

Impact of Mode-S Enhanced Surveillance Weather Observations on Weather Forecasts over the MetCoOp Northern European Model Domain

MAGNUS LINDSKOG,^a ROOHOLLAH AZAD,^b SIEBREN DE HAAN,^c JESPER BLOMSTER,^a AND MARTIN RIDAL^a

^a *Swedish Meteorological and Hydrological Institute, Norrköping, Sweden*

^b *Norwegian Meteorological Institute, Oslo, Norway*

^c *Koninklijk Nederlands Meteorologisch Instituut, De Bilt, Netherlands*

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ABSTRACT: Meteorological Cooperation on Operational Numeric Weather Prediction (MetCoOp) is a northern European collaboration on operational numerical weather prediction based on a common limited-area, kilometer-scale ensemble system. The initial states of this model are produced using a three-dimensional, variational, data assimilation scheme utilizing a large number of observations from conventional in situ measurements, weather radars, global navigation satellite systems, advanced scatterometer data, and satellite radiances. Since 2019, the MetCoOp system was enhanced by utilization of observations based on selective mode (Mode-S) enhanced surveillance (EHS) reports that are broadcast by aircraft in response to interrogation from air traffic control radar. These observations, obtained from the European Meteorological Aircraft Derived Data Center, are used to derive indirect information of atmospheric wind speed and temperature. The use of these observations compensated for the considerably reduced number of direct aircraft observations encountered as an effect of the COVID-19 pandemic. The MetCoOp observation handling system is described, with emphasis on Mode-S EHS data. The quality of these observations is evaluated, and we show that they are suitable to be used in MetCoOp data assimilation. The impact on average forecast verification scores of the additional Mode-S EHS data is slightly positive. The benefit of using Mode-S EHS was demonstrated for an individual case and also a demonstration of utilizing the Stockholm Arlanda receiver data in assimilation has been performed.

KEYWORDS: Aircraft observations; Numerical analysis/modeling; Regional models

1. Introduction

The Meteorological Cooperation on Operational Numeric Weather Prediction (MetCoOp) kilometer-scale regional numerical weather prediction (NWP) system is used to predict the future state of the atmosphere over a limited geographical area (Fig. 1) by using a numerical weather forecast model. The atmospheric state is represented by a number of variables defined on discrete grid points. The model starts from an initial state and simulates how the atmosphere evolves forward in time. Some processes take place on scales that cannot be explicitly resolved by the model and are accounted for through various parameterizations. The data assimilation (DA) produces the most optimal estimate of the true initial state, given the estimated uncertainties, by optimally blending observations with a forecast from the atmospheric model. It was realized early on by Lorenz (1965) that the forecast quality is strongly dependent on an accurate description of the initial state and, consequently, on the capability of the DA system. A regional model uses lateral boundary condition, usually in the form of forecasts from a global NWP system. The initial state is most often produced by a DA procedure (Kalnay 2002). A kilometer-scale regional NWP system, including DA, utilizes observations providing fine-scale information of the initial state to produce frequently updated detailed forecasts, up to a range of two days or so for most systems. An important challenge for the forecasting system is the ability to

capture rapidly developing, high-impact weather situations. Improved regional forecasting capability is important in a wide range of areas. Much of high-impact weather is associated with mesoscale phenomena. These can be well captured by a kilometer-scale model, provided the initial state is properly specified. Therefore, an additional source of mesoscale data might be of great interest.

In a number of studies, the use of various types of aircraft-based observations (ABOs) has been proven important for the quality of weather forecasts. Various forecast sensitivity approaches have demonstrated the importance of ABO observations in global modeling systems (Cardinali 2009; Lorenc and Marriott 2013; Langland and Baker 2004; Buehner et al. 2018). In addition, to confirm the importance of ABOs for global modeling, several observation system experiments (OSEs) have been carried out (Bouttier and Kelly 2001; Bormann et al. 2019; Lawrence et al. 2019). Also, for regional systems, several OSEs and impact studies (Amstrup 2008; Benjamin et al. 2010; Graham et al. 2000; Moninger et al. 2010; James et al. 2020; Randriamampianina et al. 2021) have been conducted. Results are pointing to the importance of ABOs. A comprehensive overview of the use and impact of ABO in NWP systems is given in Petersen (2016) and Petersen et al. (2016).

The most commonly used type of ABO observation is the global Aircraft Meteorological Data Relay (AMDAR) observing system. This observing system was initiated by the World Meteorological Organization and its members more than 30 years ago, in cooperation with the aviation industry. The COVID-19 pandemic resulted in a reduced number of

Corresponding author: Magnus Lindskog, magnus.lindskog@smhi.se

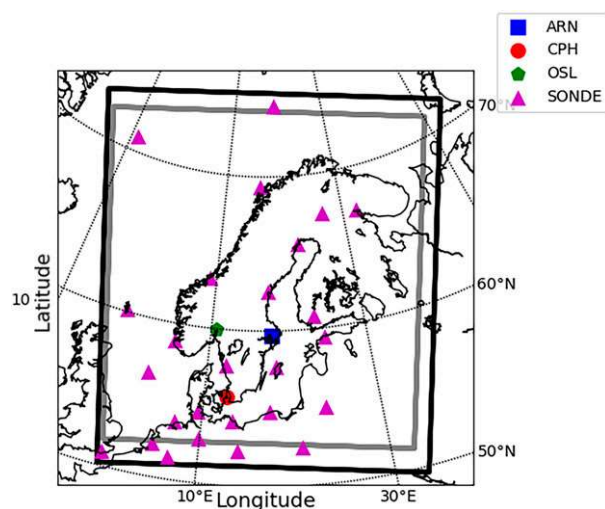


FIG. 1. Horizontal extent of operationally used MetCoOp domains before (gray outline) and after (black outline) domain extension. The three Mode-S EHS receivers of Copenhagen Kastrup, Oslo, and Stockholm Arlanda are marked with a red circle, a green pentagon, and a blue square, respectively. Magenta triangles indicate locations of radiosonde stations in the domains.

available AMDAR observations from March 2020 and then a gradual recovery. Only recently have flight numbers started to return to normal (Dube 2023).

A new type of ABO has become available during the past decade via direct tracking of aircraft by air traffic control radars (de Haan 2011; Strajnar et al. 2015). These observations, referred to as Mode-S (since air traffic control operates in selective mode), represent an increase in the volume of aircraft observations. In some air traffic control (ATC) regions, Mode-S enhanced surveillance (EHS) reports are broadcast by aircraft in response to interrogation from ATC radar. These can be processed to derive wind and temperature data (de Haan 2011). There is also a possibility to obtain meteorological information by ATC radar interrogation of a dedicated meteorological data register, called Meteorological Routine Air Report (MRAR). MRAR provides direct measurements of temperature and wind, but the information is only returned by a small fraction of aircraft. In recent years, the Royal Netherlands Meteorological Institute (KNMI) has set up the European Meteorological Aircraft Derived Data Center (EMADDC). EMADDC is collecting, processing, and distributing Mode-S EHS data for use in NWP models. During processing, several quality checks are performed, such as consistency with time in position and physical consistency of raw measurements (de Haan et al. 2023, unpublished manuscript).

The quality of Mode-S EHS data and its impact on assimilation into limited-area NWP systems have been addressed in several previous studies. The findings of different studies regarding accuracy of Mode-S EHS observations were summarized by Mirza et al. (2016). They focused on comparison with other types of observations and NWP models. A more recent study was carried out by Li (2021), using the Met Office hourly 4D-Var framework. The overall finding was that Mode-S EHS wind observations do have

a quality similar to AMDAR and with small bias. The quality of Mode-S EHS temperature observations was reported to be worse than that of AMDAR temperature observations. This is associated with the limiting precision of airspeed and Mach number used for derivation of Mode-S EHS temperatures. An improved method for derivation of temperatures for Mode-S EHS observations has more recently been developed (Sondij 2020; de Haan et al. 2022). Positive impact on forecast up to +3-h or +6-h forecast lead times from assimilation of Mode-S EHS observations has been reported for regional NWP systems (de Haan and Stoffelen 2012; Li 2021).

Here, we use Mode-S EHS data processed by EMADDC in a northern European modeling setup configured for use in MetCoOp. For two different periods, we investigate the use of Mode-S EHS in the MetCoOp modeling framework. The components of the limited-area forecasting system are the subject of section 2, with special focus on the handling of Mode-S EHS data. In section 3, the experimental design is described, followed by a presentation of results in section 4. Concluding remarks are presented in section 5, together with a future outlook.

2. Air traffic control data and processing

a. General system and dataflow

Modern aircraft carry sensors to measure the Mach number (using a pitot static probe) and air temperature. An EHS ATC radar interrogates all aircraft in sight in Mode-S, to which the aircraft replies with a message containing magnetic heading, airspeed, and Mach number. The messages can be collected by ATC or by local receivers. These raw data can be processed to obtain wind and temperature data, which are directly useful for meteorological aviation applications. Furthermore, assimilating these additional observations in numerical weather prediction models can improve the short-range forecasts. The KNMI-lead EMADDC is collecting, processing, and disseminating Mode-S EHS data for use in NWP. EMADDC has developed algorithms to derive calibrated and quality-controlled meteorological observations. The process consists of quality control of Mode-S EHS data, conversion of magnetic to true heading, and aircraft-specific corrections for heading and temperature. For the latter, a dynamic database, updated daily, of individual aircraft heading and temperature corrections is used (de Haan et al. 2023, unpublished manuscript). In short, temperature is deduced from the downlinked Mach number and airspeed. The wind vector is determined by subtracting the ground vector with the air vector. See de Haan (2011) for more details.

For several years, raw Mode-S EHS data have been sent to EMADDC from the Copenhagen Kastrup Airport ATC center in Denmark and from a local receiver in Oslo. More recently, a local receiver has been installed at Arlanda Airport, close to Stockholm, Sweden, and a data stream was set up to send the Mode-S EHS raw data to EMADDC. These three receivers are marked with a red circle, a green pentagon, and a blue square, respectively, in Fig. 1. In addition to Denmark, Norway, and Sweden, many others, including the Netherlands, are sending data to EMADDC for processing and dissemination. The obvious feature of Mode-S EHS data is the high data density. This

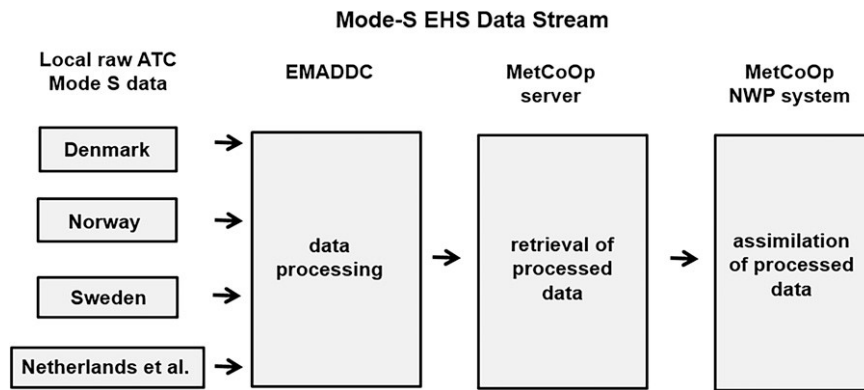


FIG. 2. Data flow for Mode-S EHS used in the MetCoOp NWP system.

is because of the high frequency of reports (up to every 4 s) and partly because almost all commercial aircraft (except, e.g., old aircraft) have to respond to the interrogations.

The MetCoOp Mode-S EHS observation data flow is outlined in Fig. 2. Local, raw, ATC Mode-S EHS data are sent every 5 min to EMADDC, which processes the data and produces files containing derived wind and temperature data in 15-min time slots. Prior to assimilation, these derived data files are fetched from EMADDC to the server to be used in the MetCoOp NWP system. The latency of this procedure is on the order of 15 min, which is remarkably short and valuable for NWP-based nowcasting systems.

Since Swedish air traffic management does not publicly share their data, the Stockholm Arlanda receiver is important for the coverage of Mode-S EHS data over Sweden. Originally, the Oslo receiver was providing the only source of Mode-S information from Norway. Now, the Norwegian Defense Research Establishment (FFI) also provides data from Norway. The local receiver at Stockholm Arlanda and its functionality are described in more detail below.

The EMADDC processing procedure for deriving weather information from the aircraft observations was described by de Haan (2011). Derivation of wind vector $\mathbf{V}$ can, for a reported flight level, be obtained from the difference in heading vector (aircraft speed relative to air) $\mathbf{V}_i$ and the ground track vector (aircraft speed relative to ground) $\mathbf{V}_g$. The true airspeed vector $\mathbf{V}_i$ is calculated from the reported airspeed V_i (m s^{-1}) and heading ($^\circ$). The ground track vector $\mathbf{V}_g$ is calculated from the reported groundspeed V_g (m s^{-1}) and track angle α_g ($^\circ$). The airspeed wind vector $\mathbf{V}$ (m s^{-1}) is given by

$$\mathbf{V} = \mathbf{V}_g - \mathbf{V}_i, \quad (1)$$

where a correction is applied to account for the fact that the Mode-S reported directions are with respect to the magnetic north, rather than to the true north. Flight level is defined using the International Standard Atmosphere relationship between pressure and pressure altitude (de Haan 2011). The air temperature T can be calculated by

$$T = \frac{1}{\gamma R_d} \frac{V_i^2}{M^2}, \quad (2)$$

where T is reported in kelvin, V_i is reported in meters per second, R_d is the gas constant of dry air, and $\gamma = c_p/c_v$ is the ratio of specific heats. The Mach number M has no dimension. The limited precision of reported V_i and M hampers the quality of derived temperatures; therefore, an improved procedure (Sondij 2020; de Haan et al. 2022) has recently been introduced.

b. Stockholm Arlanda site and technical description

Installation of a local receiver requires considerable logistical and technical considerations. Such considerations and solutions applied are described in detail below, as an illustrative example, for the Stockholm Arlanda receiver. There were some minor differences in choice of technical solutions at the Oslo site that we will not cover in detail. The reason for choosing to provide more detailed technical information regarding the Stockholm Arlanda receiver is because we were personally involved in the installation.

The site for the local receiver was chosen to have as much free line of sight as possible toward the approach and departure routes at the airport. The antenna to the receiver is mounted on the roof of a 20-m-tall building residing next to one of the taxiways (Fig. 3). Prior to installing the receiver, initial tests were carried out with a modified software-defined radio receiver. Results showed that at this location it was possible to receive Mode-S messages from aircraft on approach to runway 26 and departure from runway 19L and from aircraft on the ground at the airport. However, there were some sectors where reception was weaker because of hangars blocking the line of sight, particularly toward the middle part of runway 01L/19R.

A relatively cost-effective solution was selected, which is a setup of a Mode-S Beast receiver together with an outdoor antenna (tuned for the 1090-MHz band) and a Raspberry Pi single-board computer to handle data transfer back to the Swedish Meteorological and Hydrological Institute (SMHI).

The Mode-S Beast has been proven to have good decoding capability of the data frames it receives and is also already in operational use by the Met Office (Stone and Pearce 2016). Under good circumstances it can decode approximately 2000 frames per second (given a baud rate of 3 Mbit s^{-1} for the serial communication). One data frame is one message; however, not all data frames are Mode-S messages. Roughly one-half of the received

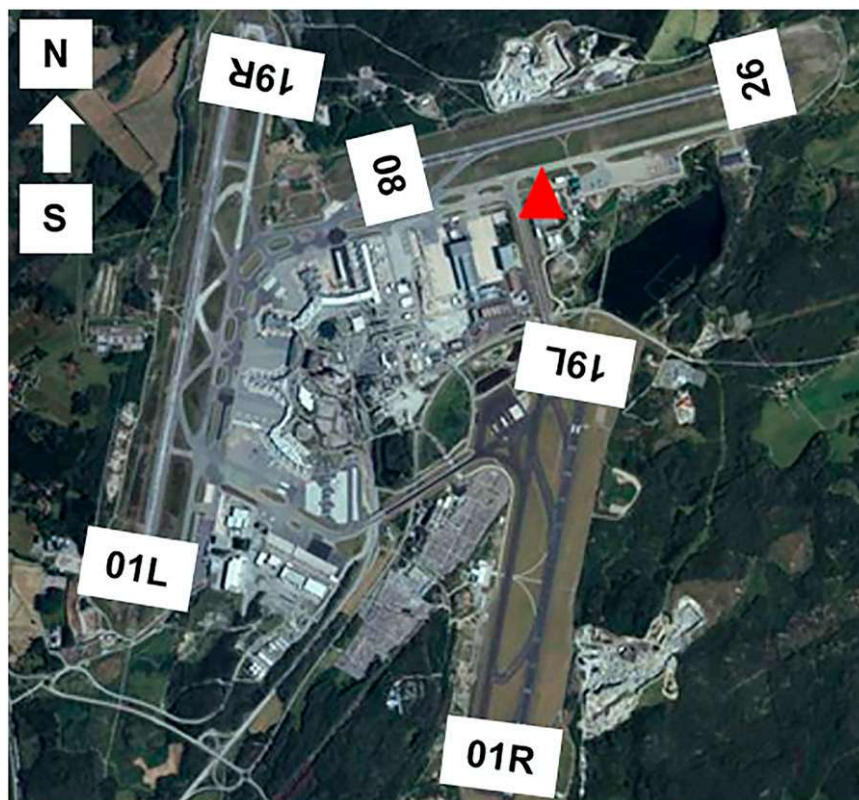


FIG. 3. Arlanda Airport and the location of the receiver (red triangle). White boxes indicate runways.

messages contain no relevant meteorological information. Connected to the Mode-S Beast is an omnidirectional high-gain antenna (+5 dBi) mounted on the roof of the building.

Output from the Mode-S Beast is transmitted over universal serial bus (USB) as serial data. Running on the Raspberry Pi, an inhouse written software program takes care of reading the serial data and converting it to ASCII format. A time stamp is attached to each message. There is also a crude filtering applied at this stage so that all messages shorter than 112 bits are excluded from the generated data files. This filtering effectively reduces the total data volume transmitted from the receiver, and it only filters out messages that do not contain relevant meteorological information. Data are collected in 5-min batches and then transferred via Secure File Transfer Protocol (SFTP) to SMHI and subsequently transferred to EMADDC for processing.

The receiver in Oslo is the so-called Radarscape, which essentially is a Mode-S Beast with a small built-in Linux computer. It is capable of both decoding the data frames sent out by the aircraft and of handling the data transmission of decoded data (the raw Mode-S messages) to a personal computer or server at another location. Like the Stockholm Arlanda receiver, the Oslo receiver uses an omnidirectional dipole antenna, but in addition to the set up at Stockholm Arlanda, it has an antenna amplifier for enhanced signal receiving.

The main difference between the Stockholm Arlanda and the Oslo setups is that the Radarscape offers a more simplified

approach to retrieving the data with fewer parts. In practice, though, the difference is very small and is not related to the retrieval of the data but only to the data transfer. Both of the receivers provide a high frequency of reports (up to every 4 s). The data processing system overview associated with each of these receivers is visualized in Fig. 4.

c. EMADDC evaluation of data sources

The Mode-S registries of an aircraft are actively triggered in the Nordic airspace. The Danish ATC is sharing this information through the Danish Meteorological Institute. These data are labeled dk. The Norwegian data are collected in the airspace around Oslo by a local receiver (no-osl), while in the rest of the Norwegian airspace, Norwegian Defense Research Establishment (no-ffi) provides the data to the EMADDC for processing. The Swedish data (se) are collected using a local receiver at Arlanda Airport, close to Stockholm. Table 1 shows the statistics of these data sources for 2021 when processed by EMADDC, version 2.2, and compared with forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF). The presence of data differs per source; dk data were present all year, whereas Norwegian data became mature and stable with the introduction of no-ffi, which from 7 March 2021 onward distributed data from the Norwegian airspace. The Swedish data came online after the installation of the local receiver in the middle of 2021. The wind speed

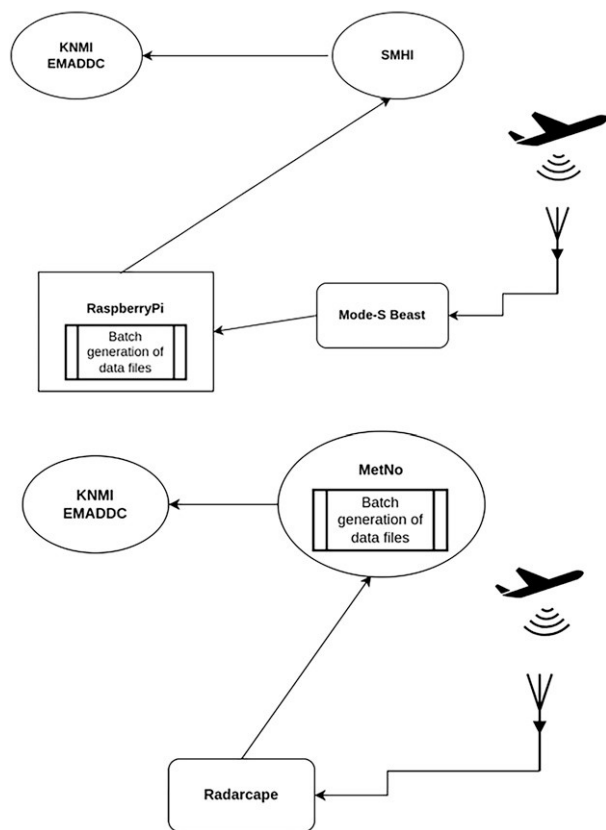


FIG. 4. Overview of the collection, processing, and distribution of data from the (top) Stockholm Arlanda Airport and (bottom) Oslo. The flow goes from the antennas, through the Mode-S Beast/Raspberry Pi (Stockholm Arlanda) or Radarcape (Oslo) via the respective national meteorological institutes SMHI and Norwegian Meteorological Institute (MetNo) and to EMADDC.

bias is slightly positive, and the wind speed standard deviation is around 2.5 m s^{-1} when compared with ECMWF forecasts. The bias in temperature is very small, and the standard deviation is close to 1 K. The small temperature bias is the result of a processing method that uses a temperature correction similar to the method described in [de Haan et al. \(2022\)](#).

The data volumes differ because of the difference in airline activity in the covered area, as can be seen in [Fig. 5](#). The collection areas clearly overlap, but during processing, the observations, which are recorded by multiple radars, are detected

and the redundant data are removed. As reported by [Lange and Janjić \(2016\)](#), the range of each receiver is around 270 km, which is also indicated by [Fig. 5](#). That means that the three receivers in [Fig. 1](#) provide Mode-S EHS data within a range of 270 km from the receivers, in case of existing air traffic.

3. The MetCoOp numerical weather prediction system

a. General system description

MetCoOp is an operational collaboration between the national meteorological weather services of Sweden, Norway, Finland, and Estonia, running a common operational kilometer-scale forecasting system ([Müller et al. 2017](#)). The forecasting system is based on a configuration of A Consortium for Convection-Scale Modeling Research and Development (ACCORD) common modeling system. ACCORD is a consortium of 26 countries in Europe and northern Africa developing advanced, high-resolution weather prediction capability for local areas. The ACCORD forecasting system can be run with different configurations; in MetCoOp, the HIRLAM–ALADIN Research on Mesoscale Operational NWP in Euromed–Application of Research to Operations at Mesoscale (HARMONIE–AROME) is used ([Bengtsson et al. 2017](#)). MetCoOp applies HARMONIE–AROME as an ensemble forecasting system. In our study, we use the cy40 and cy43 versions of the MetCoOp HARMONIE–AROME forecasting system. The northern European model domain used operationally together with cy40 in 2019 is illustrated with a gray frame in [Fig. 1](#). It has 900×960 horizontal grid points with a grid size of 2.5 km, and 65 vertical model levels, extending from roughly 12 m above the ground up to approximately 33 km (10 hPa). Our focus is thus on the troposphere, and there are plans to further increase the number of vertical levels to 90 as a first step. In 2020 and thereafter, the modeling system was changed to the later version cy43 and the horizontal extent of the domain was slightly extended to 960×1080 horizontal grid points, as illustrated by the black-outlined frame in [Fig. 1](#).

The three main components of this forecasting system are surface DA, upper-air DA, and the forecast model. The system is a continuous data assimilation based ensemble with five members per hour. The ensemble system is run with three independent 3-h data assimilation cycles. Independent means that each “stream” uses its own +3-h forecast as its first guess. These are covering 1) 0000, 0300, 0600, 0900, 1200, 1500, and 2100 UTC; 2) 0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 UTC; and 3) 0200, 0500, 0800, 1100, 1400, 1700, 2000, and 2300 UTC,

TABLE 1. Verification statistics of Mode-S EHS data sources against ECMWF forecasts. Here dk is Danish ATC, no is Norway total, no-osl is Norway Oslo local receiver, no-ffi is Norway FFI, and se is Sweden Stockholm Arlanda local receiver.

Norway source	Period	Wind speed (m s^{-1})			Temperature (K)		
		No.	Bias	Std dev	No.	Bias	Std dev
dk	1 Jan–31 Dec 2021	384.2×10^6	+0.26	2.41	319.8×10^6	+0.07	1.03
no	1 Jan–11 May 2021	12.8×10^6	+0.40	2.61	5.1×10^6	+0.01	0.93
no-osl	11–29 May 2021	0.4×10^6	+0.53	2.62	0.2×10^6	+0.05	0.95
no-ffi	7 Mar–31 Dec 2021	11.4×10^6	+0.29	2.47	7.4×10^6	0.00	1.00
se	7 Jun–31 Dec 2021	14.5×10^6	+0.32	2.52	16.4×10^6	+0.03	1.03

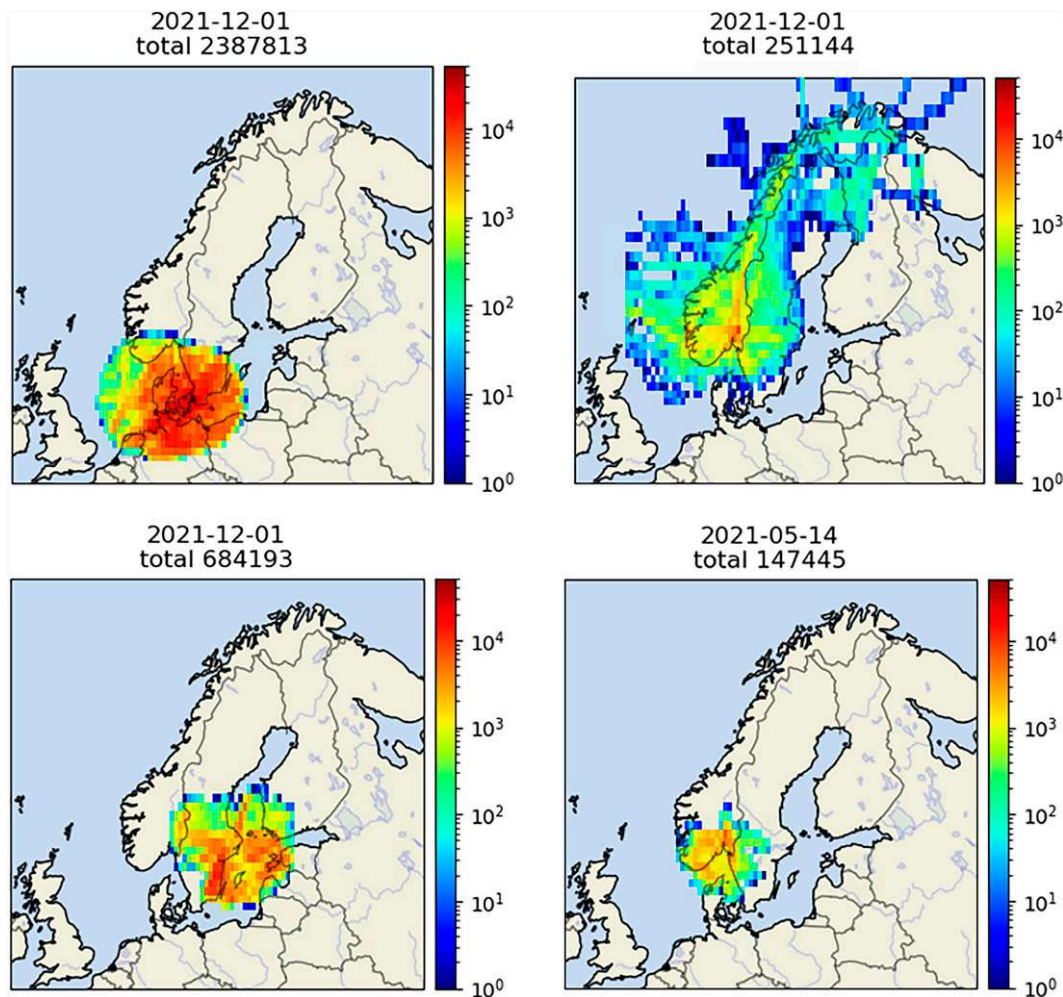


FIG. 5. Data coverage for the particular days (1 Dec 2021 and 14 May 2021), as derived from (top left) Danish ATC, (top right) Norwegian Defense Research Establishment, (bottom left) Stockholm Arlanda, and (bottom right) the Oslo local receiver. The color scale indicates the number of observations in boxes of 0.5° .

respectively. This means that over 6 h, 30 ensemble members can be obtained (Andrae et al. 2020). The observation cutoff time is 1 h and 15 min. The reason for having three separate, independent, 3-h DA cycles rather than one 1-h DA cycle containing all hours is to avoid spurious model spinup of dynamical and physical processes still on-going after 1 h of model forecast, but they have disappeared after 3 h of forecasting. The three independent DA cycles differ only in the times of DA. In the parallel data assimilation experiments described in section 4, for simplicity, only cycling covering the eight data assimilation cycles 0000, 0300, 0600, 0900, 1200, 1500, and 2100 UTC was used.

A detailed description of the forecast model setup is given in Seity et al. (2011) and Bengtsson et al. (2017). It is a nonhydrostatic model formulation with a spectral representation of the model state (Bubnová et al. 1995; Bénard et al. 2010). Subgrid-scale parameterization of clouds, including shallow convection, is handled by the eddy diffusivity mass flux (EDMF) originating from de Rooy and Siebesma (2008) and

Neggers et al. (2009). Deep convection is explicitly handled by the model, without parameterization. In the cy40 version of the model, the representation of the turbulence in the planetary boundary layer is based on a prognostic turbulent kinetic energy (TKE) equation combined with a diagnostic mixing length (Cuxart et al. 2000). In the cy43 version, turbulence and vertical diffusion are represented using the so-called HARMONIE with Racmo Turbulence (HARATU) scheme, which is based on a turbulent kinetic energy scheme by Lenderink and Holtslag (2004). The radiative transfer is modeled as described by Fouquart and Bonnel (1980) and Mlawer et al. (1997) for short- and longwave radiation processes, respectively. Surface processes are modeled using the Surface Externalisée (SURFEX) scheme (Masson et al. 2013). Global forecasts provided by ECMWF are used as lateral boundary conditions. These forecasts are run every 6 h with a 1-h output frequency. Global model information is also used to replace larger-scale information in the background state with lateral boundary information (Müller et al. 2017). The idea is to make use of high-quality large-scale information from the ECMWF

global fields, in the MetCoOp analysis. A more refined method, as described by Guidard and Fischer (2008) as well as by Dahlgren and Gustafsson (2012), would be to incorporate the global host model field as one additional term in the cost function to be minimized in the upper-air variational data assimilation described below.

In the surface DA synoptic observations of 2-m temperature, 2-m relative humidity and snow cover are used to estimate the initial state of the soil temperature, soil moisture, and snow field. The DA consists of a horizontal optimal interpolation (Taillefer 2002), which for soil moisture and temperature is followed by a vertical optimal interpolation procedure (Giard and Bazile 2000).

The upper-air DA is based on a three-dimensional variational (3D-Var) approach (Fischer et al. 2005). Many types of observations are assimilated, including conventional in situ measurements [pilot-balloon wind, radiosonde, ABO, buoy, ship, and surface synoptic observations (SYNOP)], global navigation satellite system (GNSS) zenith total delay (ZTD) data, weather radar reflectivity information, and infrared (IR) and passive microwave (PMW) radiances from satellite-based instruments. The IR radiances are sensed by the Infrared Atmospheric Sounding Interferometer (IASI) placed on board the MetOp satellites. PMW radiances are traditionally provided by the Advanced TIROS Operational Vertical Sounder (ATOVS) instrument family, including Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS). In 2020, the DA system was prepared to also utilize data from the Microwave Humidity Sounder-II (MWSH-2) instrument on board the Fengyun polar orbiting satellites (Lindskog et al. 2021) and, more recently (second half of 2021), also Advanced Technology Microwave Sounder (ATMS) from *Suomi NPP* and *NOAA-20* satellites. Background-error covariances are based on a climatological assumption, and their representation is based on a multivariate formulation under the assumptions of horizontal homogeneity and isotropy. They are calculated from an ensemble of forecast differences (Berre 2000; Brousseau et al. 2012). These are produced by ensemble data assimilation (EDA) experiments carried out with the HARMONIE-AROME system. The HARMONIE-AROME EDA uses perturbed observations and ECMWF global EDA (Bonavita et al. 2012) forecasts as lateral boundary conditions. Scaling is applied to the derived statistics to be in agreement with the amplitude of HARMONIE-AROME +3-h forecast errors (Brousseau et al. 2012).

b. Handling of Mode-S EHS in the modeling system

The observation operator H , applied to project the model state on the Mode-S EHS temperature and horizontal wind component observations (u , v) in the zonal and meridional directions, consists of a bilinear horizontal interpolation followed by a linear vertical interpolation. The vertical interpolation is carried out in the logarithm of pressure. Mode-S EHS observations are assumed to be unbiased, so no bias correction is applied. This assumption is for wind observations supported by earlier studies (Mirza et al. 2016; Li 2021). Li (2021) reported a bias of up to 0.5 K for Mode-S EHS temperature observations when a processing method with limiting precision of airspeed

and Mach number is used. The bias with an improved processing temperature method (Sondij 2020) is less studied in previous work, but Table 1 indicates that it is very small. The observation errors of the observations accepted for use in the data assimilation were assumed to have a Gaussian error distribution. These include instrument errors, representativeness errors, persistence errors, errors introduced by the EMADDC processing, and errors in the observation operator.

The presently assumed-error standard deviations are height dependent and for wind components, and vary between 2 m s^{-1} in the lower troposphere and 4 m s^{-1} around the tropopause. The temperature-error estimates vary between approximately 1 K in the lower troposphere to around 2 K close to the tropopause. These initially assumed errors are in the range reported by Mirza et al. (2016). The values will most likely be revised after continuous monitoring in the near future related to updates of the Mode-S EHS processing procedure (e.g., the recently improved temperature processing). The effects of observation-error correlations are alleviated by applying a spatial thinning of data. This thinning is carried out separately for winds and temperatures. For wind components, either both components are kept for assimilation or they are both removed in the thinning. The thinning is carried out separately for each flight and with a horizontal thinning distance of 25 km and a vertical thinning distance of 15 hPa. In the future, using more refined data assimilation systems with improved handling of observation and background-error correlations, including flow dependency, we aim to avoid this thinning. Use of more dense observation data in a proper way would enable more detailed description of initial-state mesoscale features of interest. In comparing the observation-error assumptions with Table 1, it can be seen that the assumption of unbiased Mode-S EHS observations is a reasonable approximation, keeping in mind that ECMWF forecasts cannot be regarded as the ground truth. Wind standard deviations in Table 1 are in good agreement with MetCoOp HARMONIE-AROME assumed statistics. Note that no height dependence is illustrated and that standard deviations in Table 1 contain both observation-error contributions and model-error contributions. Assumed temperature standard deviations can even be slightly more reduced in future versions of the MetCoOp HARMONIE-AROME assimilation system. Except for the differences in assumed observation errors, Mode-S EHS observations are currently treated in the same way as AMDAR observations concerning interpolation, quality control, and thinning.

In addition to the EMADDC quality control procedures, there is also an additional model-based one. Observations affected by gross errors may significantly degrade the initial state and the resulting forecast if not taken into account. Gross errors were identified and removed by a first-guess check. In this check, the background model state $\mathbf{x}_b$ was projected on the observed quantity y_i with the observation operator H . The squared background departure from the i th observation was calculated and the observation y_i was rejected if it did not satisfy the following inequality:

$$\{[H(\mathbf{x}_b)]_i - y_i\}^2 / \sigma_{b,i}^2 > L \times \lambda, \quad (3)$$

where $\lambda = 1 + \sigma_{o,i}^2 / \sigma_{b,i}^2$, L is the rejection limit, H denotes the projection of the model state on observation, and $\sigma_{o,i}^2$ and $\sigma_{b,i}^2$

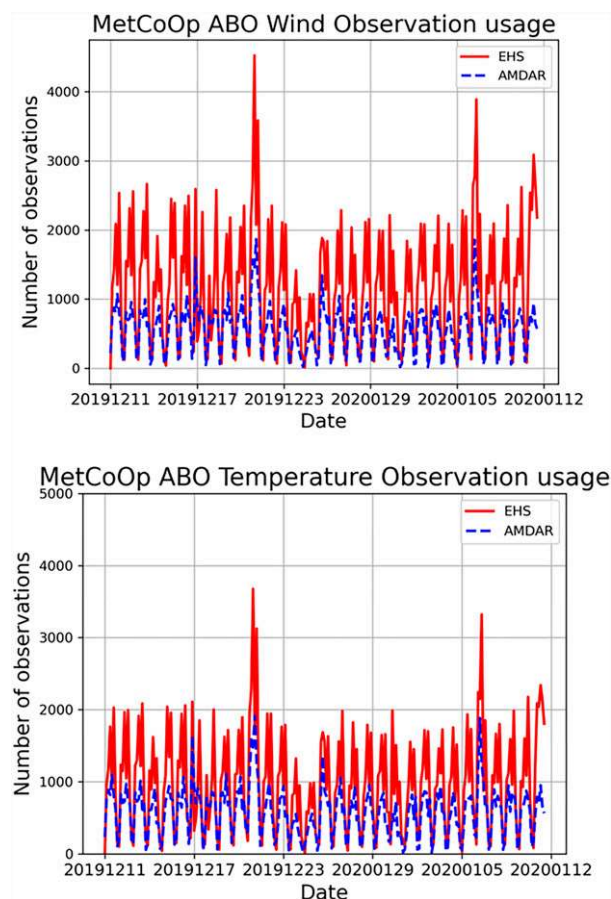


FIG. 6. Time series of the number of assimilated ABO (top) wind and (bottom) temperature observations for period 1 (11 Dec 2019–10 Jan 2020) as a function of assimilation cycle. The solid red curve is for Mode-S EHS, and the dashed blue curve is for AMDAR.

are the standard deviations of the observation error and background error equivalent, respectively. Background-error standard deviations of 0.5–0.8 K were used for temperatures and of 1.0–2.5 m s⁻¹ were used for wind components in the first-guess check. The rejection limit L for Mode-S EHS observations was set to 5. This value was inherited from AMDAR first-guess check and based on when AMDAR observation minus background departure statistics starts to deviate from a Gaussian distribution.

4. Experimental design

The MetCoOp evaluation of Mode-S EHS was done stepwise in two sets of extended parallel experiments. This stepwise introduction was a consequence of extension of the MetCoOp model domain coinciding in time roughly with the introduction of an improved methodology of EMADCC processing and a decision to start first with evaluation of assimilation of Mode-S EHS observations from the receivers located at Copenhagen Kastrup Airport and Oslo, well within the MetCoOp model domain using cy40. When extending the

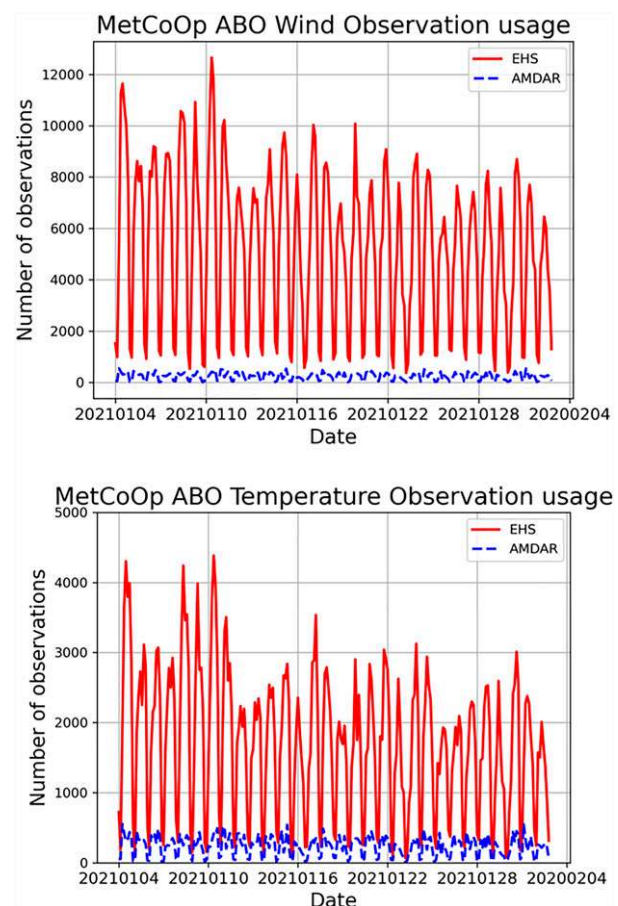


FIG. 7. As in Fig. 6, but for period 2 (4 Jan–3 Feb 2021).

model domain, more receivers processed by EMADCC were providing Mode-S EHS observations within the extended MetCoOp domain. In addition, EMADCC, at that time, had developed and improved processing of air traffic control data resulting in an improved temperature product. The first set of parallel experiments was carried out for the period 11 December 2019–10 January 2020 (hereinafter period 1). For these, we were using, at that time, a preoperational model version (cy40) and domain (gray frame in Fig. 1). The two parallel experiments differed only in the use of Mode-S EHS. CRL40 was a copy of a preoperational version of the (at that time) operational system with operational observation usage as described in section 2c. EHS40 was as in CRL40, but also assimilated Mode-S EHS wind and temperature data from Copenhagen and Oslo local receivers.

The second set of parallel experiments were carried out for the period 4 January–3 February 2021 (hereinafter period 2). We were, again, using a preoperational version of the MetCoOp HARMONIE-AROME system (cy43 this time) over an operational domain (black frame in Fig. 1). CRL43 was a copy of a preoperational version of the (at that time) operational MetCoOp HARMONIE-AROME system with operational observation usage as described in section 2c, except for that no Mode-S EHS data are assimilated. EHS43

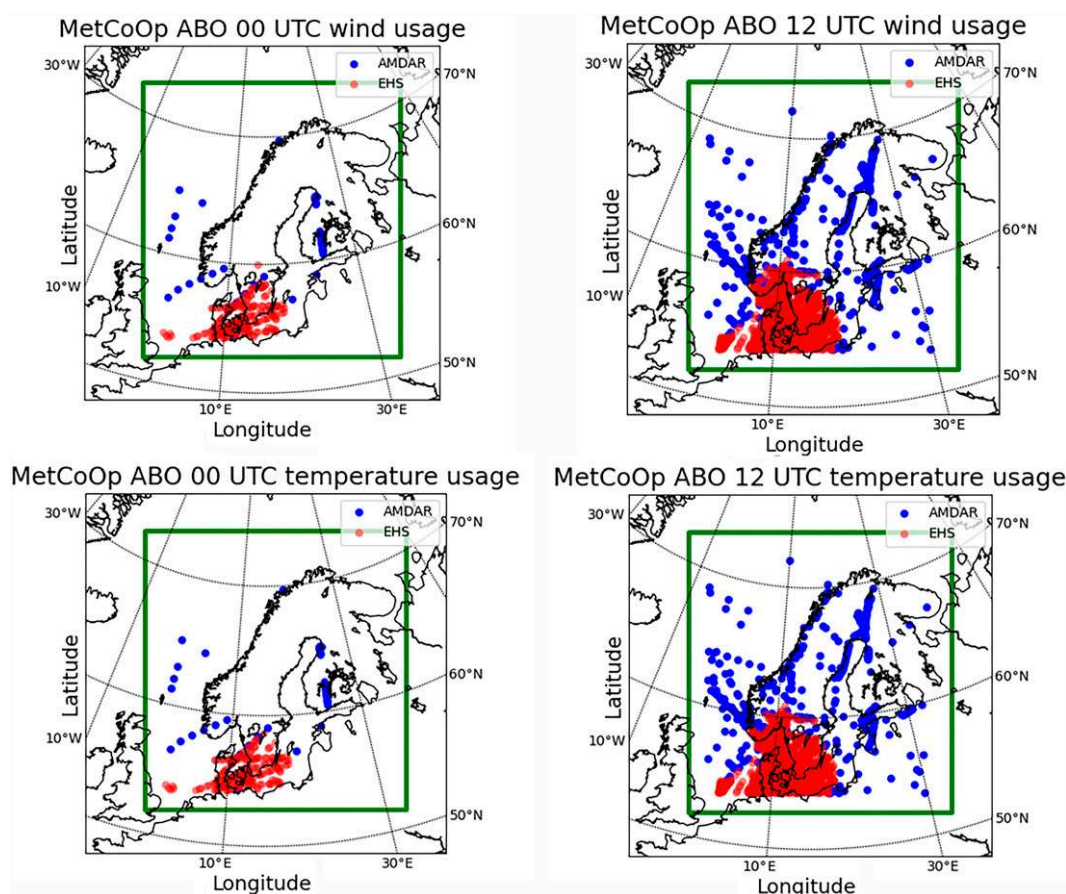


FIG. 8. Spatial coverage of assimilated ABO from (left) 0000 and (right) 1200 UTC 19 Dec 2019 (period 1) for (top) wind and (bottom) temperature observations. Blue dots represent AMDAR observations, and red dots represent Mode-S EHS observations. The green-outlined frame shows the model domain.

was as in CRL43, but also assimilated as well Mode-S EHS wind and temperature data.

In addition to the two extended experiments, a single assimilation-cycle parallel experiment was carried out for a more recent date and with the latest available observations. The experiment was only run for 1 day with the aim to demonstrate the use of Stockholm Arlanda receiver Mode-S EHS data in the MetCoOp HARMONIE–AROME modeling system. The reason for choosing two winter periods from different years was to have similar kind of synoptic weather situations during a pre-COVID-19 period with many AMDAR but fewer Mode-S EHS observations available, and during a COVID-19 period with few AMDAR available and larger fraction of the ABO being Mode-S EHS. Furthermore, the ABOs potential for Mode-S EHS observations to influence the synoptic scale weather systems can be addressed.

5. Results

a. Observation usage

The time series of the total number of assimilated Mode-S EHS and AMDAR wind and temperature observations during

the periods of the first and second parallel experiments are shown in Figs. 6 and 7. Results shown are for each assimilation cycle (eight per day) of the two parallel experiments. Both for AMDAR and Mode-S EHS, there is a clear diurnal variation of the number of observations available for assimilation, with few observations for the 0000 and 0300 UTC cycles. This diurnal variation exists both for temperature and wind observations and for both periods. This is because there are fewer flights during nighttime than during daytime. What is positive is that there are plenty of data in the preconvective or convective time of day, when summertime high-impact weather is most likely to occur. For period 1, the number of assimilated Mode-S EHS observations is roughly twice as many as the number of available AMDAR observations. For period 2, the number of assimilated Mode-S EHS wind observations has increased roughly by a factor of 4 as compared with period 1 and by a factor of 2 for temperature observations. On the other hand, the number of assimilated AMDAR observations was clearly smaller during period 2 as compared with period 1, both for winds and temperatures. This pronounced decrease is an effect of fewer flights taking place during the pandemic situation during period 2, as compared with the prepandemic (or

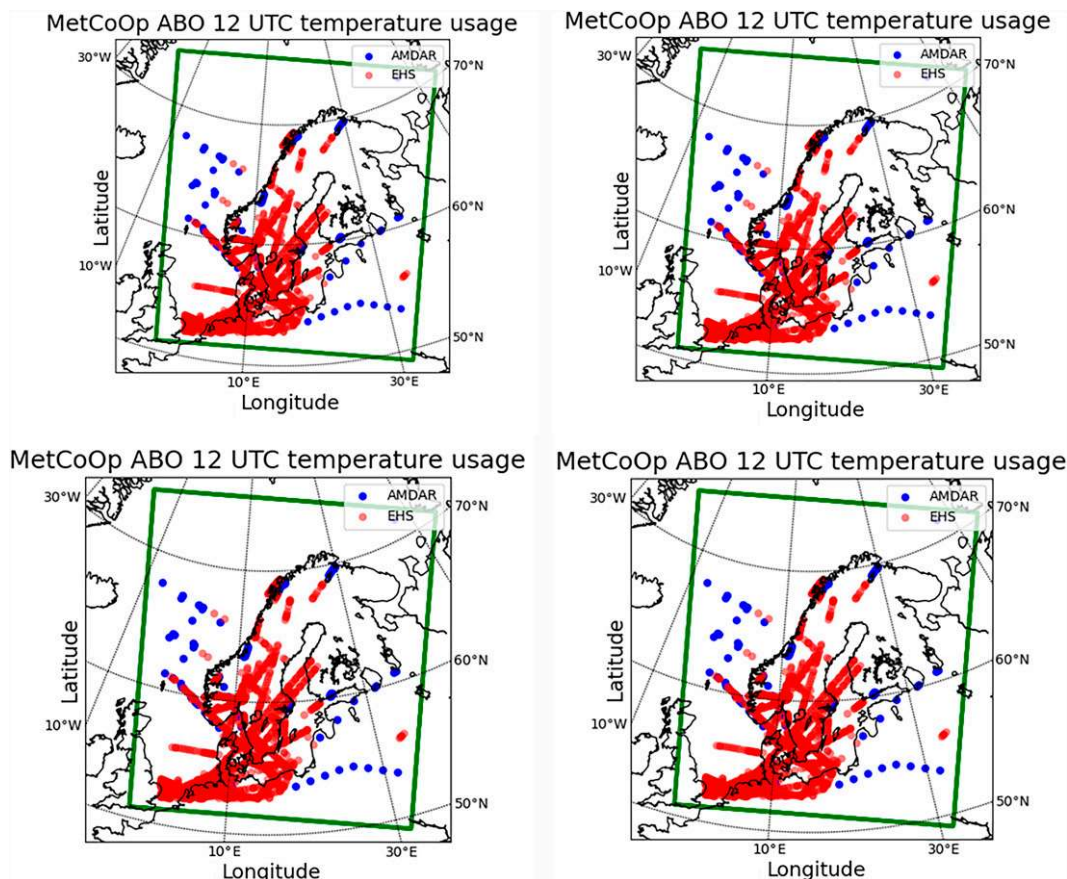


FIG. 9. As in Fig. 8, but for 13 Jan 2021 (period 2).

very early pandemic) situation during period 1. This makes the number of assimilated Mode-S EHSs during period 2 much larger than the number of assimilated AMDAR observations. The reason there are in period 2 many fewer Mode-S EHS temperature data relative to Mode-S EHS wind data is that the improved EMADDC processing for derivation of temperatures is less straightforward than the processing for derivation of wind data. Therefore, in particular situations and for insufficient quality of raw data, temperature data are not produced.

In Fig. 8, the spatial coverage of assimilated ABO is illustrated for 19 December 2019 from period 1. The date is chosen to clearly illustrate the typical daily variation in coverage and the differences between Mode-S EHS and AMDAR coverage. It is clear that the number is larger at 1200 UTC than at 0000 UTC, both for AMDAR and Mode-S EHS. However, for Mode-S EHS, the coverage does not vary so much between the 0000 and 1200 UTC cycles. As indicated by the red dots, both for 0000 and 1200 UTC cycles, the Mode-S EHS data are confined to the areas around Copenhagen and Oslo. It is clear that AMDAR can potentially cover more of the domain while Mode-S EHS data are confined to areas around the receivers. At 1200 UTC, there are plenty of AMDAR data distributed over the domain, whereas there are very few AMDAR data at 0000 UTC. Thus, for period 1, during times

of the day with many flights, the AMDAR data have the attractive feature that they are more evenly distributed over the model area. In Fig. 9, the same thing is shown but for 13 January 2021 from period 2. Also, for this case, there is a clear difference in coverage both for Mode-S EHS and AMDAR between 0000 and 1200 UTC, with much better coverage at 1200 UTC. However, the coverage of Mode-S EHS and AMDAR are quite similar and, over many areas, complementary. In comparing Figs. 8 and 9, it is obvious that AMDAR coverage has decreased from period 1 to period 2, whereas the Mode-S coverage has increased. The reason for the decrease of AMDAR is the pandemic situation with reduced number of flights. The reason for the increase in Mode-S EHS is more Mode-S EHS data sources between periods 1 and 2. In period 1, only Mode-S EHS data from the Copenhagen receiver and the Oslo receiver stations were used. For period 2, all Mode-S EHS data sources within the domain that were considered to be of good quality by EMADDC were used. These include data from the Maastricht Upper Area Control Centre (MUAC) ATCs as well as from the Norwegian Defense Research Establishment. The use of Mode-S EHS data thus compensates partly for the reduction of AMDAR data. However, note that there are some parts over the Norwegian sea, the Baltic Sea, and Finland where the coverage has become worse in period 2 than in period 1. When

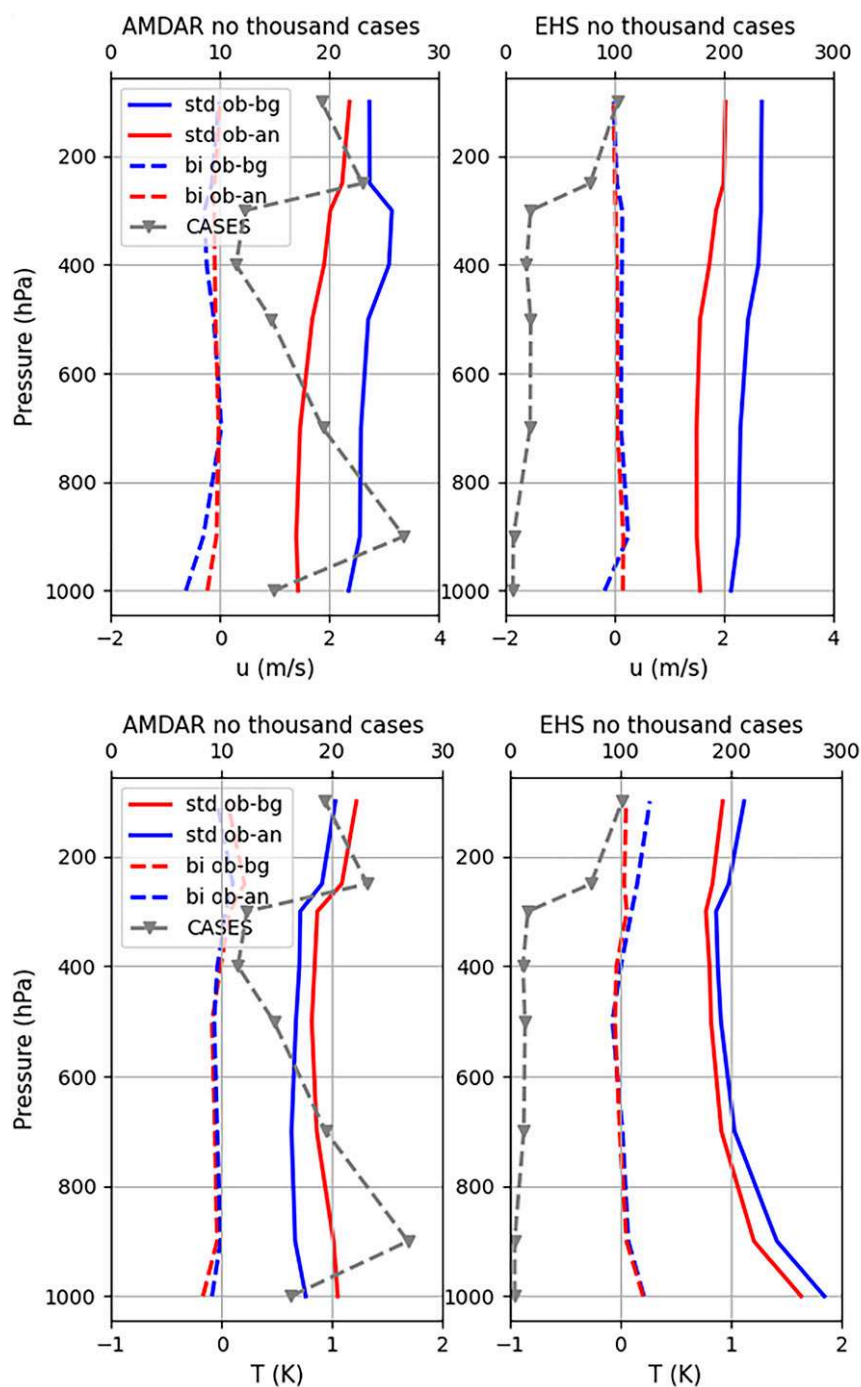


FIG. 10. Bias (dashed) and standard deviation (solid) of innovations (blue; ob-bg) and residuals (red; ob-an) for period 1 for (left) AMDAR and (right) Mode-S EHS (top) winds and (bottom) temperatures. The dashed gray line with triangles shows the number of observations on which the statistics are based for each vertical level.

it comes to the Baltic Sea and Finland, the situation will be improved, as seen from the lower left panel of Fig. 5, when introducing Mode-S EHS from the Stockholm Arlanda receiver into the MetCoOp HARMONIE-AROME data assimilation (see section 5e).

b. Observation quality and average impact on analyses

One way to evaluate the quality of various data sources and the influence these have on the initial model states is to derive statistics of observation minus background departures

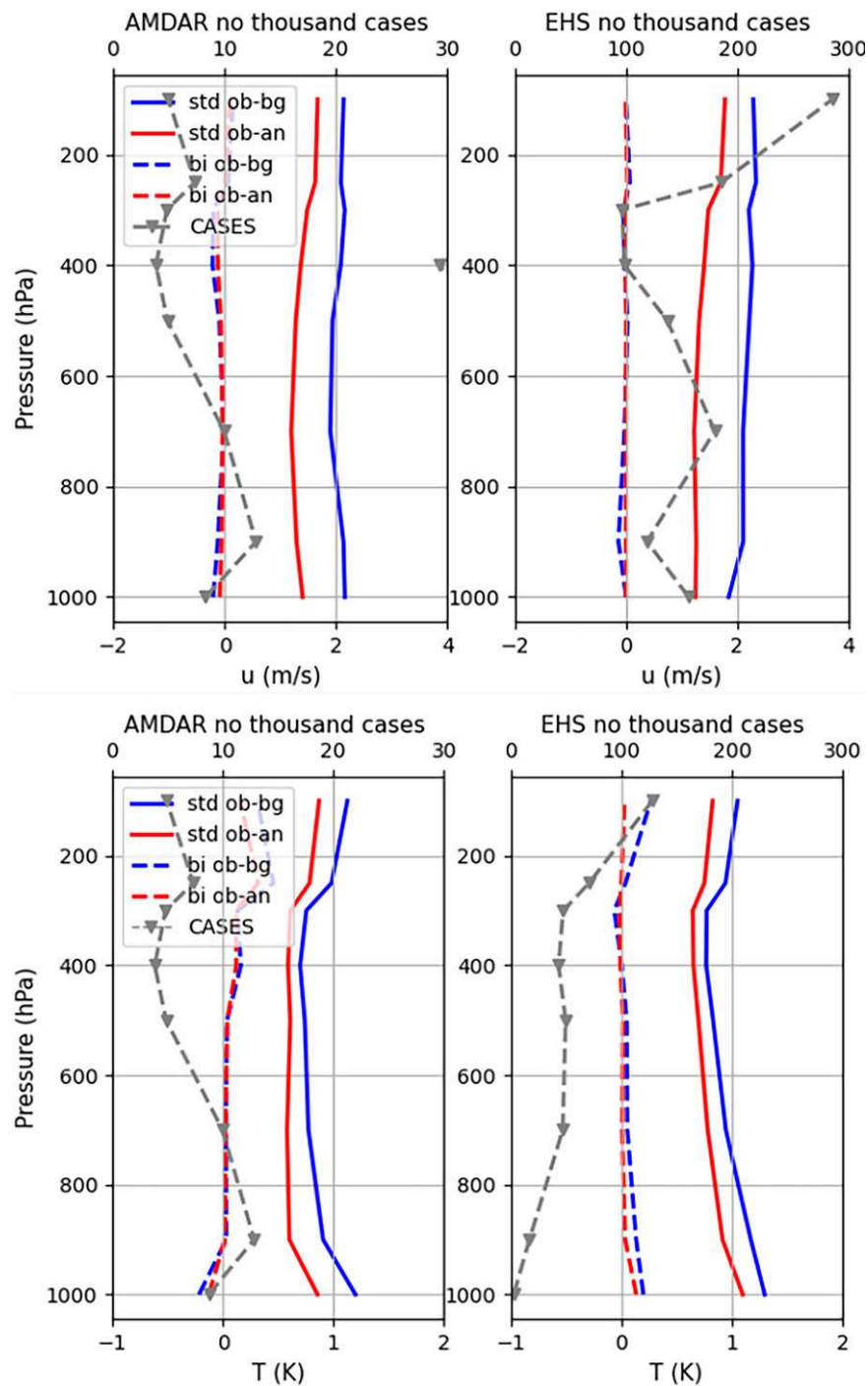


FIG. 11. As in Fig. 10, but for period 2.

(innovations) and observation minus analysis departures (residuals). Such departure statistics have been derived for Mode-S EHS and AMDAR observations for periods 1 and 2 and results are presented in Figs. 10 and 11. Looking at the innovations, it can be confirmed that for both periods, the Mode-S EHS wind observations have a similar quality to AMDAR observations. The data are unbiased relative to the

model and with a standard deviation of a similar magnitude as AMDAR. On the other hand, it seems like for period 1, the Mode-S EHS temperature observations are worse than AMDAR. Innovations for Mode-S EHS temperatures show, in the lower troposphere, a small bias, and standard deviations that are considerably larger than the corresponding AMDAR ones. However, for period 2, the standard deviation of Mode-S

EHS temperature innovations has decreased to a level comparable to AMDAR, and the small bias in lower troposphere is further reduced, as well. The improved quality of Mode-S EHS temperatures found in period 2 as compared with period 1 is in line with improvements reported by EMADDC in derived temperatures due to their refined processing procedure (Sondij 2020), avoiding the limiting precision of Mach number caused by the original procedure (de Haan 2011). Recent research activities indicate that the assumed temperature observation-error standard deviations can be reduced slightly. Furthermore, it seems that the evident bias in Mode-S EHS observations in Table 1 mainly resides from near-surface observations.

The distance between the standard deviations of the residuals and the innovations provides a measure of the influence of the observations on the analyses. These are dependent on the background- and observation-error estimates described in section 3. One can see that for winds and temperatures, the influence of the Mode-S EHS observations on the initial state is slightly smaller than the impact of the AMDAR data. Interestingly, the influence of AMDAR wind data is smaller in period 2 than in period 1. This is not due to a change of error specifications for AMDAR but to an effect of the smaller number of AMDAR observations and increasing number of Mode-S observations in period 2 as compared with period 1.

Note the slightly increasing number of Mode-S EHS observations with altitude. This is due to the EMADDC processing and its associated quality-control procedure.

It can furthermore be seen that for the second period (Fig. 11), the Mode-S EHS temperature observations are considerably fewer than the Mode-S EHS wind observations. This is the result of the improved method for derivation of temperatures (Sondij 2020) and the quality-control procedures in the enhanced version of the EMADDC processing (de Haan et al. 2023, unpublished manuscript). This obvious difference between number of temperature and wind observations cannot be seen for Mode-S EHS during period 1 (Fig. 10) nor for AMDAR (Figs. 10 and 11).

c. Impact on forecast verification scores

The average impact of Mode-S EHS on MetCoOp HARMONIE-AROME forecasts is small when measured in terms of bias and standard deviation based on comparison with radiosonde observations within the domain (Fig. 1). For the period 1 parallel experiment, the largest impact can be seen in wind forecasts. An illustration of the relative minor positive, statistically not significant, impact that can be found is given in Fig. 12. The upper part shows average bias and standard deviation of wind speed forecast errors of the parallel experiment runs at the vertical level of 925 hPa over the entire period and for forecasts launched from 1200 UTC at various ranges. The lower part shows the time series of error bias and standard deviation of all +12-h wind speed forecasts carried out from 1200 UTC during the 1-month period. On average, there is a small positive, not statistically significant, impact on these low-level wind forecasts, but there is a clear day-to-day variation. The relatively small impact on average scores could

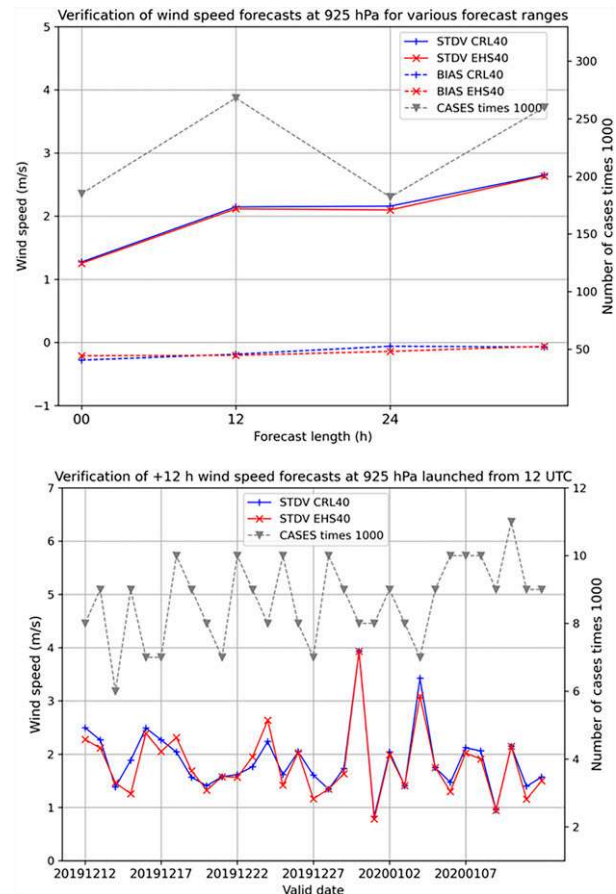


FIG. 12. Average 925-hPa wind speed forecast error bias and standard deviation for the period-1 parallel experiment launched from 1200 UTC. Solid lines are for CRL40, and dashed lines are for EHS40. The dashed gray line with triangles shows the number of observations on which the statistics are based for each vertical level. Shown are (top) bias and standard deviation verification scores as a function of forecast length and (bottom) Standard deviation for +12-h forecasts as a function of the day within the experiment. The verification is against radiosondes within the domain.

be explained by the fact that in terms of coverage, AMDAR was the dominating ABO data source for period 1, and Mode-S EHS provided limited additional information. In addition, the quality of the Mode-S EHS temperature observations were, for period 1, worse than AMDAR temperature quality, which may be one contributing factor to the small impact of the additional Mode-S EHS observations on the temperature forecast. The reason for finding more impact in forecasts launched from 1200 UTC than from the ones launched at 0000 UTC is most likely the larger Mode-S EHS amount at 1200 UTC. From the upper panel of Fig. 12 it can be seen that slightly fewer radiosonde data are available at 1200 UTC than at 0000 UTC.

Also for the parallel experiment for period 2, the impact of the additional Mode-S EHS observations is relatively small. For the period 2 experiment, however, the largest impact is seen on the temperature forecasts, but, as for

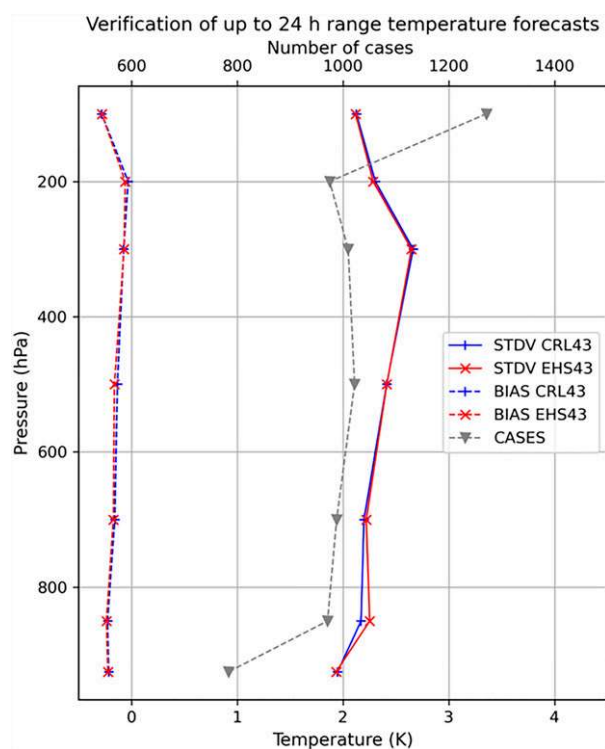


FIG. 13. Temperature forecast error bias and standard deviation for the period-2 parallel experiment. Statistics are accumulated over forecast lengths up to +24 h. Blue lines are for CRL43, and red lines are for EHS43. The dashed gray line with triangles shows the number of observations on which the statistics are based for each vertical level. The verification is against radiosondes.

period 1, it is not statistically significant. Figure 13 shows bias and standard deviation of temperature forecast errors over the entire period and accumulated over ranges up to +24 h, for verification against radiosondes. In terms of standard deviations the most evident difference between CRL43 and EHS43 can be seen below 700 hPa, where EHS43 scores are better.

d. Case study

The prevailing weather condition at the end of study period 2 is a large-scale low pressure system developing over the North Atlantic and moving toward the west coast of Norway. While this system gradually becomes weaker and moves northward, another frontal system develops in the southern part of the MetCoOp domain, and, finally, a secondary low pressure system evolves to the north of the Baltic Sea (Fig. 14). We provide a case study for these three features where we compare the short-range forecasts between the reference and the Mode-S EHS experiments.

Figure 15 shows the time series of mean sea level pressure at the center of the low pressure system. We use the MetCoOp operational analysis as the truth. The comparison between CRL43 and EHS43 indicates that the center of the low pressure system in EHS43 is slightly closer to

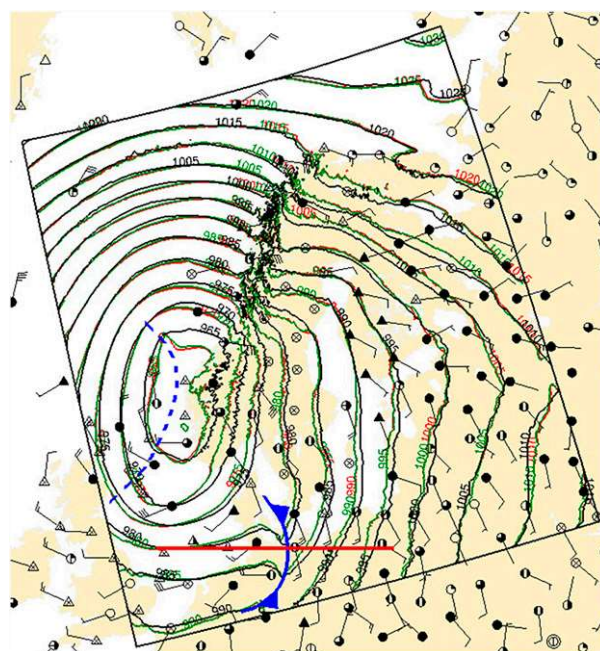


FIG. 14. Synoptic map for 0600 UTC 22 Jan 2021 showing the mean sea level pressure for MetCoOp operational verifying analysis (black), reference forecast from 18 h prior to analysis (green), and Mode-S EHS forecast from 18 h prior to analysis (red). The contour interval is 5 hPa. Synoptic stations are also shown in black. The blue dashed line shows the low pressure trajectory from -24 to +24 h moving from south to north. The blue cold front is in the bottom part of the domain to the east of Denmark. The red line shows the position of the cross section in Fig. 16, below.

the operational analysis for +6-h forecasts. The same is true when the distance between low pressure centers in operational analysis is compared for CRL43 and EHS43 +12-h forecasts, where the center in EHS43 is closer to the operational analysis. Figure 16, which portrays the tropopause folding over the small cold front in Fig. 14, shows that the assimilation of Mode-S EHS winds shifts the relative humidity minimum to a lower level and slightly to the west. This affects both the strength and the position of the cold front and the subsequent wind and temperature fields if not for the precipitation at the surface. The arrows along the x axis near the bottom of Fig. 16 depict the cyclonic circulation at the surface. We show arrows for each plot to make comparison easier and to show that the cyclonic circulation is displaced when assimilating Mode-S EHS.

e. Introduction of Stockholm Arlanda receiver data in data assimilation

At the time of writing, the new data stream including the Stockholm Arlanda receiver has just become available. A test run over one day (0300–2100 UTC) shows that there is a large increase in observations relative to the current operational data stream. Figure 17 shows the number of

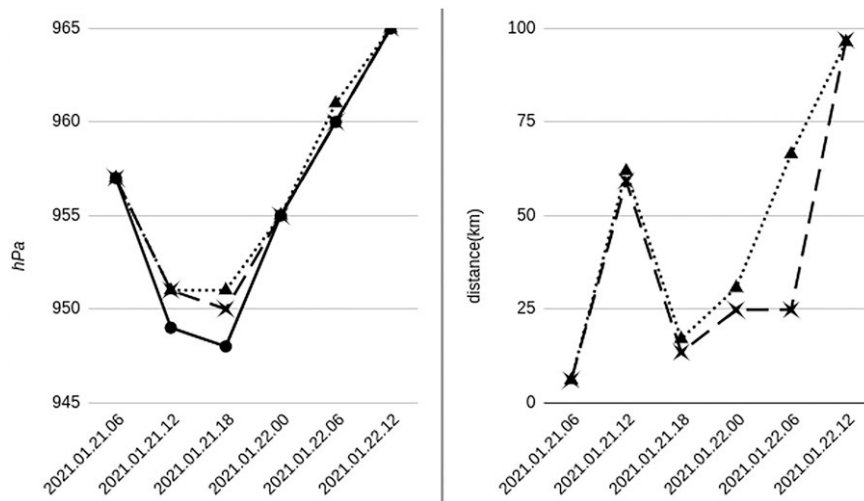


FIG. 15. Time series of (left) mean sea level pressure at the center of low the pressure system for the MetCoOp operational analysis (solid line with circles), CRL43 +6-h forecasts (dotted line with triangles), and EHS43 +6-h forecasts (dashed line with stars), and (right) the distance (km) between low pressure centers in operational analysis against CRL43 +12-h forecasts (dotted lines with triangles) and EHS43 +12-h forecasts (dashed line with stars).

wind observations during this test run for three different pressure levels: 925, 600, and 225 hPa. The number of observations is about three times higher in the new data stream at midday. Early in the morning, at 0600 UTC, there are very few observations in the old distribution, but up to almost 5000 observations, depending on pressure level, with the increased coverage. Figure 18 shows the horizontal distribution of the additional observations. Note that there is also additional data from Finland and the Baltic states in the new dataset, and the coverage in the northern and eastern part of the domain is largely improved. With these additional observations, we believe that the impact will improve, since they cover both areas with rather few other observations, as over the Baltic and North seas, as well as times of the day when there are rather few other upper-air observations.

f. Comparison of results with others' findings

The results presented here have shown a moderately positive impact on average short-range verification scores of assimilating Mode-S EHS. A clear positive impact was demonstrated in a case study.

Early studies by de Haan and Stoffelen (2012) have demonstrated a larger positive impact and with application of the same assimilation algorithm. There are several potential explanations for this difference. The major ones are the use of large-scale mixing in MetCoOp to replace the large-scale information in the background state with ECMWF boundary file information and the more extensive use of various types of remote sensing data in the MetCoOp system. Both of these factors limit the impact of one individual observation type, in this case, Mode-S EHS.

In a recent study by Li (2021), utilizing the Met Office hourly 4D-Var (Lorenc et al. 2000), a clear positive impact of Mode-S EHS was demonstrated. Again there are several potential contributing factors to the larger impact obtained in the Met Office system: 1) the use of a more-advanced data-assimilation algorithm allowing for evolved flow-dependent structures and use of more Mode-S EHS observations at the correct time, 2) optimization with respect to the applied thinning distances, and 3) no replacement of large-scale background state information with host model large-scale information.

Also, in the COSMO-KENDA (Kilometre-scale Ensemble Data Assimilation) NWP system, utilizing a local ensemble transform Kalman filter (Hunt et al. 2007) data-assimilation procedure, a positive impact of Mode-S EHS observations on short-range forecasts was reported by Lange and Janjić (2016). Here it should be mentioned that only a 6-day parallel experiment was carried out and with conventional types of observations only. The flow-dependent background error statistics and use of conventional types of observations only are main contributing factors explaining the larger impact in the COSMO-KENDA NWP system as compared with MetCoOp HARMONIE-AROME. In addition, no large-scale host model information was used to replace large-scale information within the COSMO-KENDA NWP background states.

6. Conclusions

Use of ATC-based Mode-S EHS data in the MetCoOp northern European regional kilometer-scale forecasting system is described. The processing of raw data to obtain atmospheric winds and temperatures is presented as well

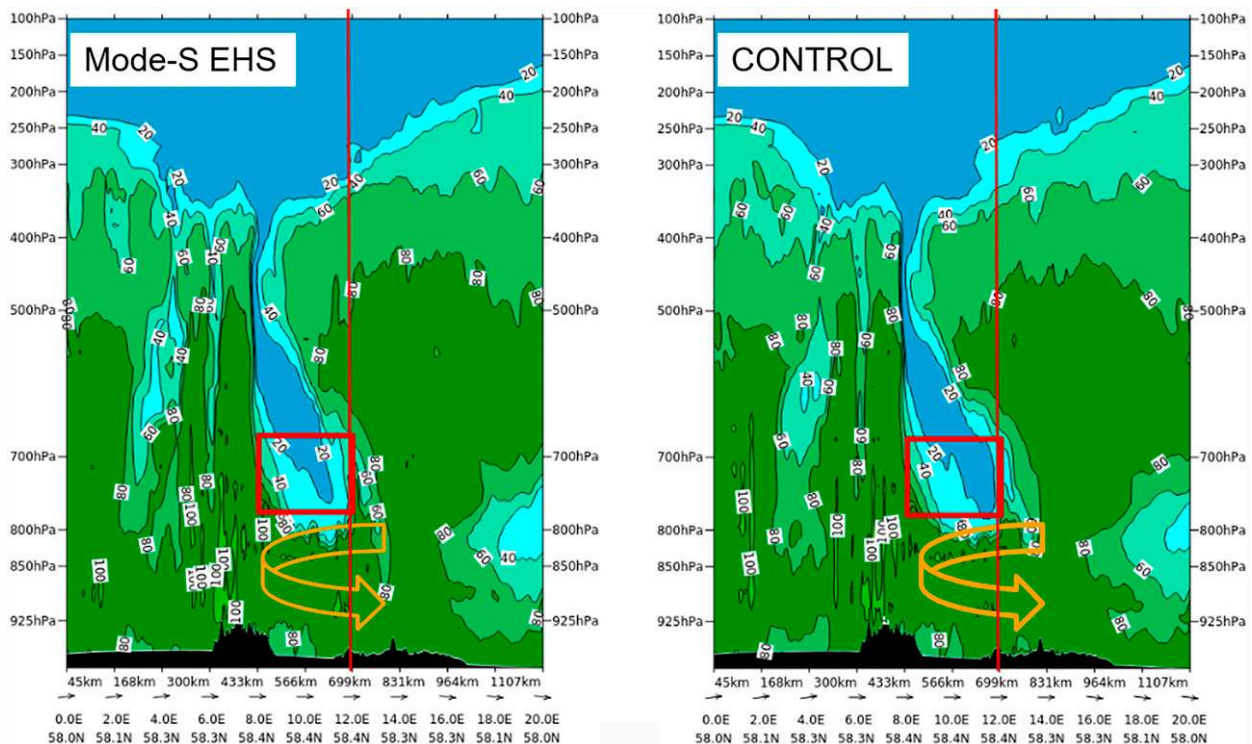


FIG. 16. Tropopause folding shown with relative humidity cross sections for (right) the reference +6-h forecast and (left) the Mode-S +6-h forecast. The identical red-outlined box and red vertical line in both cross sections indicate that in the Mode-S experiment the maximum dry air at around 800 hPa is shifted slightly upward and westward for the +6-h forecast, slightly shifting the cyclonic circulation and the surface front to the west.

as the general handling of the derived observations, including several aspects, such as specification of error characteristics and exclusion of gross errors. Extending the regional forecasting system with assimilation of Mode-S EHS was demonstrated to compensate for the reduction of AMDAR observations that has taken place during the COVID-19 pandemic.

Comparisons with model data reveal that after the introduction of the EMADDC enhanced handling of temperatures in 2020, the Mode-S-derived wind and temperature observations are of the same quality as direct AMDAR measurements. The impact of the additional Mode-S EHS on forecast quality is shown to be very small, on average. In a case study, we demonstrated that for an individual case, the impact of Mode-S EHS data on forecasts may be larger. In our case, it was demonstrated for a developing low pressure system, which is an important task for a regional forecasting system to accurately forecast. Also, a first demonstration using Stockholm Arlanda receiver Mode-S EHS data within the MetCoOp HARMONIE-AROME data assimilation was performed. On 2 June 2020, Mode-S wind observations from Copenhagen and Oslo receiver stations were introduced in the operational MetCoOp HARMONIE-AROME data assimilation. On 23 March 2021, it was further enhanced to also assimilate Mode-S EHS temperature observations and observations from an extended set of data sources.

The impact of the new observation type on average forecast verification scores found in our study was smaller than reported in other studies. The reason is likely a combination of our extensive observation usage, blending of large-scale host model information into the background state, and the relatively simple data assimilation method concerning the handling of flow dependency. Also, optimization of Mode-S EHS quality control and thinning procedures may play a role. There is room for further enhancements regarding use of Mode-S EHS observations in the MetCoOp NWP system. The data selection procedures and error specification should be further investigated. In addition, the impact is limited by the climatological background-error statistics used in combination with 3D-Var, in addition to applying a spectral merging of large-scale host model information to the background state, prior to assimilation.

Near-future enhancements include refined handling of Mode-S EHS observations, including objective tuning of error characteristics, rejection limits, thinning procedure, and thinning distances, following Desroziers et al. (2005), Anderson and Järvinen (1999), and Bormann and Bauer (2010). Recent findings of Li (2021) revealed the sensitivity of forecast impact to thinning. The high observation density, in time, will be better taken into account utilizing four-dimensional variational data assimilation. This will better take the flow of the actual meteorological situation

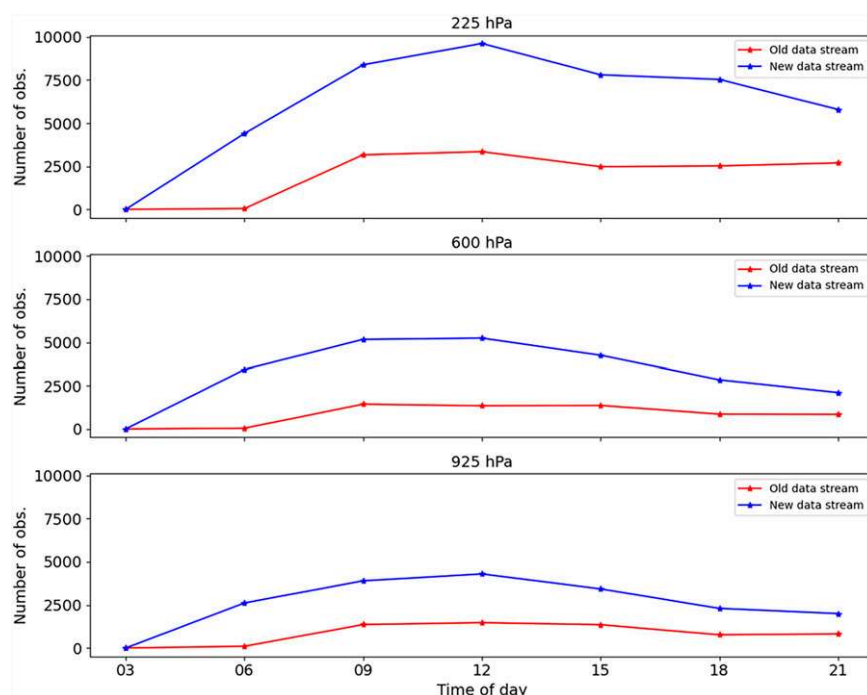


FIG. 17. Time series of the number of wind observations for a 1-day experiment, 0300–2100 UTC, for three different pressure levels, using the operational observations from the old data stream (red lines) in comparison with the same experiment using Mode-S EHS data from the new data stream (blue lines) including the Stockholm Arlanda receiver.

into account. In the longer term, we foresee use of ensemble-information within the data assimilation procedure to relax the assumption of climatological background-error statistics. It could be beneficial to introduce the large-scale host model information as one additional term in the minimization of the cost function. Next, series of parallel data assimilation and forecast experiments should include also a summer period

to evaluate the impact of assimilation of Mode-S EHS on prediction of short-range convective situations. Finally, it should be mentioned that, thanks to activities described in this paper, on 3 May 2022, Mode-S EHS data from the Stockholm Arlanda receiver and the additional data as shown in Fig. 18 were introduced into the MetCoOp HARMONIE–AROME operational system. There are also some early plans to install

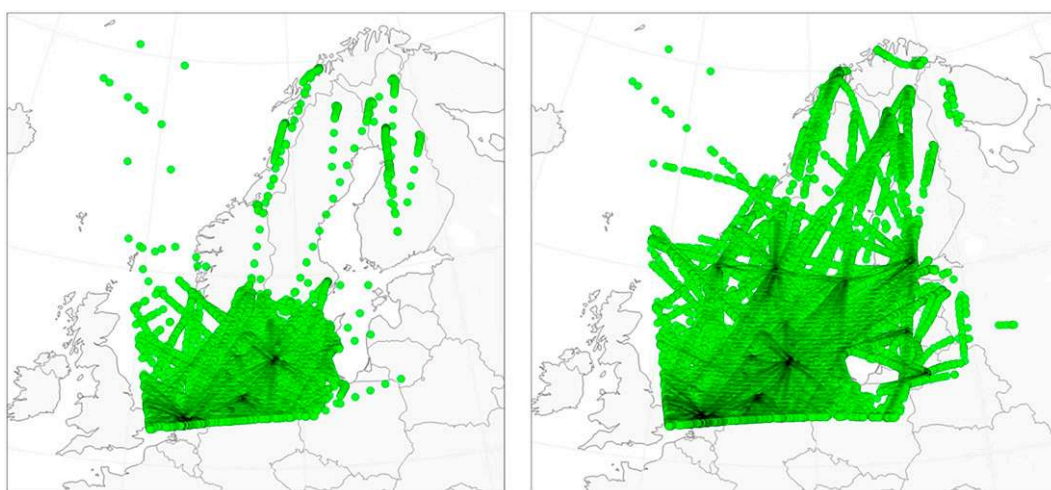


FIG. 18. Horizontal coverage of ABO (Mode-S EHS and AMDAR) (left) in the operational data stream in March 2022 in comparison with (right) the new data stream including the Stockholm Arlanda receiver at noon.

additional local receivers and to identify suitable locations for these.

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Data availability statement. Datasets used in the paper are publicly available upon request.

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