

The Operational Forecast Process at MetCoOp

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Convective-scale processes;
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ABSTRACT: The governmental meteorological offices of Estonia, Finland, Latvia, Norway, and Sweden maintain joint production of regional forecasts based on numerical weather prediction (NWP). The collaboration is organized in a continuing project called Meteorological Cooperation on Operational NWP (MetCoOp). The operational products contribute to weather data for daily use and form the base for official weather warnings in the participating countries. The forecasts are distributed to the public, to specific users such as the national road authorities, and to other governmental institutes. MetCoOp operates two NWP suites: 1) The MetCoOp Ensemble Prediction system (MEPS) is a lagged ensemble of 30 members that is updated hourly by running five members out to the 66-h lead time, whereas 2) the MetCoOp Nowcasting System (MNWC) is a deterministic run out to the lead time of 12 h. The suites share a common modeling domain that covers Scandinavia, Finland, and Baltic countries with 2.5-km horizontal grid spacing. There is an additional postprocessing suite, the MetCoOp Ensemble Calibration System (MECaS), that uses the raw MEPS forecast as input. MECaS produces a statistically calibrated ensemble forecast of near-surface parameters in a 1-km grid. The convection-permitting grids and frequent update cycles create added value on top of global forecasts that are received at no finer than 8-km horizontal grid spacing and no more than two–four times per day.

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1. Introduction

Governmental weather services are responsible for issuing timely warnings of potentially hazardous weather that can affect society's functions. At high latitudes, that is, at the latitudes poleward of 60°, the most influential types of severe weather include hail, lightning, heavy rain and snowfall, and convective gusts. To realistically simulate severe weather, one needs to apply numerical weather prediction (NWP) on a grid that is sufficiently dense to allow explicit representation of convection. Due to the rapid evolution of such events, it is critical to update the numerical forecast frequently. Furthermore, due to the chaotic nature of the atmosphere (Lorenz 1969) and limitations of the modeling system, an ensemble approach is essential to guide decision-making when issuing weather-related warnings to the public and society as a whole.

Products based on global NWP modeling systems are widely used in applications of short-, medium-, and long-range forecasting. However, requirements specific to the forecasting at the high latitudes are not covered by the sole use of the global NWP systems. Typically, global suites are initialized two–four times per day, which can be too infrequent to capture changes in rapidly evolving situations. Moreover, the relatively coarse horizontal resolution of global forecasts limits their ability to simulate strong convective events. It is computationally more affordable to apply a limited-area suite to provide both the temporal frequency and the horizontal resolution required to forecast severe weather.

While operational global NWP systems are presently being run at resolutions that correspond to horizontal grid spacing of ca. 10 km, the majority of operational limited-area systems apply grid spacings on the order of 1–3 km. Examples of such convective-scale NWP systems include the Met Office's high-resolution model and its implementations overseas (Lean et al. 2008; Dipankar et al. 2020; Rennie et al. 2022) and the models of the COSMO,¹ ALADIN,² and HIRLAM³ consortia (Baldauf et al. 2011; Müller et al. 2017a; Termonia et al. 2018; Lapillonne et al. 2026). Convective-scale NWP systems typically deal with fundamental challenges that are associated with (i) dynamics and partial differential equations, (ii) turbulence, (iii) probability, (iv) data assimilation, (v) observability, (vi) stochasticity, (vii) physics, (viii) parameterizations, and (ix) numerics (Yano et al. 2018). One specific application area of high-resolution limited-area modeling is the nowcasting of convective precipitation (Sun et al. 2014).

In the Scandinavian and Baltic countries, the operational production of regional NWP is (to a large extent) coordinated by the “Meteorological Cooperation on Operational NWP” (MetCoOp) project. MetCoOp is a joint operational and development effort of Estonian, Finnish, Latvian, Norwegian, and Swedish governmental meteorological agencies. The primary motivation for the collaboration is the need to deliver better forecasts for the local domain

¹ Consortium for Small-Scale Modeling.

² Aire Limitée Adaptation Dynamique Développement International.

³ High Resolution Limited Area Model.

compared with the available global models. In light of the high costs of running an NWP system (both from human-resource and financial perspectives), joining in a collaboration with neighboring countries offers several opportunities. An initial study performed by the Norwegian Meteorological Institute (MET) and the Swedish Meteorological and Hydrological Institute (SMHI) identified the following benefits (Agersten et al. 2015):

- 1) Having access to high-performance computing (HPC) resources at several institutes makes it feasible to run more expensive NWP systems.
- 2) Sharing competence across various areas of NWP among the member institutes allows for a greater number of staff to work on the maintenance and development of common systems.
- 3) Joining the voices of the Nordic and Baltic institutes secures their role in, and eases communicating of their needs to, the wider NWP community, in particular through international limited-area modeling consortia.
- 4) Joint operational production promotes and enhances collaboration in areas beyond NWP. Examples of such enhanced collaborations include exchanges of remote sensing based data, joint development of aviation forecasts, and production of regional reanalyses.

MetCoOp started as a collaboration between MET and SMHI in 2011, and it was expanded to include the Finnish Meteorological Institute (FMI), the Estonian Environment Agency (ESTE), and the Latvian Environmental, Geological and Meteorological Centre (LEGMC) in 2017, 2020, and 2024, respectively. Additionally, the Lithuanian Hydrometeorological Service (LHMS) has an observer status and is likely to join as a full member in the future. In western Europe, there is a similar collaboration ongoing under the name “United Weather Centres–West.” This encompasses the Royal Netherlands Meteorological Institute (KNMI), the Danish Meteorological Institute (DMI), the Irish National Meteorological Service (Met Éireann), and the Icelandic Meteorological Office (IMO).

MetCoOp started operational production in 2014 using a version of the Applications of Research to Operations at Mesoscale (AROME) NWP system (Seity et al. 2011). The initial deterministic configuration was described and evaluated in Müller et al. (2017b). In 2017, the operational suite was extended to include an ensemble prediction component, and the primary suite has since been referred to as the MetCoOp Ensemble Prediction System (MEPS). Since 2022, there has been an additional operational NWP suite, that is, the MetCoOp Nowcasting System (MNWC), that provides an hourly refreshing deterministic very short-range forecast. From late 2024 onward, the family of operational products has also included a statistically calibrated (postprocessed) ensemble forecast of near-surface meteorological parameters [MetCoOp Ensemble Calibration System (MECaS)]. The operational forecasting process consists of a series of partially overlapping tasks that are schematically displayed in Fig. 1.

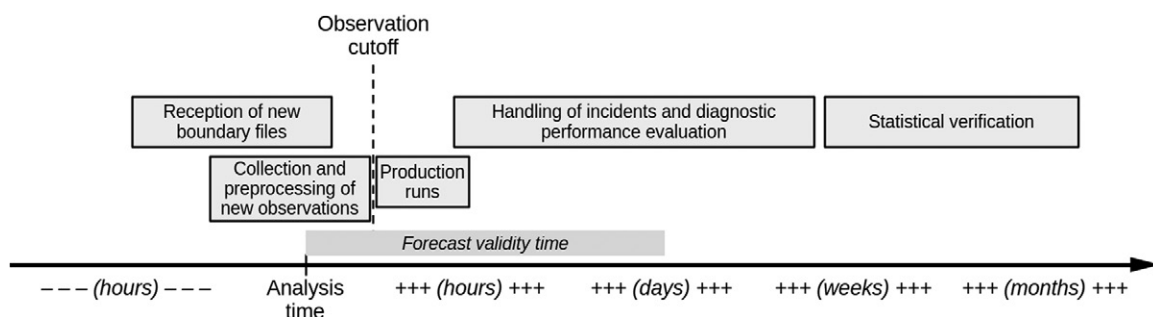


FIG. 1. Timeline of the operational forecasting process at MetCoOp.

2. The unique characteristics of the MetCoOp NWP systems

The MEPS and MNWC suites share a common modeling grid that covers northern Europe as shown in Fig. 2. Table 1 lists the main characteristics of the suites. The production runs are conducted on national HPC facilities, and they make use of computing time and storage capacity contributions granted in kind by the partners. In the context of the state of the art in operational limited-area NWP, the MetCoOp systems are made unique by several advanced aspects:



FIG. 2. The operational NWP model domain at MetCoOp. The figure was created using the tool available online (<https://hirlam.github.io/nwptools/domain.html>).

- 1) Geographically distributed processing: As detailed in Table 2, the production of the MEPS forecast is distributed across HPC platforms located in different countries. The geo-redundancy makes the production robust and allows for graceful degradation at times of scheduled maintenance or technical problems. The multiple architectures also facilitate running two instances of MNWC in parallel and thus guarantee operational production at all times.
- 2) International cooperation: There is a strong international aspect present at all stages of the operational process. These include (i) the monitoring of the runtime environment, (ii) handling of incidents and general maintenance of the suites, (iii) testing and implementation of new developments, and (iv) strategic research planning toward further improvements in time scales from months to years ahead. The partners also contribute to long-term scientific research within the ACCORD⁴ consortium consisting of 26 nations.

⁴ A Consortium for Convection-Scale Modeling Research and Development.

TABLE 1. Properties of MEPS and MNWC.

Common properties		
Horizontal grid	960 × 1080 points at 2.5-km spacing uniformly across the domain	
Vertical grid	65 hybrid sigma/pressure terrain-following levels: lowest at 12 m above the ground; highest at 10-hPa pressure	
Forecast integration	Semi-implicit time stepping at 75-s steps	
Lateral boundary forcing	Global ECMWF forecast (backed up by ARPEGE)	
Suite-specific properties in MEPS and MNWC:		
	MEPS	MNWC
Ensemble	Lagged production of 30 members over 6 h	—
Observation cutoff time	75 min after the analysis time	25 min after the analysis time
Forecast range	66 h	12 h
Output time resolution	1 h	15 min
Product dissemination	2 h after the analysis time	1 h after the analysis time

TABLE 2. Distribution of the operational workload across the HPC facilities. The asterisk (*) indicates that each member runs once per 3 h; hence, the full 30-member ensemble refreshes once per 6 h.

HPC/host institute(s)	Manufacturer	MEPS members*	Production of MNWC?
Cirrus/SMHI and MET Norway	Clustervision	0 (control), 7, 8, 14	No
Stratus/SMHI and MET Norway	Clustervision	1, 2, 3, 4, 5, 6, 12, 13	Yes
Vinha/FMI	Atos	9, 10, 11	Yes

- 3) Aggressive use of observations: There is wide use of observation types in the analyses of surface parameters and upper-air meteorological fields. The use of infrared and microwave sounders is relatively aggressive for a regional system, and advanced use is made of ground-based weather radars including both reflectivity and Doppler wind data. The analysis of surface parameters benefits from satellite-based snow-coverage data. Immediately after the main analysis, MNWC takes an additional step and improves its cloud fields by ingesting cloud information from geostationary satellite imagery (Gregow et al. 2020). Observations are automatically monitored for quick detection of anomalies and gaps in data dissemination.
- 4) Physical parameterizations appropriate for high latitudes: Tuning of physical parameterizations respects the regional particularities. The tunings include (i) adapting the cloud droplet number concentration to better account for the clean air of the polar regions, (ii) reducing the amount of ice clouds in response to feedback collected from forecasters, (iii) advecting convective precipitation instead of letting it fall down to the ground immediately, and (iv) adjusting the surface exchange coefficient to improve the description of the stable boundary layer in the cold season.
- 5) Rapid refresh: Both MEPS and MNWC are refreshed hourly. While each member of MEPS is updated once per 6 h, the initialization of the whole ensemble is distributed in time such that each hourly refresh updates five members. Spreading the production over time is advantageous through evening out of the workload on the HPCs, thus allowing an increased number of members for a given maximum computer capacity. The approach benefits end users via providing frequent updates and through reducing the jumpiness of the ensemble forecast. A similar approach has been reported in Porson et al. (2020) and Kuchera et al. (2021).
- 6) Secured access to boundary field data: The lateral boundary forcing is backed up through preparedness against dissemination failures from the primary source of boundary field data. Whenever necessary, the production switches automatically from using the ECMWF⁵ boundary fields to using those of the Meteo-France global ARPEGE⁶ system (Bouysse et al. 2022) instead.

⁵ European Centre for Medium-Range Weather Forecasts.

⁶ Action de Recherche Petite Echelle Grande Echelle.

3. Preparation of a new forecast cycle

As schematically illustrated in Fig. 1, the tasks conducted in preparation of the production runs include 1) the reception of new boundary files and 2) the collection and preprocessing of new observations.

Reception of lateral boundary fields. Limited-area models require external forcing at their lateral boundaries (Davies 2014). At MetCoOp, new boundary fields are received four times per day, and they come from the operational runs of the ECMWF Integrated Forecasting System (IFS). There are separate streams corresponding to the unperturbed control member (HRES—soon to become ENS Control) and the perturbed ensemble members (IFS-ENS) of the global IFS run. While both HRES and IFS-ENS data are provided in a horizontal grid spacing of 9 km, the reception of IFS-ENS is currently at half the native resolution, that is, 18 km,

because of storage constraints. The time resolution of these data is 1 h. The MEPS control member is unperturbed and takes the lateral boundary forcing from the HRES stream, as does the MNWC run. From the IFSENS stream, MetCoOp makes use of 28 individual members. This is implemented by running each of the 14 perturbed MEPS members (see Table 2) twice per 6 h and alternating the input IFSENS members in consecutive cycles. This approach increases the spread and results in the full 30-member MEPS ensemble that refreshes once per 6 h.

In the interest of reducing computational workload in the time-critical path, a dedicated preoperational suite has been set up with the sole purpose of interpolating the boundary field data to the MEPS grid in advance. The availability of such preinterpolated boundary fields reduces the operational production time by up to 5 min.

COLLECTION AND PREPROCESSING OF OBSERVATIONS. MEPS and MNWC runs assimilate a variety of observations. The observation types are listed in Table 3, and Fig. 3 shows typical data coverage for selected observation types. The observations are collected from several data sources including the Global Telecommunication System network, the dissemination systems of the European meteorological satellite organization, and data hubs of the EUMETNET cooperation. Radar observations are mostly obtained through Baltic radar co-operation (Michelson et al. 2018), except for the Norwegian data that is fetched directly from MET Norway.

Some of the observation types are subjected to preprocessing prior to transferring the data to the HPCs. This is particularly important in the case of radar data, which each country samples in a different way and which comes in a very high horizontal resolution. The preprocessing harmonizes the data on the one hand and reduces excessive data volumes on the other. The preprocessing of radar observations is described in detail by Ridal and Dahlbom (2017) and Ridal et al. (2023).

The collection of Global Navigation Satellite System (GNSS) signal delay data for NWP models is coordinated by the EUMETNET GNSS Water Vapor Program. The observations

TABLE 3. Observation types assimilated in MEPS and MNWC.

Observation type	Description	Reference
SYNOP	Measurements of surface-level pressure, near-surface temperature, humidity, wind, and snow depth at synoptic observing stations	
SHIP	Measurements of surface-level pressure and near-surface wind at ship-based platforms	
Buoy	Measurements of surface-level pressure and near-surface wind at drifting buoys	
Radiosonde	Vertical in situ profiles of temperature, humidity, and wind	
Aircraft	Measurements of temperature and wind at conventional aircraft-based sensors and as derived from the selective mode enhanced surveillance reports	Lindskog et al. (2023)
GNSS	Signal delay data from ground-based receiver networks of Global Navigation Satellite Systems	Lindskog et al. (2017)
Radar	Measurements of reflectivity and radial wind by weather radars	Ridal and Dahlbom (2017), Ridal et al. (2023)
Scatterometer	Retrievals of near-surface wind from polar-orbiting satellite data	Valkonen et al. (2017)
Radiance	Microwave and infrared sounder radiances from polar-orbiting satellites	Lindskog et al. (2021)
Imagery	Visible and infrared imagery from geostationary satellite data	Gregow et al. (2020)
Satellite snow	Snow-coverage data based on visible and infrared imagery from polar-orbiting satellites	

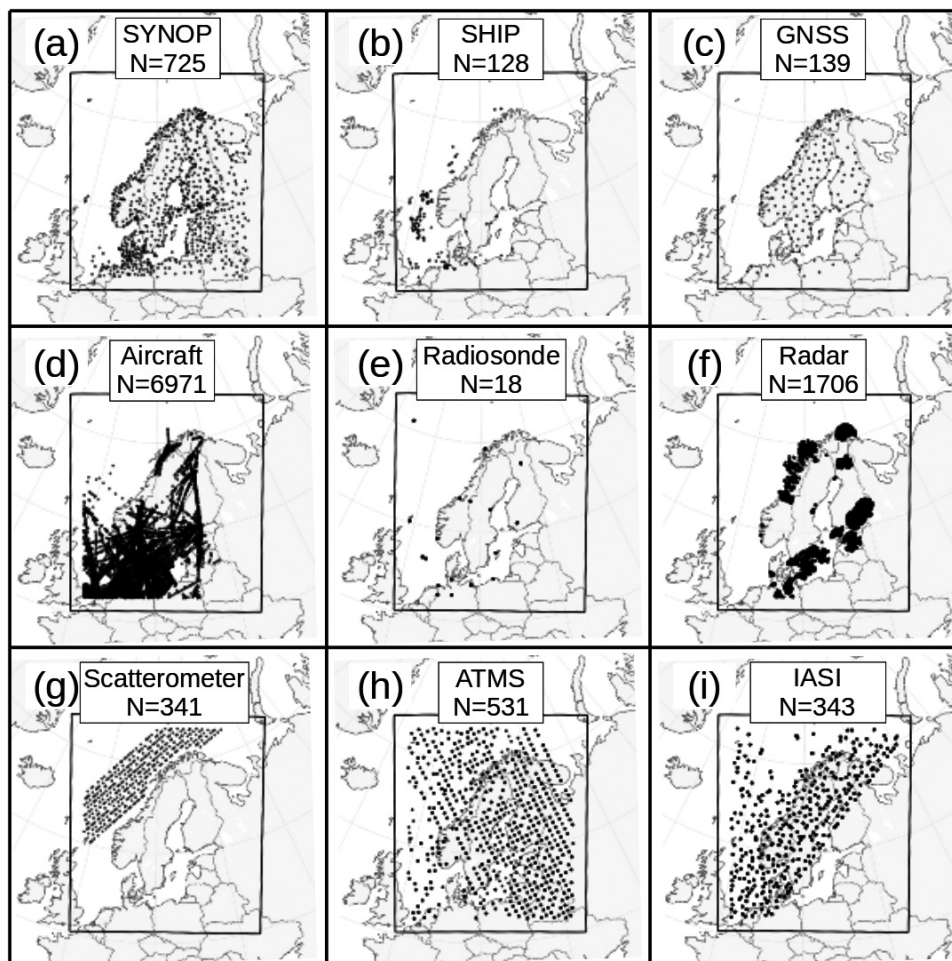


FIG. 3. Coverage of various observation types in the analysis of upper-air fields in MEPS at 1200 UTC 3 Dec 2024: (a) SYNOP, (b) SHIP, (c) GNSS signal delay, (d) all aircraft-based data, (e) radiosonde measurements, (f) reflectivity data from radar stations, (g) *MetOp-B* Advanced Scatterometer data, (h) *NOAA-20* Advanced Technology Microwave Sounder (ATMS) microwave sounder, and (i) *MetOp-C* IASI infrared sounder. At the top of each panel, N indicates the number of data points.

fetches at MetCoOp originate primarily from the Nordic processing center and secondarily from the processing centers at the Met Office and the Royal Observatory of Belgium. The preprocessing of GNSS data selects observations from a predefined station list and ensures the horizontal separation of at least 70 km between the data points such that the effect of correlated errors is reduced. There are more details on the preprocessing and handling of ground-based GNSS receiver data in Arriola et al. (2016) and Lindskog et al. (2017).

The preprocessing of satellite snow data involves the use of tools provided by the Hydrology and Water Management Satellite Application Facility of the European meteorological satellite organization.

4. Production runs

As illustrated in Fig. 1, the production runs are conducted immediately after the observation cutoff time. The production runs consist of 1) the NWP system runs (MEPS and MNWC) and 2) the statistical ensemble calibration run (MECaS). The NWP system runs are based on reference system architectures that, until the end of 2025, were provided by the HIRLAM consortium and continue to be provided by the new UWC⁷ consortium from 2026 onward. The schematic shown in Fig. 4 illustrates the NWP system workflow as applied in the deterministic suites (MEPS control member and MNWC).

⁷ United Weather Centres.

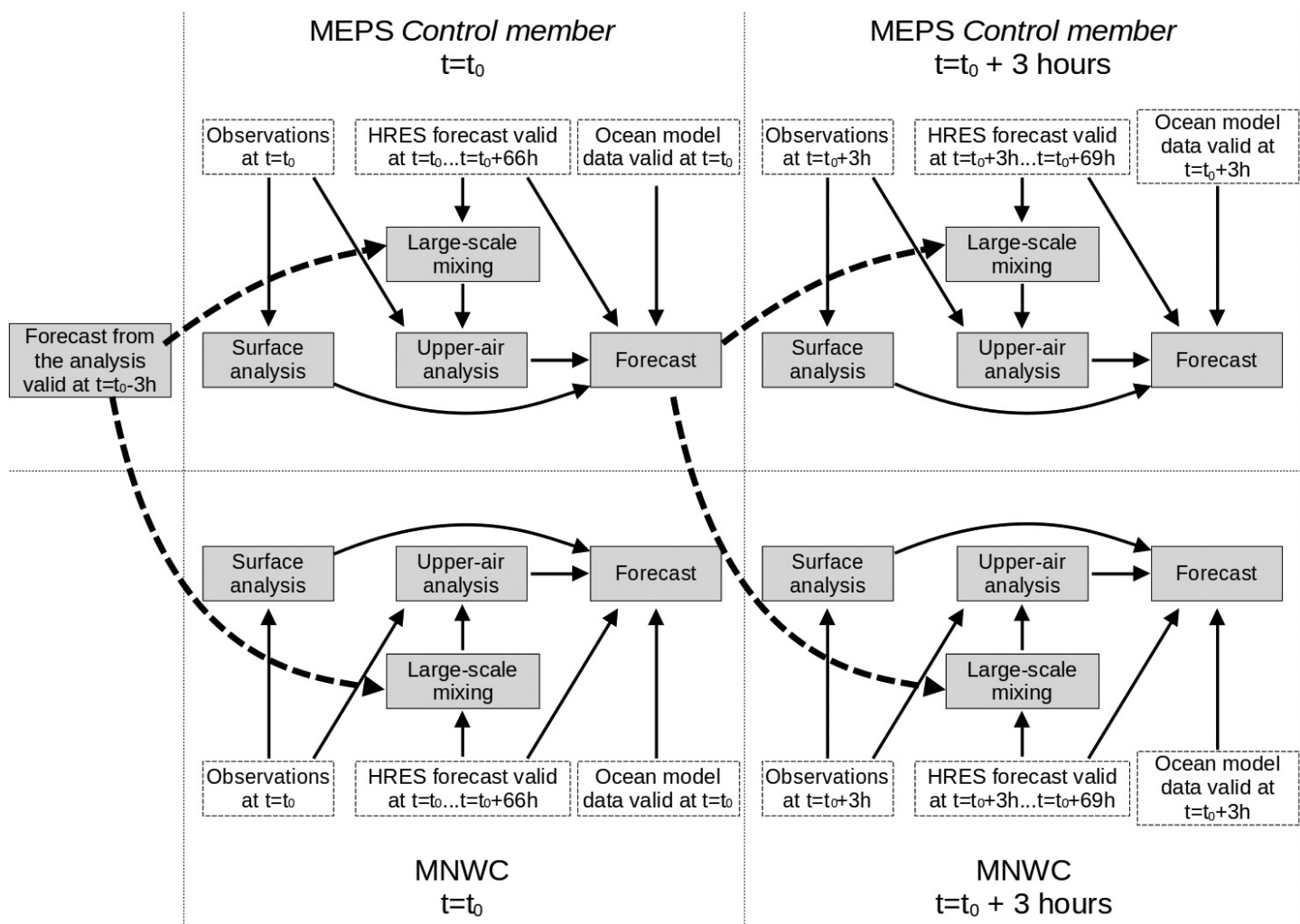


FIG. 4. Workflow of the deterministic suites at two consecutive synoptic hours in the (top) MEPS control member and (bottom) MNWC. Shaded boxes indicate tasks conducted within the HARMONIE-AROME run. Boxes with dashed outlines indicate external inputs. Time t_0 is any synoptic hour (i.e., 0000, 0300, 0600, 0900, 1200, 1500, 1800, or 2100 UTC).

a. Analysis of surface parameters. Applying the settings of the HARMONIE-AROME⁸ reference system (Bengtsson et al. 2017; Gleeson et al. 2024), version 43h2.2, the surface analysis of MEPS utilizes the CANARI⁹ (Taillefer 2002) optimal interpolation system. The analysis relies on SYNOP observations of near-surface temperature and relative humidity to update surface temperature, soil temperature, and soil moisture. The analysis is conducted at all forecast cycles. Once per day, there is an additional analysis of snow water equivalent, snow density, and albedo. The analysis of snow parameters benefits from both the SYNOP observations and satellite imagery. CANARI applies spatial quality control and a first-guess departure check to the assimilated data.

The analysis of surface parameters in MNWC is implemented somewhat differently. This analysis comprises separate steps including (i) the TITAN spatial observation quality control (Båserud et al. 2020), (ii) the GridPP optimal interpolation (Nipen 2020), and (iii) the offline SURFEX¹⁰ data assimilation code (Le Moigne et al. 2018). MNWC does not analyze snow but instead retrieves these parameters from the most recent deterministic MEPS forecast.

Neither MEPS nor MNWC conducts its own analysis of sea surface temperature or sea ice concentration. These parameters are initialized at each forecast cycle by interpolating from

⁸ HIRLAM-ALADIN Research on Mesoscale Operational NWP in Euromed-Applications of Research to Operations at Mesoscale.

⁹ Code d'Analyse Nécessaire à ARPEGE pour ses Rejets et son initialisation.

¹⁰ Surface Externalisée.

external data sources including the HRES or IFSENS boundary field (in most of the domain) and a Nordic version of the NEMO¹¹ ocean model (Kärnä et al. 2021) (in the largest Swedish lakes and in the Baltic Sea). This information is passed directly to the forecast model, and it is kept fixed during the forecast integration.

¹¹ Nucleus for European Modelling of the Ocean.

b. Analysis of upper-air variables. Again, consistently with the HARMONIE–AROME reference, the analysis of upper-air fields applies three-dimensional variational assimilation (Lorenc et al. 2000; Gustafsson et al. 2001). The background field for the MEPS analysis is taken from the previous 3-h forecast of the same ensemble member. In MNWC, the background field comes from the most recent forecast of the MEPS control member. Prior to the analysis, large-scale mixing is applied to merge the background and lateral boundary fields. This process is scale-selective and improves the representation of planetary- and synoptic-scale circulations (Dahlgren and Gustafsson 2012). The background error statistics are static and prescribed from samples of ensemble forecast differences in experimental runs. The same background error statistics are applied in both MEPS and MNWC.

The observation errors are assumed to be mutually uncorrelated. The HARMONIE–AROME reference specifications are applied in the setting of the observation error variances, first-guess departure-based screening thresholds, and horizontal data thinning. The assimilation of satellite radiances makes use of a fast radiative transfer model (Saunders et al. 2013) and an adaptive bias-correction algorithm (Auligné et al. 2007). The latter is also applied in the assimilation of GNSS signal delay data.

c. Forecast integration. The numerical integration of MEPS and MNWC forecasts is conducted in single precision. The applied physical parameterizations are listed in Table 4. With respect to the HARMONIE–AROME reference, there is a small number of deviations that aim to improve the forecast system performance at high latitudes (as discussed in section 2). The modeling of the interaction with the surface is based on SURFEX, version 8.1, surface model (Le Moigne et al. 2018). There are no differences in the setup of the forecast integration between MEPS and MNWC.

d. Representation of uncertainty in the NWP run. The representation of uncertainty in MEPS is a combination of contributions originating from the initial conditions, the model formulation, and the use of IFSENS lateral boundaries. In the initial conditions, the uncertainty is represented through mechanisms described in Frogner et al. (2019), including 1) the addition of perturbations to the assimilated observations and 2) the addition of the scaled difference between the respective IFSENS member and the IFSENS control member. Perturbations in the representation of the surface are made in roughness, albedo, sea

TABLE 4. Physical parameterization schemes applied in MEPS and MNWC.

Processes	Parameterization scheme
Surface–atmosphere momentum, energy, and matter exchange	Monin–Obukhov similarity theory (Monin and Obukhov 1954); specific coupling and dimensionless functions used over nature, sea, lakes, and urban areas; based on SURFEXv8.1 (Le Moigne et al. 2018)
Radiation	ECMWF IFS Rapid Radiative Transfer Model (RRTM) (ECMWF 2016)
Aerosol climatology	Monthly aerosol climatology (Tegen et al. 1997)
Cloud microphysics	Single-moment (ICE3) scheme (Cohard and Pinty 2000a,b); OCND2–Clouds in Cold Conditions (Müller et al. 2017b)
Boundary layer	1.5-order closure turbulence scheme (de Rooy et al. 2022; Lenderink and Holtslag 2004); dual mass flux shallow convection (Neggers et al. 2009); statistical cloud scheme (de Rooy et al. 2022)

surface temperature, and soil temperature following Bouttier et al. (2016). The perturbation of soil water goes through the soil wetness index and accounts for the wilting point and field capacity of the present soil type.

The uncertainty in the description of the parameterized physical processes is represented by a stochastically perturbed parameterization (SPP) scheme (Frogner et al. 2022; Tsiringakis et al. 2024). Five parameters are perturbed impacting cloud and rain formation, shallow convection, and length scales for vertical mixing. The perturbation fields are obtained by a stochastic pattern generator (Tsyrlunikov and Gayfulin 2017).

e. Statistical calibration of the ensemble forecast (MECaS). MECaS is based on the Bernstein quantile network (BQN) method (Bremnes 2020; Schulz and Lerch 2022). The Bernstein polynomials are used to represent the underlying forecast uncertainty distribution, and neural networks are applied to link this to the MEPS ensemble. Each forecast parameter (i.e., temperature, wind speed, and the maximum wind gust speed) is described by a separate BQN model that is trained from all station measurements in such a way that probabilistic forecasts can be made at any spatial location. As input, the following is included:

- 1) Ordered ensemble members of the main variable supplemented by ensemble means of additional variables
- 2) Digital elevation model (DEM) data at 30-m horizontal grid spacing
- 3) Surface type from ECOCLIMAP (Champeaux et al. 2005) at 136-m horizontal grid spacing
- 4) Temporal and spatial metadata including the lead time, initialization time, time of day, month and season, and geographic coordinates

The models are trained on 1 year of data. From the BQN-generated forecast distributions, 30 quantiles are computed and converted into ensemble members using ensemble copula coupling (Schefzik et al. 2013) that preserves spatial and temporal dependencies. The MECaS forecast is produced on the 2.5-km grid as well as on a 1.0-km grid that covers the same horizontal area. Since there is a lot of variability in the orographic features within the 2.5-km grid cells, the finer 1.0-km grid provides added value that originates from the high-resolution DEM and ECOCLIMAP databases. The updated MECaS forecast becomes available to users approximately 20 min after the raw MEPS forecast.

f. Handling of incidents and diagnostic performance evaluation. Monitoring of the operational production is organized on three levels as listed in Table 5. There is an automated email-based alert system that passes information on technical incidents to the project team. Past incidents are reviewed in weekly meetings, where decisions regarding any corrective actions are also made. In these meetings, the team also regularly assesses the use of observations and monitors patterns in analysis increments with the aim to detect any unexpected changes that might be indicative of degradation in the quality of observational data.

5. Statistical verification

The operational system output is regularly verified against meteorological observations taken at ground and radiosonde stations. The statistical verification relies on intercomparisons of

TABLE 5. Organization of technical support.

Level	Host	Role
First line	FMI	Continuous monitoring at all times
Second line	SMHI	Immediate technical assistance by NWP specialists on request from the first line
Third line	All partners	Non-time-critical monitoring; implementation of corrective actions

forecast scores in MEPS, MNWC, and MECaS against each other as well as against the scores computed from the ECMWF global forecasts. The deterministic forecasts are verified separately over various geographical regions and groups of stations. Summary and threshold-based scores are repeatedly computed over the most recent 7- and 30-daytime periods and over calendar months and seasons. The verification of the ensemble forecasts makes use of the Harp software (Singleton and Deckmyn 2024). Again, statistics are accumulated and stored over the most recent 30-daytime period and additionally separately for each calendar month and season. All results are displayed on an internal web server and are accessible to the participating institutes.

While the verification scores are produced and archived automatically, evaluation and interpretation of the results requires a continuous human effort. The statistical verification is a recurring topic of discussion in the weekly meetings of the project team.

In recent times, statistical verification has consistently indicated that the MetCoOp forecasts provide additional value on top of the global forecast of ECMWF. Figure 5 shows an example of the verification scores in the deterministic runs of MEPS (blue lines and symbols) and the ECMWF operational run (red). The added value of MEPS is the greatest in the forecast of near-surface temperature, wind speed, and the maximum wind gust speed. Frequently (though not so clearly in the case of Fig. 5), MEPS and MNWC outperform ECMWF also in terms of cloud cover and precipitation. On the other hand, MEPS and MNWC tend to show relatively little additional skill against variables that are related to humidity. In some cases, the additional value occurs only at certain thresholds of observed values. An example of the latter behavior is the visibility, which MEPS forecasts well in the range 0–1 km, but does relatively poorly at values in excess of 1 km.

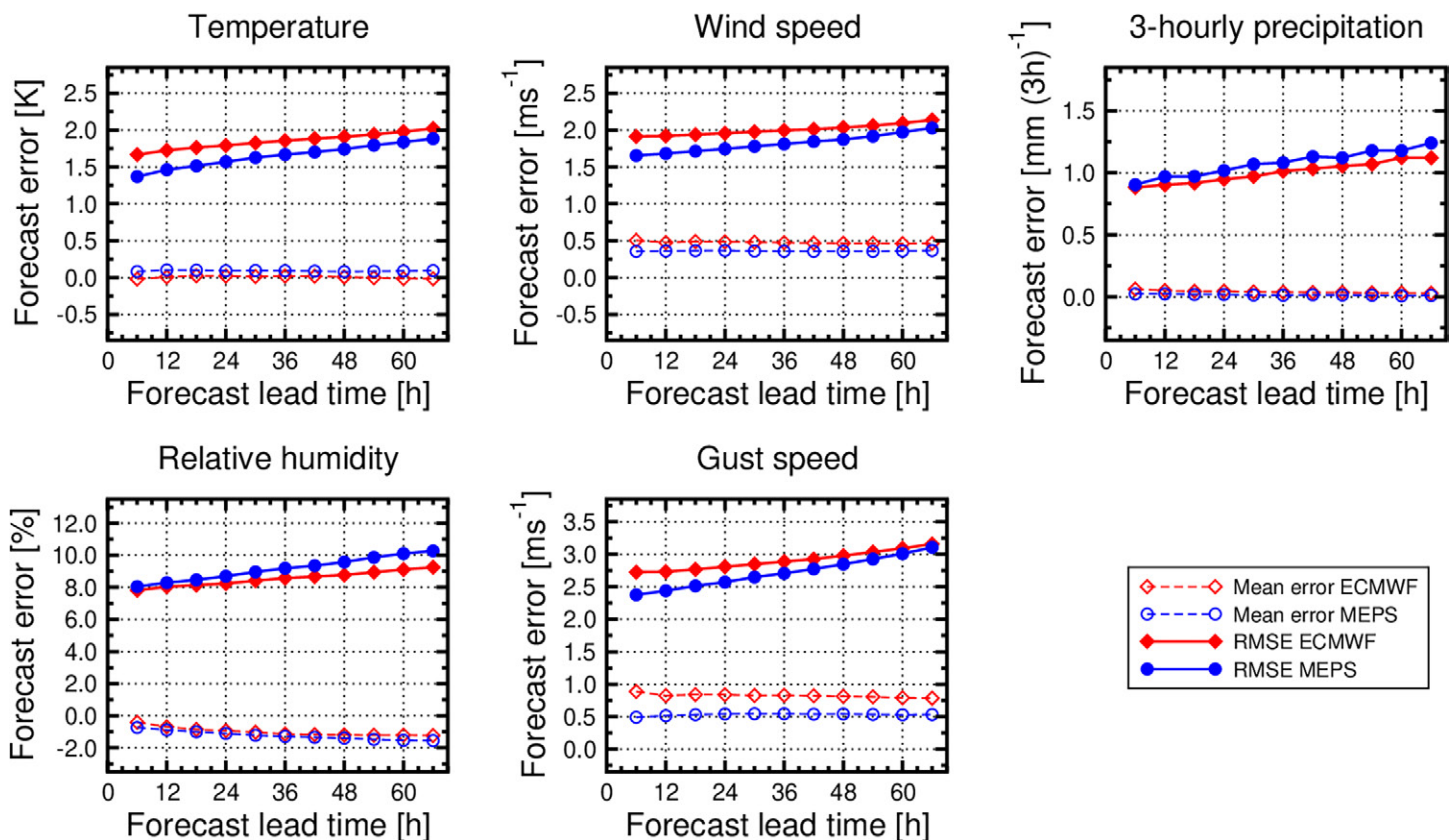


FIG. 5. Objective verification scores computed against ground stations in autumn 2024 for the MEPS control member (blue circles) and the ECMWF deterministic forecast (red diamonds). The mean and root-mean-square forecast errors are shown by dashed lines with open symbols and solid lines with filled symbols, respectively. The scores are shown for near-surface temperature, wind speed, precipitation accumulation over 3 h, relative humidity, and maximum wind gust speed. The scores are computed from all ground stations located inside the horizontal domain shown in Fig. 2.

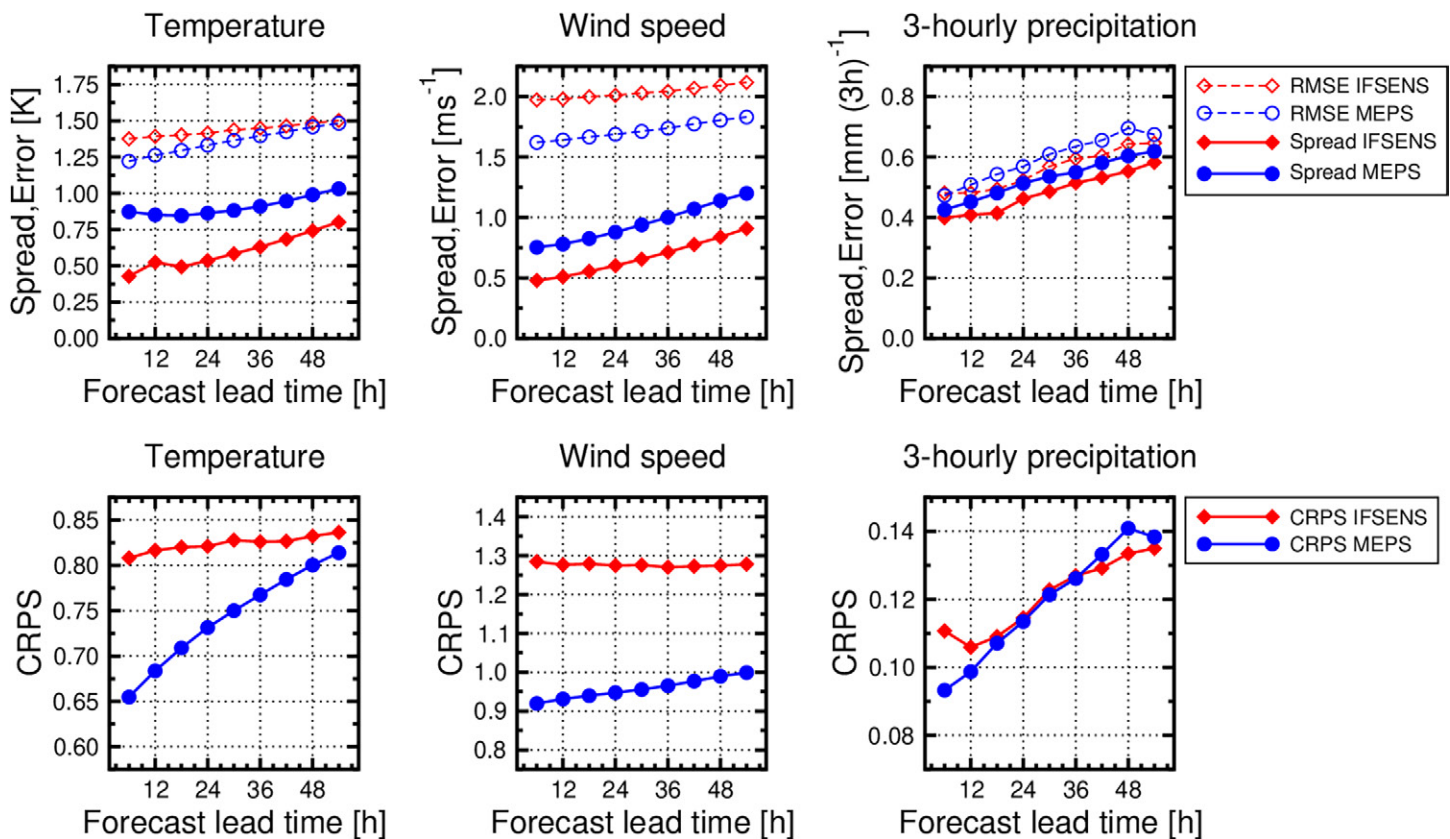


FIG. 6. Probabilistic verification scores in MEPS (blue circles) and IFSENS (red diamonds) in October 2024. (top) The root-mean-square forecast error (dashed lines with open symbols) and the ensemble spread (solid lines with filled symbols). (bottom) The continuous ranked probability score (note that lower values are better). The scores are shown as a function of forecast lead time for near-surface temperature, wind speed, and precipitation accumulation over 3 h, and they are computed from the ground stations located inside the horizontal domain shown in Fig. 2.

Figure 6 illustrates the probabilistic verification of MEPS and IFSENS. In comparison with IFSENS (red lines and symbols), MEPS (blue) shows reduced root-mean-square error (i.e., increased accuracy) in near-surface temperature and wind speed. On the other hand, MEPS shows reduced accuracy in accumulated precipitation. In particular, in temperature and wind speed, there is more spread in MEPS than in IFSENS, and the gap between the spread and accuracy is greatly reduced in MEPS. This indicates that forecast uncertainty is represented better in MEPS. The superior performance of MEPS is also apparent in the continuous ranked probability scores shown in the bottom row, although in the case of accumulated precipitation, there is added value only during the first 12–18 forecast hours.

The added value of the ensemble calibration in MECaS is demonstrated in Fig. 7. In all forecast parameters, the continuous ranked probability scores (bottom row) indicate performance gains in comparison with the raw MEPS ensemble (red lines and symbols). The performance gain is clear already in the 2.5-km horizontal grid (blue), and it is further enhanced in the 1.0-km grid (black). Similar improvements are seen in the forecast accuracy curves (dashed lines and open symbols in the top row), particularly in the wind and maximum gust speeds. In terms of the ensemble spread, there is no consistent improvement in MECaS. Especially toward the longer lead times, the spread of MECaS fails to reach that of the raw MEPS ensemble, which suggests that the representation of forecast uncertainty is insufficient.

Since the horizontal domain of the models covers different kinds of geographical regions, the statistical verification scores often vary across subdomains or station groups. The benefit from the relatively high horizontal resolution comes out clearest in regions characterized by

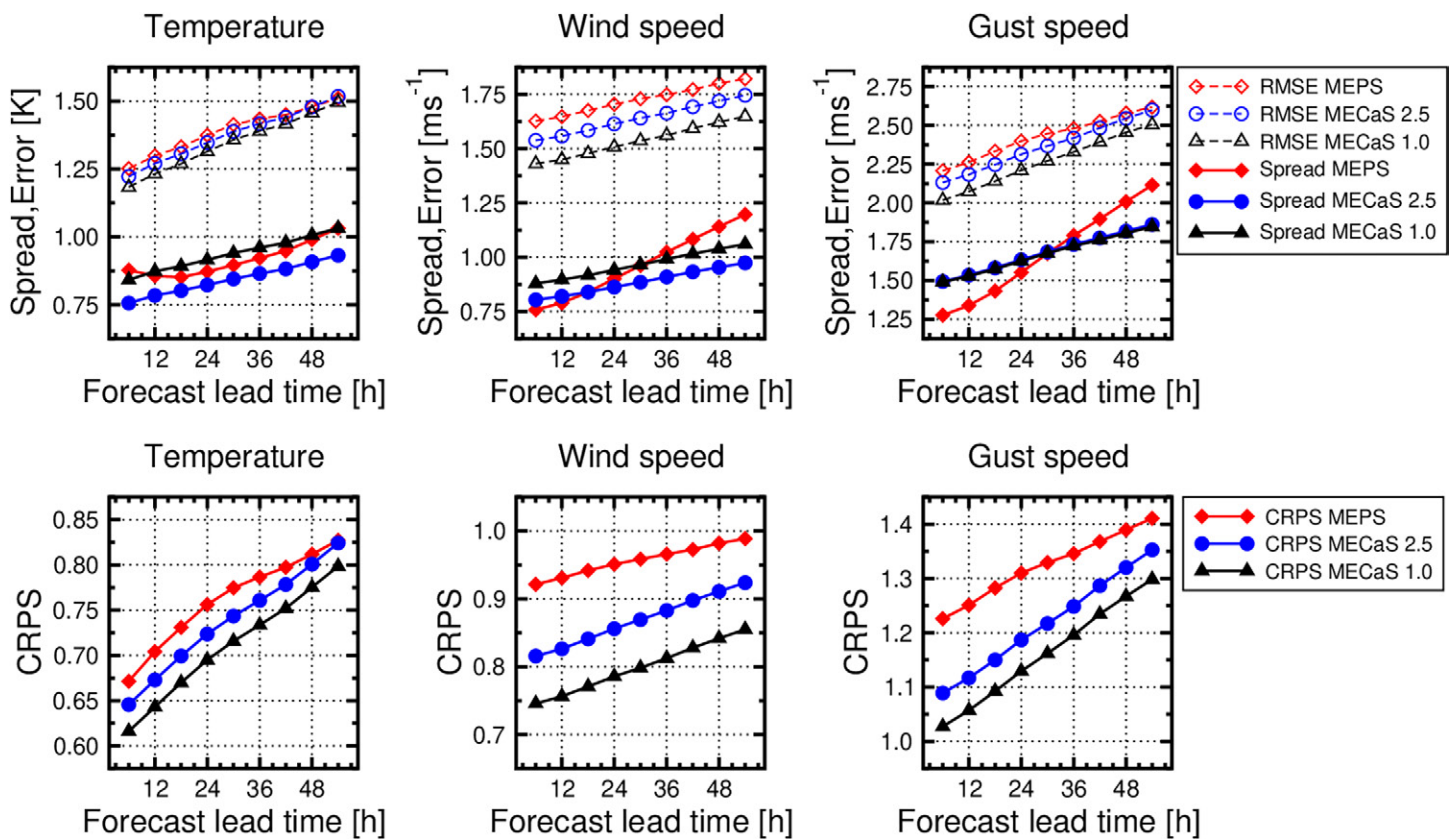


FIG. 7. Probabilistic verification scores in MEPS (red diamonds), MECaS 2.5-km grid (blue circles), and MECaS 1.0-km grid (black triangles) in October 2024. (top) The root-mean-square forecast error (dashed lines with open symbols) and the ensemble spread (solid lines with filled symbols). (bottom) The continuous ranked probability score. The scores are shown for near-surface temperature, wind speed, and maximum wind gust speed.

complex coastlines and/or steep orographic features, such as around the Norwegian fjords and mountains and the Finnish Archipelago. There are also temporal variations attributable to differences in dominating weather types typical for each season. One example is the tendency to underforecast low clouds in high pressure situations in winter while also overforecasting them during the spring melting season. Another example is convection, which is challenging to forecast at times from late spring to early autumn but rarely during the cold season.

6. Developments to the operational systems

The statistical verification scores (and forecasters' subjective feedback) often point out issues and deficiencies that call for further system development. Substantial development usually requires coordinated research effort that may take several years and involve scientists from modeling groups other than MetCoOp. The majority of the development in the long term therefore happens within wider international research consortia that the member institutes also belong to. The ACCORD consortium constitutes a framework for purely scientific studies. Partnership within the UWC program, on the other hand, is particularly essential since it ensures continued access to new quality-assured versions of the HARMONIE-AROME reference architecture. New major versions of the reference architecture are released once every 2–3 years typically.

To facilitate additional development in the short term, MetCoOp maintains a fleet of preoperational suites that allow incremental system development on time scales from months to up to 2–3 years. During a calendar year, 5–10 substantial (i.e., significant in either meteorological or computational sense) developments may enter the preoperational testing. Depending on

the outcome of that, the operational suites are updated three–six times per year, and these updates each include one–three different developments. Preoperational testing of new developments is usually preceded by extensive offline testing in a research experiment framework (on HPCs different from those listed in Table 2).

Recent examples of upgrades to the operational suites include the use of the scalable acquisition and preprocessing system (Fucile et al. 2014) in the observation preprocessing workflow and reducing the production time through switching the forecast integration to the single precision. Upgrades foreseen in the first half of 2026 include an extension to the SPP scheme to include new parameters and an upgrade to the newest quality-assured version of the HARMONIE–AROME reference.

There are several major developments that will be considered for implementation in a longer perspective (within the next 5 years or so). Increasing the NWP model grid resolution is perhaps the most urgent major development under consideration. Given that the grid resolution has remained unchanged since the start of the production in 2014, the project team is looking for opportunities to increase both the horizontal and vertical resolution in both MEPS and MNWC. This would allow maintaining the additional value on top of global NWP in the forecast of near-surface parameters in complex orography. The roadmap toward increased resolution includes key elements as listed in Table 6. The vertical resolution upgrade from 65 to 90 levels is currently in preoperational testing, and Fig. 8 illustrates the properties of these vertical grids. Other potential major developments to be considered in the coming years include a more sophisticated extraction of observational information through advanced data assimilation based on the 3DEnVar method (Brousseau et al. 2025) and improving the description of the atmosphere–surface interaction through a multilayer-based surface scheme (Monteiro et al. 2024). These developments still require substantial research effort, and they are not immediately sufficiently mature for operational use at MetCoOp.

7. Interaction with users

The project team includes forecaster representatives at each member institute. The forecaster representatives review recent meteorological performance in regular feedback sessions that are organized two–four times per year. They also frequently attend the weekly meetings and are encouraged to bring up topics for discussion.

The forecasters’ use of the MetCoOp products at the member institutes ranges from routinely issuing forecasts to the general public and commercial customers to evaluating the potential of extreme and dangerous weather. On a daily basis, both the deterministic and ensemble forecasts provide support to applications where short-range forecasting is essential, such as prediction of aviation weather at airports. When issuing weather-related warnings, the probabilities of strong wind, heavy rainfall, and heavy snowfall, as derived from the MEPS ensemble, are among the most important sources of information. These products provide added value not only for making the decision on whether or not to issue a warning but also

TABLE 6. The roadmap toward increased grid resolution.

Action	Time frame	Notes
Increased vertical resolution	During 2026	Will apply to both MEPS and MNWC. A 90-level grid has been in preoperational testing since March 2024.
Reduce the horizontal grid spacing of MNWC to 1.5 km	Within 1–2 years	Computationally affordable since there is no ensemble in MNWC. The main obstacle is to ensure sufficient functionality in own cycling (i.e., without taking the background field from the MEPS forecast).
Reduce the horizontal grid spacing of MEPS to ca. 1.5	Within 2–3 years	Will rely on both increased computational performance on new HPC facilities and improved load balancing across the available platforms.

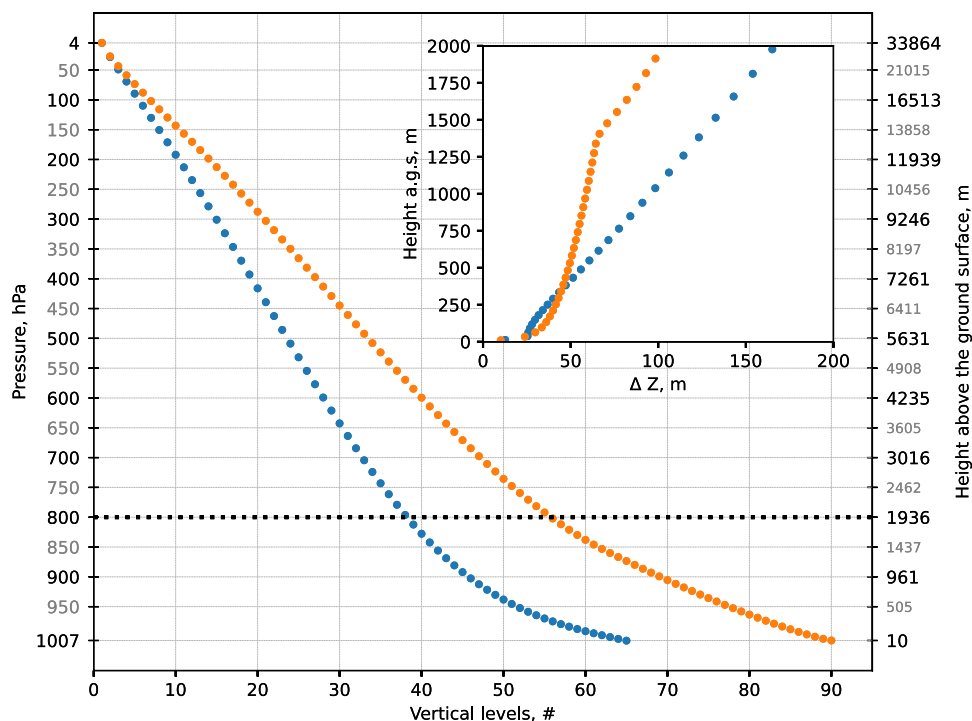


FIG. 8. Vertical model levels (65 levels in blue, 90 levels in orange) and their corresponding values in pressure and height above the ground surface. The smaller vertical grid spacing in the 90-level grid within the lower troposphere (the first 2 km from Earth's surface, indicated by the horizontal black dotted line) is highlighted in the embedded panel.

for communicating information on uncertainties and potential risks to relevant authorities. The products are also in a central role when evaluating risk levels of forest and bush fires.

As a notable example, accessing the MEPS forecast allowed the Norwegian forecasters to recognize the potential of heavy precipitation in August 2023, such that early warnings could

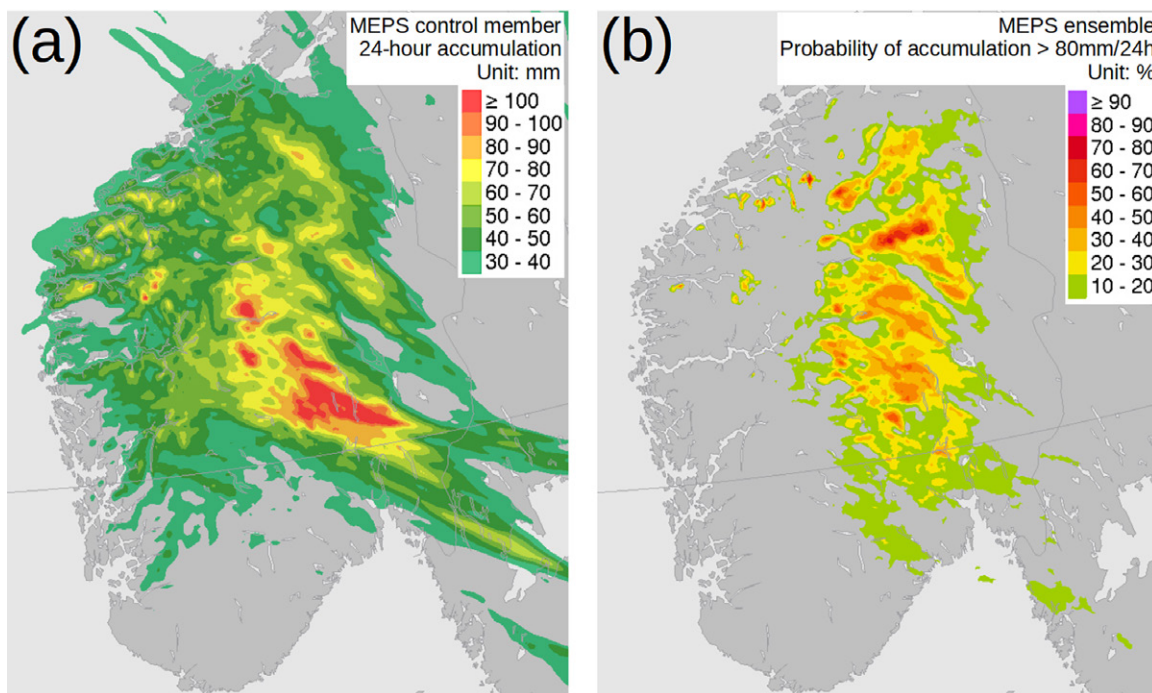


FIG. 9. Forecast of precipitation accumulation over 24 h during the extreme weather event Hans in Norway in August 2023. The forecast is based on the MEPS 0600 UTC run on 6 Aug 2023. (a) The accumulation at lead times from 24 to 48 h in the MEPS control member. (b) Ensemble-based probability of accumulation in excess of 80 mm at lead times from 24 to 48 h. The figures are from Granerød et al. (2023).

TABLE 7. Use cases of the MetCoOp products.

User or use case	Description	Reference
The SmartMet nowcasting system	Additional support to the forecasters by integrating the MetCoOp forecasts with local high-density observations	Hieta et al. (2021)
Model training	Training datasets for artificial intelligence and machine learning–based postprocessing systems	Hieta and Partio (2025)
General public	Collaborations with national broadcasting corporations make an impact on up to millions of users of weather data	For example, www.yr.no
National road agencies	Prediction of winter road weather and issuing warnings of icing based on the temperature and precipitation forecast data	
The Norwegian Water Resources and Energy Directorate	Issuing warnings of rainfall-induced landslides based on weather forecasts	Krøgli et al. (2018)
Renewable energy sector	Activities of universities and industry partners to optimize technologies related to renewable energy	Manninen et al. (2024)

be issued 1–2 days in advance at the time of the significant weather event “Hans” (Granerød et al. 2023). As illustrated in Fig. 9a, the deterministic run forecasted accumulations in excess of $100 \text{ mm (24 h)}^{-1}$ in parts of Southern Norway. Figure 9b complements the forecaster’s view by showing the probability of precipitation in excess of $80 \text{ mm (24 h)}^{-1}$; this rate of precipitation corresponds to the 50-yr return period and is used as a threshold for extreme precipitation in the inland areas of eastern Norway. The observations taken at ground stations during the event were in a good agreement with the forecast.

In addition to the forecasters’ direct use of MEPS, MNWC, and MECaS, there are downstream users and developers who build on top of the MetCoOp products. Some notable use cases are listed in Table 7.

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Data availability statement. The data generated and analyzed during the MetCoOp project are publicly available through several repositories and platforms. MEPS data can be accessed via the SMHI and MET Norway websites, as well as through the Norwegian Meteorological Institute’s THREDDS Data Server, that provides data in the OPeNDAP format. Additionally, users can access forecast data through MET Norway’s API and other publicly available interfaces. Some data may be subject to restrictions based on privacy, legal, or ethical considerations and requests for access to restricted datasets can be directed to the corresponding institutes. MET Norway’s API is documented at <https://open-meteo.com/en/docs>.

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