parameters is unambiguously on the positive side at most lead times. While the scores against near-surface wind, precipitation accumulations, and upper-air observations remain inconclusive for the most part, the positive suggestions clearly outnumber the negative ones. The scores of

lower-tropospheric humidity, mid-tropospheric geopotential height, and upper-tropospheric wind speed all feature a statistically significant positive impact at more than one isolated lead time without showing any suggestions of a negative impact.

In contrast to the MetCoOp winter runs, the summer runs with the AROME–Arctic settings show relatively little evidence of a positive forecast impact. In the single-orbit scenario (Figure 4), there is a robust and significant negative impact on mean sea-level pressure and near-surface temperature, and also the impact on near-surface wind is significantly negative at most lead times. On the other hand, there are suggestions of a positive impact on near-surface humidity, total cloud cover, and precipitation accumulations. In the verification against radiosonde data, the scores of geopotential height

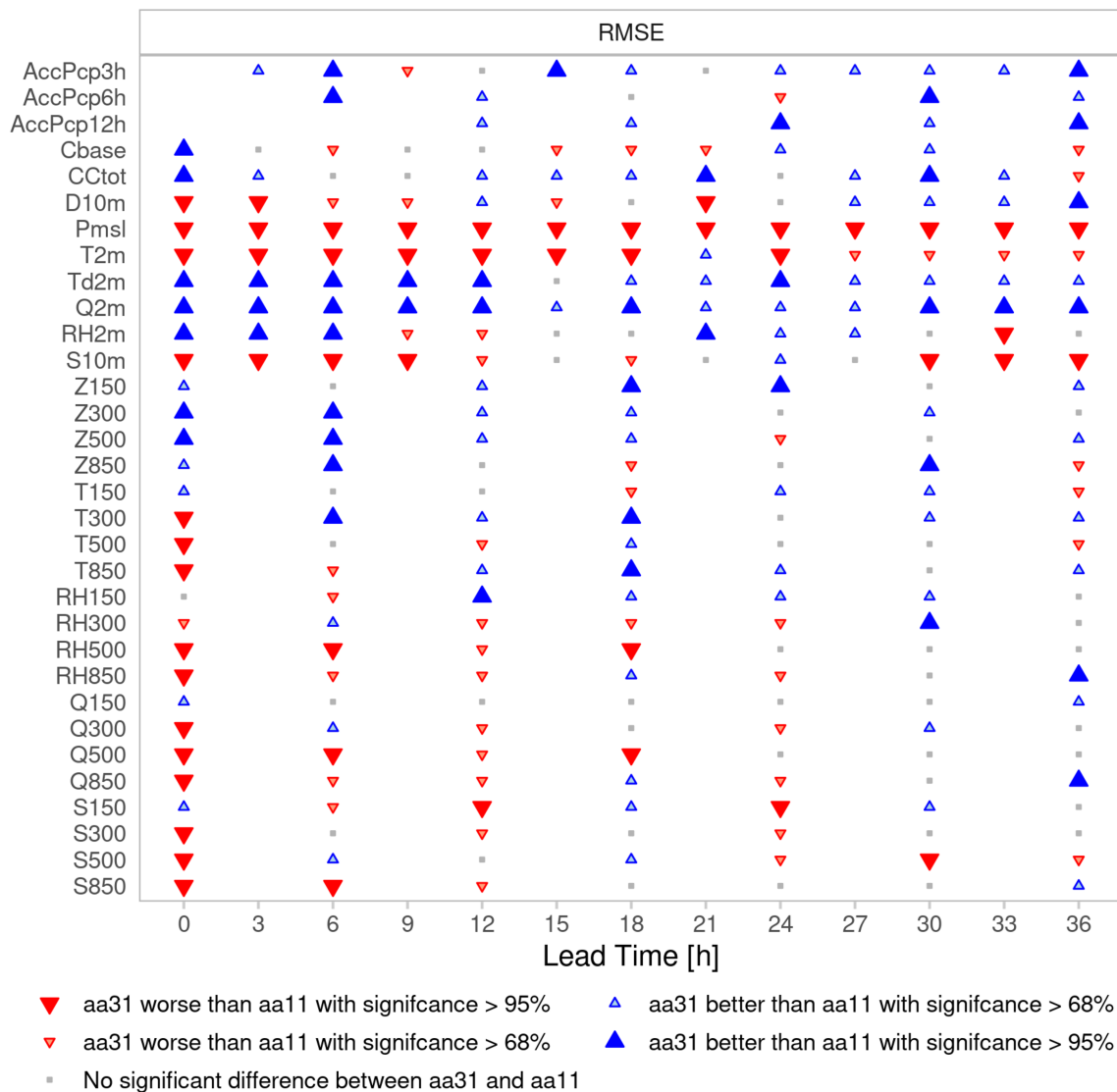


FIGURE 4 As Figure 2, but when using the AROME–Arctic settings in summer.

and temperature are mostly positive, but they tend to lack statistical significance.

Consistently with the results from the MetCoOp runs, the complementary orbits scenario (Figure 5) also outperforms the single-orbit scenario in the AROME–Arctic summer runs. There is a significant positive impact on near-surface temperature and humidity at most forecast lead times. The negative impact on mean sea-level pressure is less consistent than in Figure 4. Other near-surface parameters are inconclusive or only occasionally on the positive side. The verification of geopotential height shows a consistently positive impact at the 300- and 500-hPa levels, and this is supported by individual positive indications on temperature at 500 and 850 hPa. On the other hand, there are individual suggestions of a negative impact on humidity at 300 and 500 hPa.

5.1.2 | Magnitude of the impact

The scorecard representation discussed above gives a qualitative overview of which forecast parameters are affected by the use of microwave radiance data. To provide a quantitative idea, Figure 6 shows the normalized change in the forecast RMSE for selected parameters measured at ground stations in the three-satellite runs of the complementary orbits scenario. The normalization is with respect to the one-satellite baseline run in each case. Negative scores indicate a positive forecast impact, and the confidence intervals correspond to the statistical significance at the 95% level. It is clear that the positive impact is stronger with the MetCoOp settings in winter (black lines) than with the AROME–Arctic settings in summer (red lines). In the forecast of near-surface humidity (Figure 6b), the

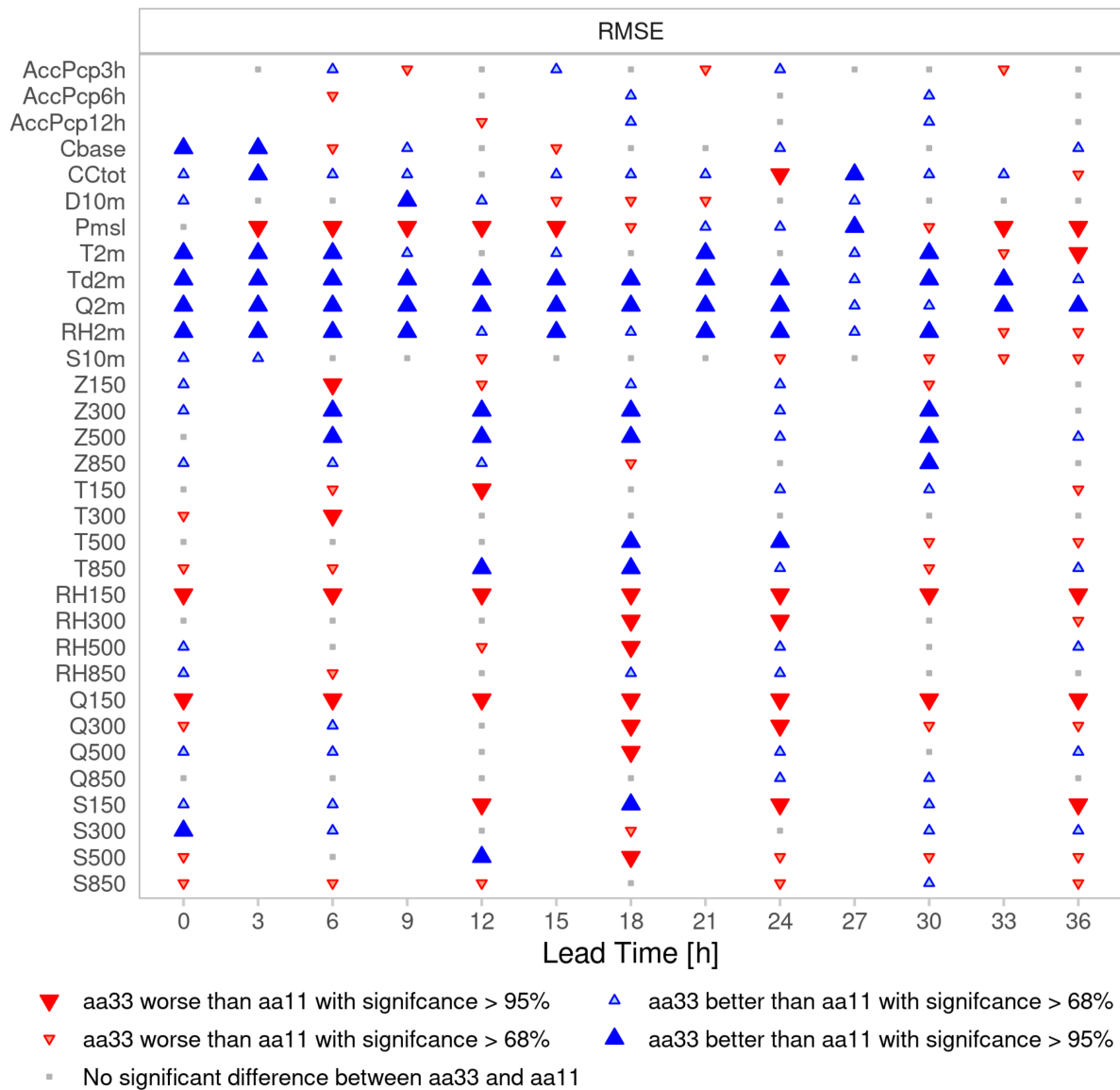


FIGURE 5 As Figure 2, but for introducing two satellites in the complementary orbits scenario when using the AROME–Arctic settings in summer.

error reduction in the former is close to 5% at very short lead times and remains in excess of 2% out to the 18-h lead time, while in the latter it barely exceeds 1% even at the shortest lead times. The forecast of cloud cover (Figure 6c) behaves similarly to that of humidity, although the magnitude of the impact is less. For near-surface temperature (Figure 6a), the error reduction only reaches 1% at lead times up to 12 h and only in the MetCoOp winter run. Cloud-base height (Figure 6d) shows a 1%–2% error reduction in the MetCoOp winter run, but no robust signal in the AROME–Arctic summer run.

The forecast RMSE reductions discussed above are in a certain sense ambiguous, since they could result from either reducing systematic errors (biases) or reducing random uncertainty (or both). To resolve the ambiguity,

we show the mean (solid lines) and standard deviation (dashed lines) of forecast error for the selected surface-based forecast parameters in the MetCoOp winter runs in Figure 7. These scores are not normalized, but produced separately for both the one-satellite baseline run (black lines) and the three-satellite run of the complementary orbits scenario (red lines). All parameters feature a substantial change in the mean forecast error and in most cases this is towards smaller forecast biases (an exception is the temperature beyond the 18-h lead time). The reduction in the standard deviation of forecast error is most evident in total cloud cover and screen-level humidity at short lead times, although there are indications of a small improvement in this aspect in temperature and cloud-base height as well.

TABLE 2 The forecast parameters presented in the scorecard figures.

Acronym	Explanation
AccPcp3h	Accumulated precipitation over three hours
AccPcp6h	Accumulated precipitation over six hours
AccPcp12h	Accumulated precipitation over 12 hours
Cbase	Cloud-base height
CCtot	Total cloudiness (octas)
D10m	Wind direction at the height of 10 metres
Pmsl	Pressure at mean sea level
T2m	Temperature at the height of two metres
Td2m	Dew-point temperature at the height of two metres
Q2m	Specific humidity at the height of two metres
RH2m	Relative humidity at the height of two metres
S10m	Wind speed at the height of 10 metres
Z300, Z500, Z850	Geopotential height at 300-, 500-, and 850-hPa levels
T300, T500, T850	Temperature at 300-, 500-, and 850-hPa levels
RH300, RH500, RH850	Relative humidity at 300-, 500-, and 850-hPa levels
Q300, Q500, Q850	Specific humidity at 300-, 500-, and 850-hPa levels
S300, S500, S850	Wind speed at 300-, 500-, and 850-hPa levels

5.1.3 | The impact obtained from individual satellites

We will next consider how the combined impact of two additional satellites builds up from individual satellites in the single-orbit and complementary orbits scenarios. The forecast RMSE reduction with respect to the one-satellite baseline run, as computed against the selected surface-based verifying observations, is illustrated in Figure 8 for the four experiment runs of the MetCoOp winter case. When verifying against near-surface temperature (Figure 8a) or cloud-base height (Figure 8d), the various experiment runs score similarly and the few differences between the runs fall largely within the confidence intervals. The differences in scores are more robust, and

the behaviour thus easier to interpret, in the verification against near-surface humidity (Figure 8b) and total cloud cover (Figure 8c). These parameters indicate a positive impact each time that another satellite is brought into the assimilation system. The findings based on Figure 8 are listed as follows.

1. The impact is greatest in the three-satellite run of the complementary orbits scenario (green lines). The forecast RMSE reduction here amounts up to 5% in humidity and up to 3.5% in total cloud cover.
2. The two-satellite run of the single-orbit scenario (black lines) shows the least impact. The RMSE reductions in this run amount up to 1.5% in humidity and up to 1% in total cloud cover.
3. Remarkably, the complementary orbits scenario shows more impact from even just one additional satellite (blue lines) than the single-orbit scenario does from two additional satellites (magenta lines).
4. The additional satellites make twice as much impact in the complementary orbits scenario as in the single-orbit scenario. This is the conclusion regardless of whether it is the two-satellite runs (black and blue) or the three-satellite runs (magenta and green) that are compared with each other.
5. The impact obtained from the second satellite (on top of the one already included in the baseline run) is twice as large as the follow-up impact from the third satellite (on top of already including two). This can be verified by intercomparing the two runs of the single-orbit scenario (black and magenta), but, again, the intercomparison of the two runs of the complementary orbits scenario (blue and green) leads to the same conclusion.

5.1.4 | Seasonal variation of the impact

The results presented above, in particular Figure 6, indicate that the microwave sounders make a by far stronger positive impact in the MetCoOp winter runs than in the AROME–Arctic summer runs. However, the material presented so far does not distinguish whether (i) the stronger impact is because of the MetCoOp settings being more favourable for the extraction of meteorological information from the data and (ii) the HARMONIE–AROME settings respond more favourably to the satellite data in winter than in summer conditions. The additional complementary runs conducted at the later stage of the study (as discussed in Section 4) become useful for the purpose of disambiguating this aspect.

The verification results from the various combinations of HARMONIE–AROME setups and seasons are collected

FIGURE 6 Normalized change in the forecast RMSE for (a) near-surface temperature, (b) near-surface specific humidity, (c) total cloud cover, and (d) cloud-base height in the three-satellite runs of the complementary orbits scenario when using the MetCoOp settings in winter (black) and AROME-Arctic settings in summer (red). The normalization is with respect to the one-satellite baseline run and the confidence intervals correspond to 95% statistical significance.

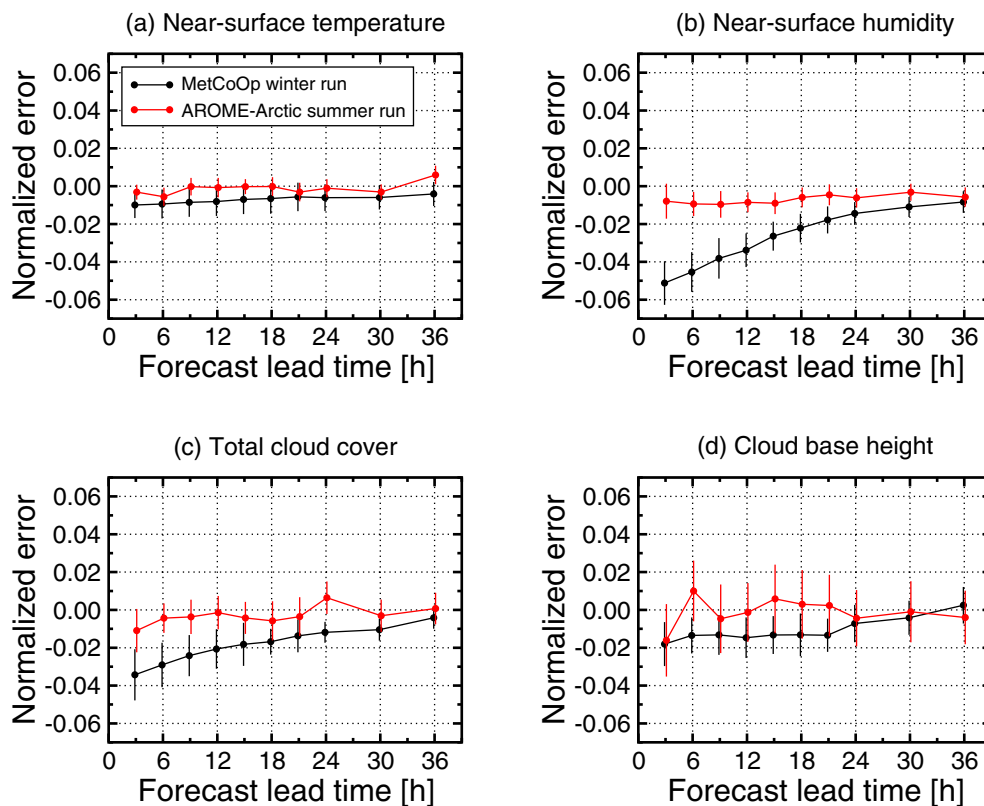
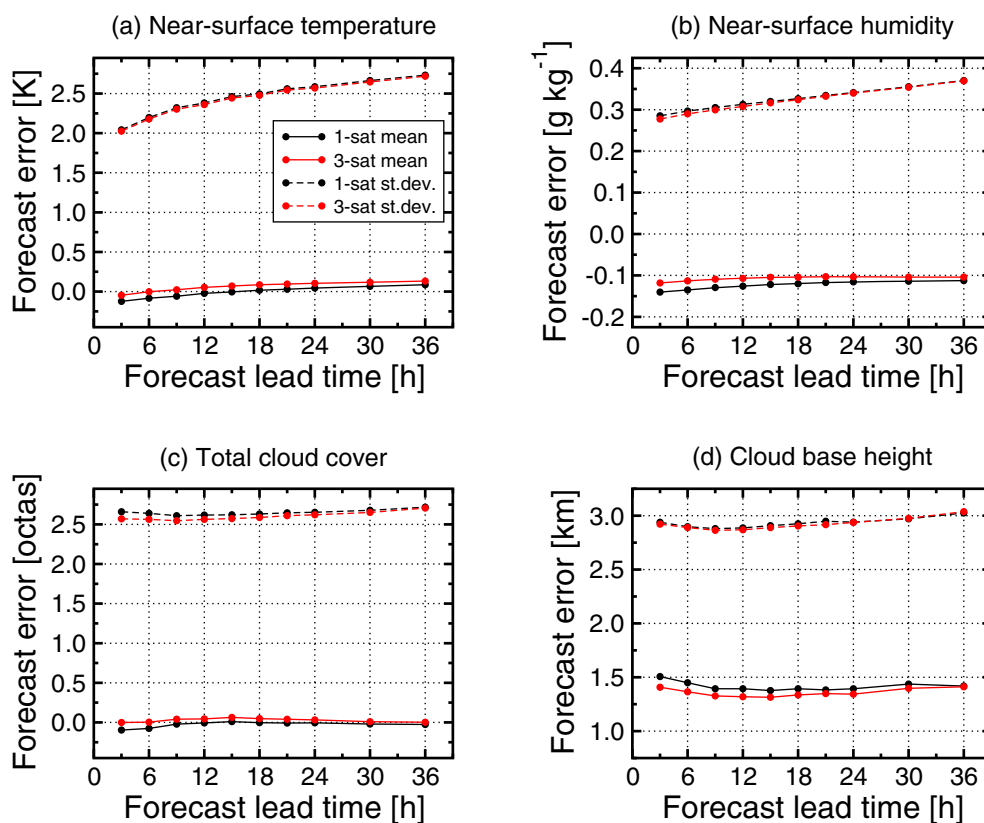


FIGURE 7 Mean (solid) and standard deviation (dashed) of forecast error as a function of lead time for selected surface-based parameters in the one-satellite baseline run (black) and in the three-satellite run of the complementary orbits scenario (red) when using the MetCoOp settings in winter.



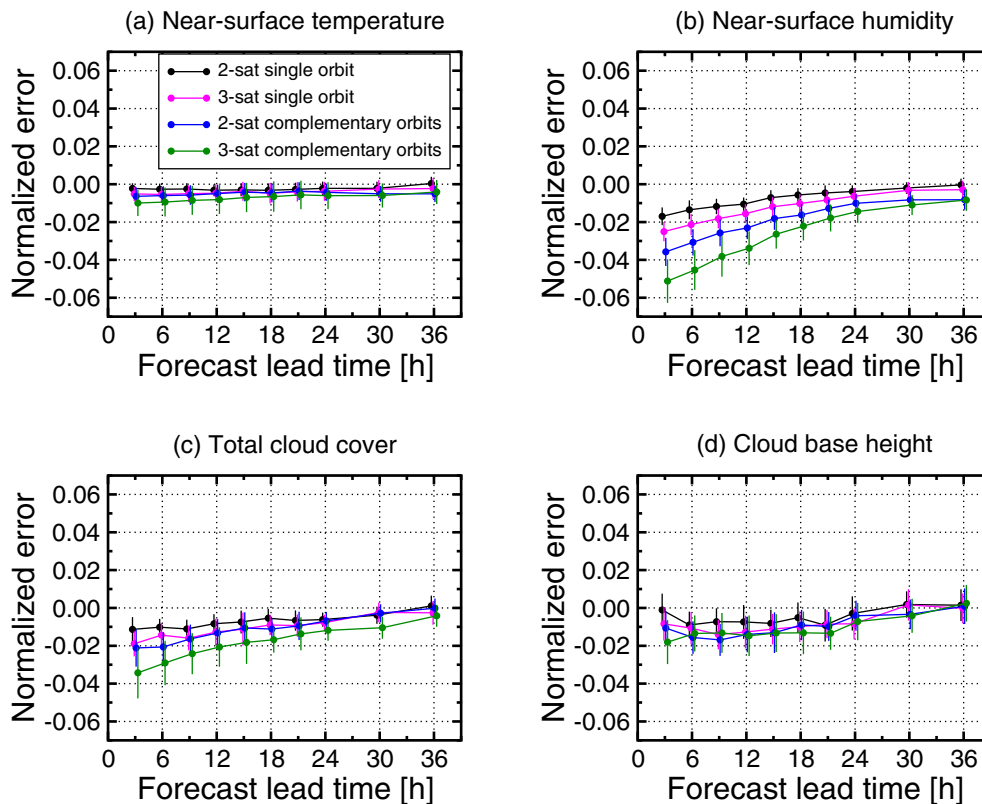


FIGURE 8 As Figure 6, but only for the MetCoOp settings in winter and highlighting the various experiment runs: two- and three-satellite runs of the single-orbit scenario (black and magenta, respectively) and two- and three-satellite runs of the complementary orbits scenario (blue and green, respectively).

in Figure 9. All of the results presented here represent the three-satellite run of the complementary orbits scenario as normalized by the one-satellite baseline run. The layout of the forecast parameters is the same as in Figures 6–8. Again, the results against cloud-base height appear noisy and inconclusive. Other parameters show a consistent picture, where the impact in winter is stronger than that in summer. This is especially evident when verifying against screen-level humidity, but the suggestion is the same against screen-level temperature and, in the MetCoOp case, also against total cloud cover. The seasonal variation is particularly large when using the MetCoOp settings, where there are only isolated suggestions of a statistically significant positive impact in the summer run. In the AROME–Arctic settings, the seasonal variation is less than at MetCoOp, but there is still a notable difference in favour of the impact being stronger in winter.

5.2 | Discussion points around the results presented

It is remarkable that the impact of microwave radiance assimilation appears relatively strong in the verification against surface-based observations and is much more vague when verifying against radiosonde data. The sounding channels used here are primarily sensitive to mid- to upper-tropospheric temperature and humidity and they

are not thought to influence the NWP model's surface properties through any direct mechanism, although Randriamampianina *et al.* (2021) also reported a relatively strong impact at surface level in the AROME–Arctic domain in winter. We attribute this discrepancy primarily to the number of available radiosonde data being insufficient for proper statistical verification. The reasonably smooth scores, such as those presented in Figure 8, that is, those obtained from the surface-based verification in the MetCoOp domain, represent data collected from 600 to 1000 observing stations that each report at least once per three hours over the course of the full six-week evaluation time period. The number of radiosonde data included in the verification is much lower: there are only 20–30 regularly reporting stations inside the MetCoOp domain and most of them only report once per 12 hours. The consequence is that the scores are prone to jump erratically from one lead time to another and the confidence intervals are wide, making it difficult to draw firm and statistically significant conclusions. The verification against radiosondes is weakened further by the reduced representativeness associated with the data being treated as point observations taken at the time and place of the radiosonde launch. In reality, the measurements are taken along the trajectory of the balloon.

The interpretation discussed above is supported by data fit comparisons against independent satellite-based observations, which indeed suggest a considerable impact

FIGURE 9 As Figure 6, but including the various domain–season combinations. Black and magenta lines represent the MetCoOp winter and summer runs, respectively. Similarly, blue and green lines represent the AROME–Arctic winter and summer runs, respectively.

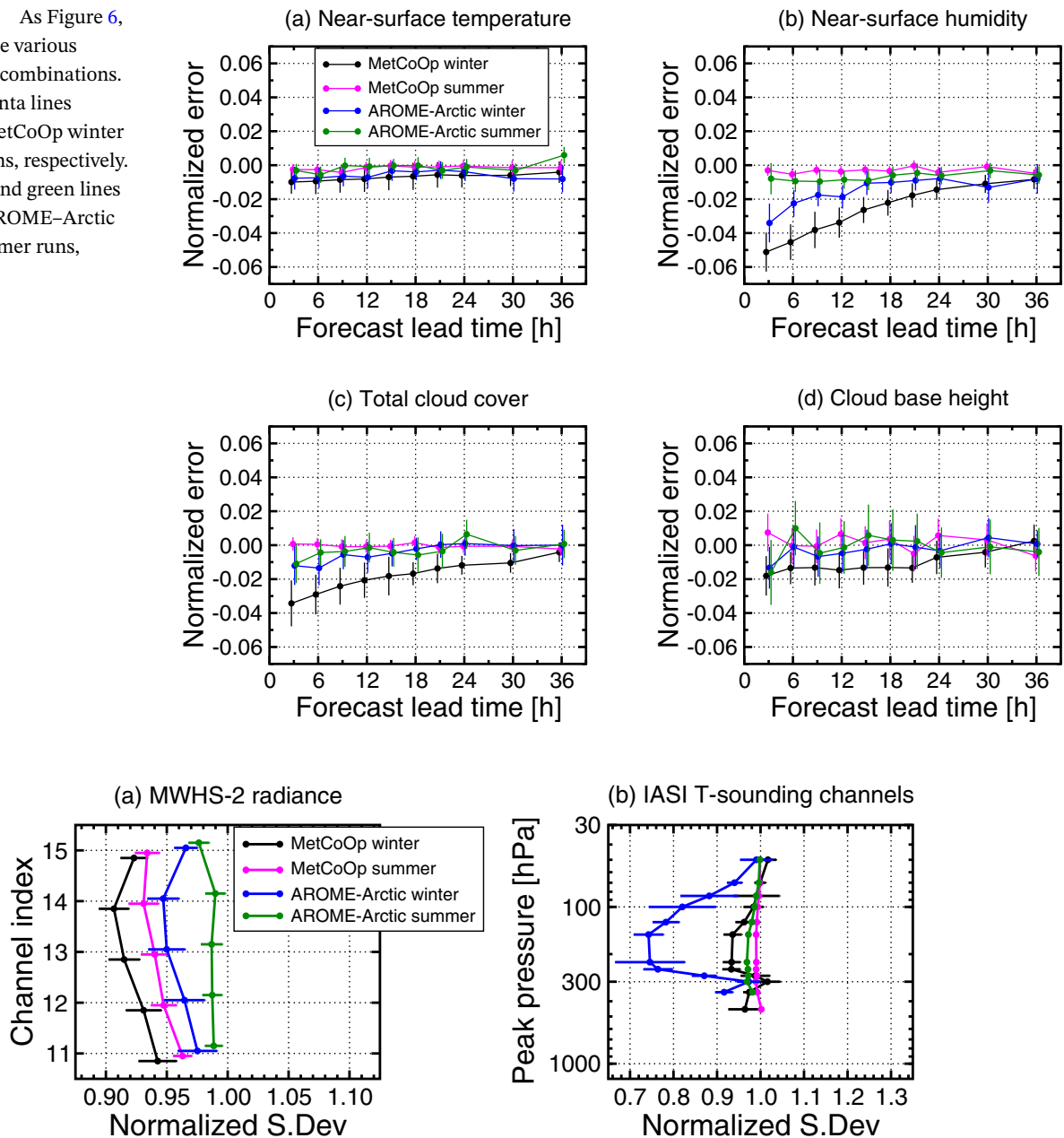


FIGURE 10 The standard deviation of the observation minus background departure in the three-satellite run of the complementary orbits scenario, normalized by the value in the one-satellite baseline run, for (a) humidity-sounding channels of MWHS-2 and (b) temperature-sounding channels of IASI. Values less than unity indicate a data fit improvement from the use of *Metop-B* and *NOAA-19* microwave sounders. The bars indicate the 95% confidence intervals. Black, magenta, blue, and green lines represent the MetCoOp winter, MetCoOp summer, AROME–Arctic winter, and AROME–Arctic summer runs, respectively.

on tropospheric temperature and humidity. Figure 10 shows the baseline-normalized standard deviation of the observation minus background departure for humidity-sounding channels of MWHS-2 (Figure 10a) and temperature-sounding channels of the Infrared Atmospheric Sounding Interferometer (IASI; Figure 10b). In both cases, the normalized standard deviation tends to be less than unity and thus indicates a positive impact

from the inclusion of the microwave sounders of *Metop-B* and *NOAA-19*. Similarly to Figure 9, the impact appears stronger in winter than in summer. In the AROME–Arctic winter run, the IASI data fit suggests a particularly strong impact on temperature near the tropopause level. This prominent impact illustrates the large magnitude of stratospheric forecast errors in the Arctic winter and the very limited availability of radiosonde observations to constrain

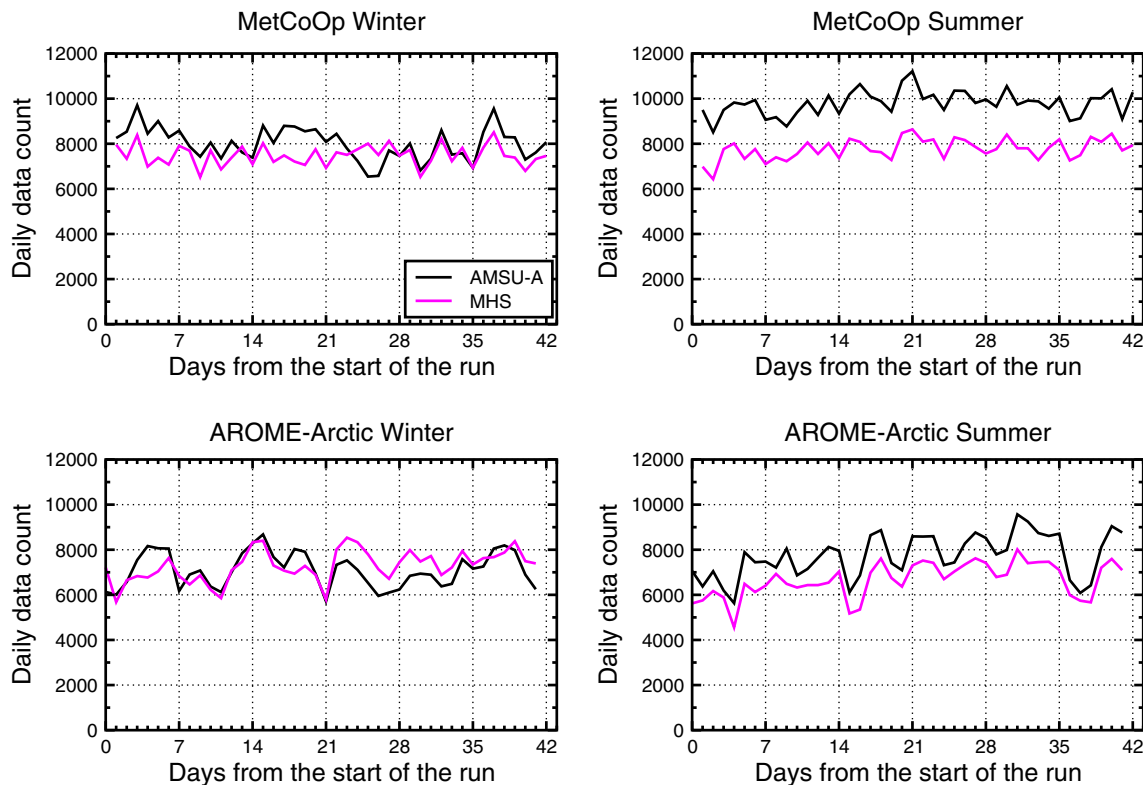


FIGURE 11 Number of assimilated data per day from the *Metop-B* and *NOAA-19* AMSU-A (black) and MHS (magenta) instruments in the three-satellite runs of the complementary orbits scenario when using the MetCoOp settings in winter (top left), MetCoOp settings in summer (top right), AROME–Arctic settings in winter (bottom left), and AROME–Arctic settings in summer (bottom right). The numbers shown include all channels.

these errors specifically inside the AROME–Arctic domain.

The accumulation of the impact in the complementary orbits scenario is consistent with Duncan *et al.* (2021), who demonstrated the incremental benefit of multiple satellites in observing-system experiments using the global NWP system of ECMWF. Also, the EDA-based study of Lean *et al.* (2025) presented a qualitatively similar behaviour in the context of hypothetical constellations of small satellites placed in complementary orbits.

There is a seasonal dependence, such that the impact of satellite data appears far stronger in winter than in summer, and this result holds in both the MetCoOp and AROME–Arctic domains. The result is in agreement with the study of Randriamampianina *et al.* (2021), who also applied the AROME–Arctic NWP system framework, although their data assimilation system was based on 3D-Var and the HARMONIE–AROME reference was older than in our case. Given that the data are still assimilated only in clear-sky conditions, which occur more frequently in summer, one might expect to see the opposite behaviour (i.e., stronger impact in summer). The daily counts of assimilated AMSU-A and MHS data in the three-satellite runs of the complementary orbits scenario

are shown for reference in Figure 11. While the data count of MHS (magenta lines) is at approximately the same level regardless of the season, that of AMSU-A (black lines) indeed confirms the expectation of more data being assimilated in summer. From the forecast impact point of view, this is counterintuitive. The behaviour can perhaps be understood by considering the typical variation of meteorological circumstances over the course of a year at high northern latitudes. In winter, the weather is dominated by baroclinic synoptic-scale activity such as fronts and low-pressure systems. Mesoscale convective cells play only a minor role in winter. In summer, convective events are common and the influence of baroclinic activity on synoptic scales tends to be relatively small (though still significant at times). A possible interpretation is that the data assimilation methods as implemented in the HARMONIE–AROME reference are more effective at handling synoptic rather than convective scales. In principle, the grid resolution and the non-hydrostatic dynamical core of the NWP system would allow for explicit description of convection. However, the response of the data assimilation system is largely determined by the correlation lengths assumed in the background-error statistics. The data assimilation systems applied in this study each

apply a time-constant background-error covariance matrix with error correlation lengths that are arguably more representative of synoptic-scale features than convective cells. An alternative (or complementary) interpretation is that the existing network of verifying surface-based and radiosonde observations is not truly capable of capturing genuine forecasting system improvements on convective scales.

The seasonal variation in the impact of microwave sounder data in the Arctic, as reported in Randriamampianina *et al.* (2021) and confirmed in this study, is in fact opposite to what has been reported in the context of the global NWP system of ECMWF before. According to Lawrence *et al.* (2019), the relative impact of microwave sounders is greatest during Arctic summer rather than winter. Given the more advanced data assimilation, including flow-dependent modelling of background errors and the ability to use cloud- and precipitation-affected microwave sounder data, the variations in the impact of satellite data in the ECMWF system may be driven by completely different processes compared with the present study. The interpretation of Lawrence *et al.* (2019) is that the impact of microwave data varies primarily because of reduced capability to make use of data over snow and sea ice. This interpretation does not seem so relevant in the context of our study, especially when considering that we estimate surface emissivity dynamically and consequently assimilate all sounder channels over all surface types.

We have concluded the season to be the most important predictor for the impact of microwave sounder data. However, substantial inter-domain differences remain even when the impact evaluations are compared within each season. Therefore, it is worth bringing the known system differences up for discussion. At least the following aspects may be relevant when the MetCoOp and AROME–Arctic settings are considered.

1. The specification of the background-error statistics is different. Specifically, the standard deviation of the assumed background error is of the order of 50%–70% larger in the AROME–Arctic setup than at MetCoOp. There are no differences in the specification of observation-error statistics, which implies that the analysis will draw relatively more towards observations at AROME–Arctic than at MetCoOp. Nevertheless, it remains unclear what implications this difference has on the extraction of meteorological information from the data.
2. The diurnal evolution of the satellite data availability and usage is surprisingly different in the two systems. At MetCoOp, the daily dose of data from each polar orbiter consists of descending-node overpasses

at two consecutive analysis times and ascending-node overpasses at another two consecutive analysis times. In between the descending and ascending nodes, there is one analysis time that sees no data. The AROME–Arctic domain is further north and sees many more overpasses, so that data from a given satellite may be used at up to five consecutive analysis times. Consequently, there is relatively little benefit from the third orbital plane: even with just two orbital planes, some satellite data will be available for the assimilation at all times. At MetCoOp, or more generally in similar convective-scale models at lower and midlatitudes, not all analysis times can be covered by two orbital planes alone, so the third orbital plane is truly complementary.

3. The AROME–Arctic domain suffers from a particularly poor coverage of synoptic and radiosonde observing stations, and therefore the verification scores are inevitably less reliable than those at MetCoOp. The situation is worsened further by having the majority of the observing stations near the edges of the domain and generally having only a few stations located outside the Scandinavian peninsula.

5.3 | Interpretation in the context of the future *EPS-Sterna* constellation

The results presented above provide solid ground, such that we can expect the *EPS-Sterna* constellation to make a significant boost when it comes to the numerical prediction of near-surface temperature, humidity and cloud cover. The benefit will be greatest in the prediction of humidity and cloud cover at lead times less than 24 hours. We expect the constellation impact to be far greater in winter than in summer. In order to derive a quantitative estimate, we make a series of assumptions, as follows.

1. The impact from a single microwave-sounding satellite is similar regardless of whether the sounding technology relies on ATMS, the combination of AMSU-A and MHS, or the AWS microwave sounder.
2. The one-satellite baseline run is a reasonable representation of a state-of-the-art limited-area NWP system at the time when the *EPS-Sterna* constellation becomes operational.
3. The three-satellite run of the complementary orbits scenario is a reasonable representation of a state-of-the-art limited-area NWP system that assimilates microwave sounding data from two AWS-like satellites that are placed in mutually complementary orbital planes.
4. Doubling the number of AWS-like satellites will strengthen the constellation impact by 50%.

5. Yet another 50% increase in the number of AWS-like satellites will strengthen the constellation impact by another 25%.

The first assumption above implies that the new AWS sounding channels at 325 GHz are not expected to add considerably to the impact on NWP. In the case in which this is not a realistic expectation, the quantitative estimate here will fall somewhat short of the real impact. Furthermore, we note that, even if the assumptions are valid, this reasoning will only provide an estimate of the impact of six satellites placed in two complementary orbital planes. One might expect to gain more impact from the real *EPS-Sterna* constellation, where the six satellites are placed in three rather than two orbital planes. Therefore, our reasoning might again lead to a slight underestimation of the real impact. For the sake of argument, we have no choice but to ignore these inconsistencies for the time being.

The assumptions presented above add up to an estimate that the constellation impact may be up to 80%–90% stronger than the impact we obtain in the three-satellite run of the complementary orbits scenario. In terms of numbers, this would imply up to around 5%–10% reduction in the forecast RMSE of cloud cover and humidity and up to 2%–3% reduction in the forecast RMSE of temperature. These numbers are in broad agreement with the OSSE-based estimates presented in Guedj *et al.* (2023) and Rivoire *et al.* (2024). It needs to be emphasized that the impact will be strongly seasonally dependent, such that the greatest impact will occur during the boreal winter season.

The crude nature of the assumptions listed above means that the quantitative estimate provided comes with considerable uncertainty. As an example, it is questionable whether the forecasting-system performance of the one-satellite baseline system used in this study is perfectly representative of that of a future operational regional NWP system. Furthermore, it is unclear how the operational use of satellite data in the regional systems will evolve in the next few years, and this evolution will potentially alter the capability to extract meteorological information from the measurement data. Particularly in the area of using cloud-affected radiances through the so-called all-sky assimilation route (Geer *et al.*, 2018; Zhu *et al.*, 2019; Chardon-Legrand *et al.*, 2026), the probability of operational implementation is high and the potential implications also include a considerably enhanced impact from the *EPS-Sterna* constellation.

6 | CONCLUSIONS

We have run a series of 4D-Var assimilation experiments in regional convective-scale NWP systems that are similar

to operational setups used at high northern latitudes in Europe. The experiments are used to evaluate the present impact of the assimilation of microwave-sounder radiance data from the currently operated polar-orbiting satellites, and the results are interpreted in the context of the future impact that can be expected from assimilating data from the six satellites of the *EPS-Sterna* constellation.

The forecast impact from the microwave-sounding radiance assimilation displays a considerable seasonal dependence, such that it is far stronger in winter than in summer conditions. When verifying against in situ measurements, the impact is most clearly visible in the forecast of near-surface humidity and cloud cover, but there is also a significant impact in the near-surface temperature and mean sea-level pressure. The upper-air verification scores computed against radiosonde data are generally inconclusive in the samples obtained in this study.

The impact from the satellite data is evaluated in two alternative scenarios, where additional satellites are brought either into orbital planes complementary to each other or into a single orbital plane. The forecast impact in the former case is approximately twice as large as in the latter. Furthermore, the impact from bringing in two new satellites is approximately 50% larger than from bringing in only one.

By making certain assumptions and approximations, we have derived a quantitative estimate of the future *EPS-Sterna* constellation impact. At forecast lead times less than 24 hours, the projected constellation impact amounts to a 5%–10% reduction in the forecast RMSE in near-surface humidity and cloud cover in winter. In the case of near-surface temperature, the expected RMSE reduction is up to 2%–3% in winter. The expected forecast-error reductions are considerably smaller in summer.

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CONFLICT OF INTEREST STATEMENT

The authors have no competing interests to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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