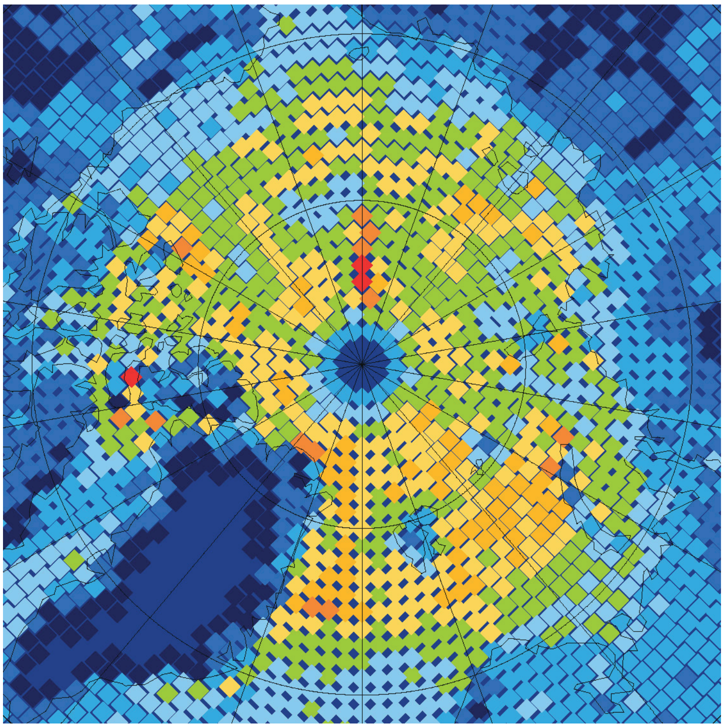
ECMWF Feature article

from Newsletter Number 168 – Summer 2021

METEOROLOGY

How APPLICATE contributed to ECMWF core activities



www.ecmwf.int/en/about/media-centre/media-resources
doi: 10.21957/ir5fk44das

This article appeared in the Meteorology section of ECMWF Newsletter No. 168 – Summer 2021, pp. 24–31.

How APPLICATE contributed to ECMWF core activities

Irina Sandu, Gabriele Arduini, Jonathan Day, Linus Magnusson, HeatherLawrence, Niels Bormann, Peter Bauer, Sarah Keeley, Gianpaolo Balsamo, Thomas Haiden

ECMWF's main goal is to continuously improve medium-range forecast skill for the benefit of its Member and Co-operating States. In recent decades, predictive skill has steadily increased in the ECMWF Integrated Forecasting System (IFS) from the tropics to polar regions. Predictive skill in the Arctic remains lower, however, than in the northern hemisphere mid-latitudes (Figure 1). ECMWF's participation in the EU's Horizon 2020 project APPLICATE stimulated a concerted effort across ECMWF to examine in more detail the challenges that limit forecast skill in Arctic regions, and to identify ways to overcome them. It also fostered close interactions between ECMWF scientists and many colleagues in national meteorological services, universities and research institutes in the Member and Co-operating States and beyond, in particular at the Alfred Wegener Institute (Germany), Stockholm University (Sweden), MET Norway, the German National Meteorological Service (DWD), the UK Met Office, and Environment and Climate Change Canada (ECCC). Moreover, it supported ECMWF's contribution to the World Meteorological Organization's Year of Polar Prediction (YOPP).

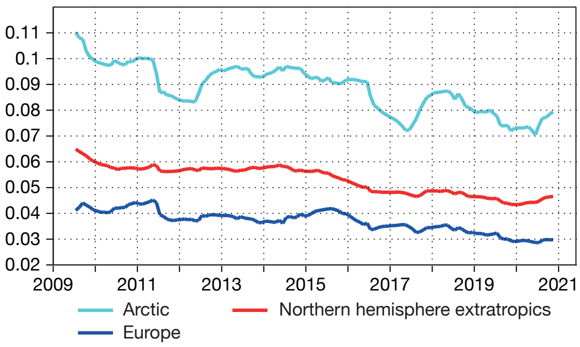


Figure 1 Fraction of large 2-metre temperature errors in the ECMWF operational ensemble forecasts (with CRPS values larger than 5 K) at day 5 for the Arctic, the northern hemisphere extratropics and Europe.

This article summarises the advances made at ECMWF in the framework of APPLICATE in the key ingredients for improving weather forecasts in the Arctic and beyond (see Box a): coupled modelling and process-based diagnostics, effective use of observations, and data assimilation and ensemble techniques.

Key ingredients for accurate weather forecasts

A

The accuracy of weather forecasts depends on the quality of the forecast model and on the initial conditions. The quality of the forecast model is key both for ensuring that the forecast errors are the smallest possible, and for an effective use of observations in data assimilation when creating the initial conditions. The initial conditions are produced with comprehensive data assimilation systems, which cover a time window (12 hours for the operational ECMWF system) in which they optimally combine the available observations with short-range forecasts to produce a best estimate of the state of the atmosphere, land and ocean including sea ice. This is called the analysis.

Observations are thus used to correct forecast errors, leading to increments in state variables such as temperature, wind, humidity and geopotential height. This process relies on the observations and their usage, including how model variables like temperature are transformed in satellite radiances and an observation bias removal or correction. It also relies on weighting the observations and short-range forecasts (or background) by the respective observation and background error covariance matrices. In the ECMWF system, this weighting depends in part on the flow-dependent background errors, which are described using the spread of a 50-member Ensemble of Data Assimilations (EDA). The EDA is an ensemble of independent 4D-Var data assimilations, in which the main analysis error sources (observation errors, model errors, and boundary condition errors) are represented by perturbing the related quantities (observations, model, sea-surface temperature, etc.). To provide reliable background errors, the spread of the EDA needs to capture both the magnitude and the variation of the errors in the short-range, as well as the correlations of these errors (Lang et al., 2019).

 doi: 10.21957/ir5fk44das

Challenges limiting predictive skill in Arctic regions

The work done within APPLICATE allowed us to better examine the specific challenges posed by Arctic regions and identify ways forward.

In terms of coupled modelling and diagnostics, the key challenges in the Arctic are related to the representation of stable boundary layers and strong near-surface temperature inversions, mixed-phase clouds, snow and sea ice, plus the coupling between these different elements of the Earth system. Work done in APPLICATE at ECMWF showed for example that fluxes of heat, momentum and radiation at the interfaces can be erroneously represented, particularly in very cold conditions (Day et al., 2020).

There are also challenges related to the use of observations at high latitudes when creating the initial conditions of weather forecasts. There are far fewer conventional observations (radiosondes, buoys) than in other regions (Figure 2a), and it is harder to assimilate them than at lower latitudes due to a variety of reasons (e.g. larger model errors, larger representativeness errors). The Arctic is well observed by polar-orbiting satellites because of their high revisit time over polar areas. An analysis of the use of Arctic observations in the IFS performed within APPLICATE, based on diagnostics from the ECMWF data assimilation system, has however shown that satellite sounding observations are particularly difficult to use in numerical weather prediction (NWP) systems over sea ice and snow covered surfaces and in the shallow polar atmosphere (again due to a variety of reasons detailed in Lawrence et al., 2019a). Figures 2b,c illustrate that the number of assimilated observations from microwave sounding channels peaking in the lower troposphere is indeed much lower during winter than during summer, in particular in regions covered by snow and sea ice.

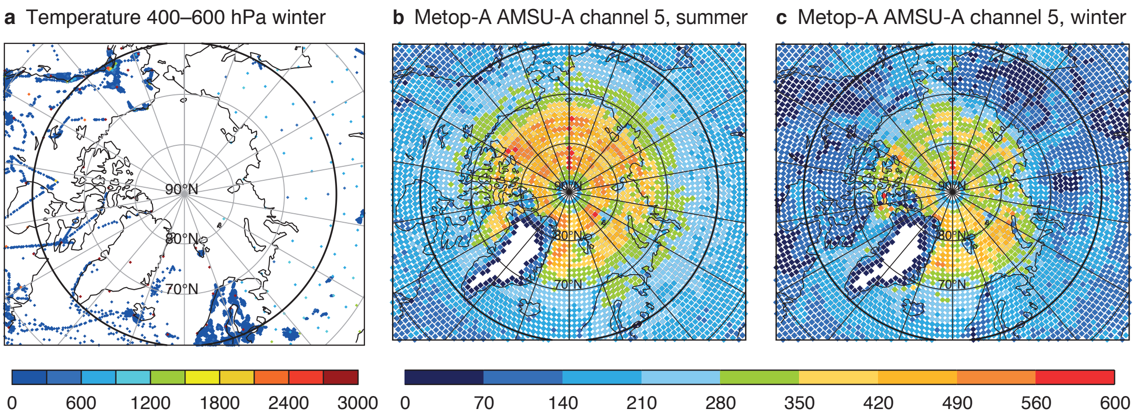


Figure 2 Number of observations assimilated in the ECMWF operational system from (a) temperature (radiosonde and aircraft) observations between 400 and 600 hPa for the period December 2017 to March 2018; (b) Metop-A AMSU-A channel 5 (peaking around 650 hPa) for June–September 2016 and (c) the same as (b) but for December 2017 to March 2018. Figure from Lawrence et al. (2019b), CC BY 4.0 (*https://creativecommons.org/licenses/by/4.0/*).

Finally, there are challenges in data assimilation methodologies. These are related, for example, to how much weight is given to observations versus the model in the data assimilation process, and how bias correction is dealt with. Work within APPLICATE has also shown that the spread of the Ensemble of Data Assimilations (EDA) is underestimated in the lower troposphere and in the upper troposphere/lower stratosphere in polar regions (Lawrence et al., 2019a). This means that the adjustments observations make to the short-range forecasts in the Arctic in these regions during the assimilation are probably too small.

The issues highlighted above all require detailed evaluation to guide progress. For this purpose, it is useful to complement the forecast evaluation against analysis, reanalysis or regular observation networks with evaluation against observations from field campaigns and supersites. A considerable effort in APPLICATE consisted in more systematically using such comprehensive suites of observations of the coupled Earth system to investigate model errors by applying newly developed process-oriented diagnostics.

Coupled modelling and novel process-based diagnostics

In terms of coupled modelling, the APPLICATE focus at ECMWF was on the representation of snow and the coupling of the atmosphere, ocean, snow and sea ice. Advances on these aspects, the representation of which currently limits forecast skill, were facilitated by the development and application of novel process-based diagnostics. Targeted diagnostics and observational verification are key for pinpointing sources of systematic model error, and for ensuring that changes to the forecasting system lead to forecast improvements for the right reasons and do not introduce compensating errors. A novel aspect within APPLICATE was to make more regular and extensive use of observations from so-called observational supersites, which include a variety of observations spanning the snow–atmosphere and sea-ice–atmosphere interfaces (Day et al., 2020).

Snow modelling

One of the main sources of forecast errors over snow-covered surfaces is the use of a bulk snow scheme in the current version of the IFS. Representing the snowpack with a single layer of snow leads to an overestimation of the thermal inertia of the snowpack, particularly for deep snowpacks. For such snowpacks, the temperature variations near the snow surface are much larger than at the base (Figure 3), and therefore a single-layer snow model overestimates the strength of the snow–atmosphere coupling. This leads to forecast biases in terms of snow depth, snow temperature and near-surface air temperature. Generally, the snow depth is too large, the near-surface air temperature too high, and its diurnal cycle is underestimated. To address these systematic errors, a multi-layer snow scheme was further developed in APPLICATE. This scheme, which builds on Dutra et al. (2012), represents the snowpack with several (up to five) layers. It also brings improvements in terms of the representation of certain physical processes, e.g. considering the penetration of solar radiation in the snowpack and a prognostic liquid water content.

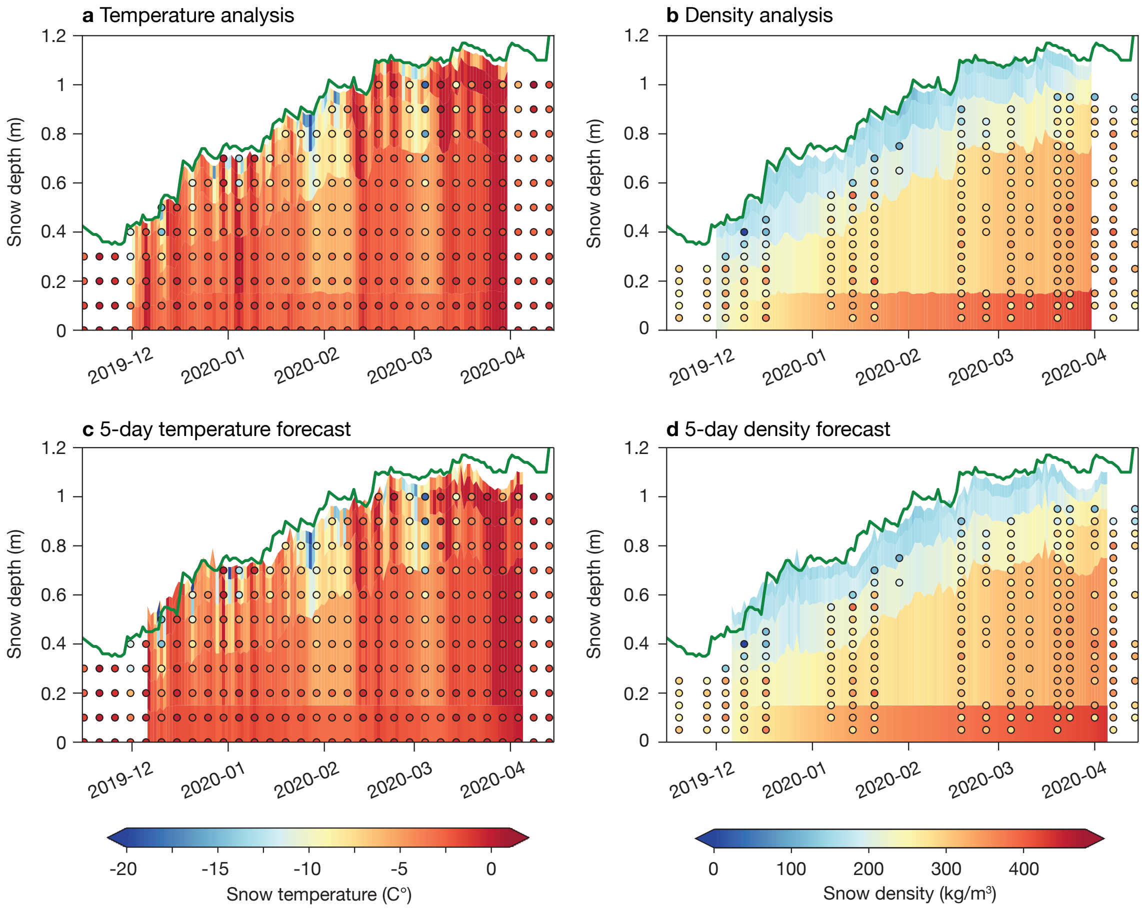


Figure 3 Time-height plots showing the analyses of (a) snow temperature and (b) snow density at Sodankylä, and 5-day forecasts of (c) snow temperature and (d) snow density, all with the multi-layer snow model (background colours) and observations (coloured dots) for the 2019/2020 season. The snow depth from observations is superimposed (green line). Observational data are courtesy of Anna Kontu (Finnish Meteorological Institute).

 doi: 10.21957/ir5fk44das

The multi-layer (ML) snow scheme was first evaluated in offline integrations and coupled deterministic medium-range forecasts starting from the operational analysis. A description of changes to the snow representation and this initial evaluation can be found in Arduini et al. (2019). More recently, complex code changes were made to be able to use the ML scheme in the data assimilation cycles, and to run the IFS in an operational-like configuration, which is used to produce operational analyses and forecasts. These included developments in the 4D-Var data assimilation system and in the snow optimum-interpolation analysis.

As the ML scheme is planned for operational implementation in IFS Cycle 48r1 in 2022/23, its performance was evaluated across the range of configurations used for operational forecasts: analysis and coupled medium-range deterministic and ensemble forecasts, monthly and seasonal forecasts. It was also assessed in the context of snow-impacted hydrology observations. Figure 4 illustrates improvements to the snow depth from pilot data assimilation experiments, in which the ML scheme is used both in the coupled ten-day forecasts and in the 4D-Var and snow optimum-interpolation analysis. The root mean square error of the forecasts of snow depth at 12 hours is reduced in the ML compared to the single-layer (SL) data assimilation experiments. This suggests that the first-guess snow depth, which is cycled from one analysis cycle to the next, is of better quality in the ML experiment.

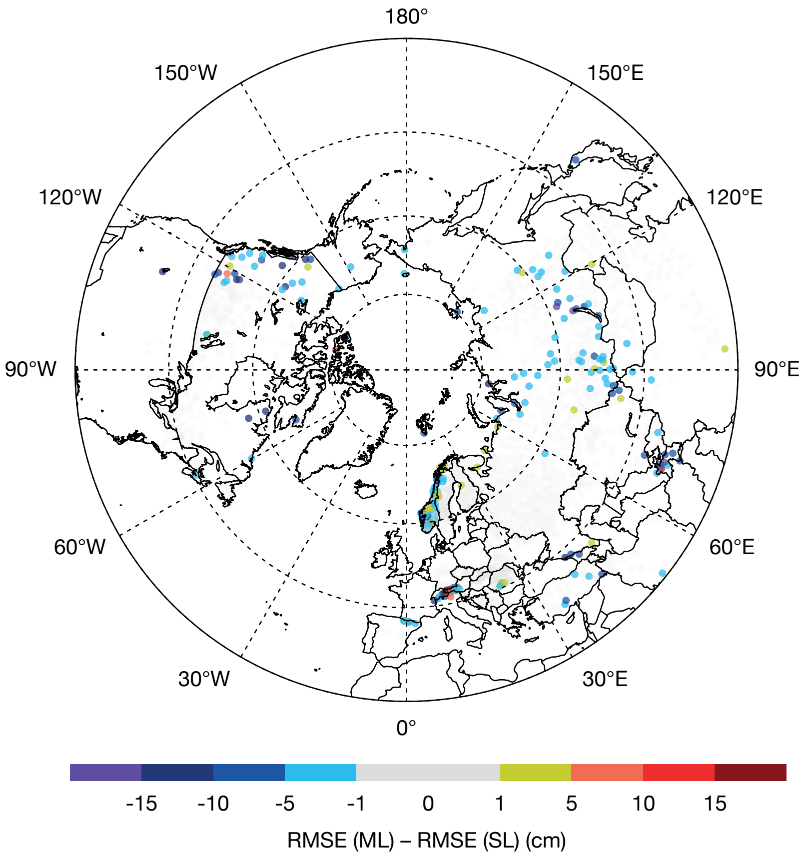


Figure 4 Difference between the root-mean-square error (RMSE) of snow depth between coupled forecasts at a lead time of t+12 hours using the multi-layer (ML) and single-layer (SL) snow schemes and initialised from a consistent analysis using a multi-layer and single-layer snow scheme, respectively, from December 2019 to January 2020.

The benefits seen in snow depth using the ML scheme are related to an increased realism in the representation of snow properties. This can be shown by using observations of internal snow temperature and density collected routinely at snow supersites like Sodankylä (Finland). The snow temperature from the analysis shows good agreement with the observations, in particular in representing the alternance of episodes of cooling and warming of the snowpack, e.g. during December 2019 (Figure 3a). The snow density is in good agreement with the observations in the upper part of the snowpack, but it is overestimated in the bottom layer (Figure 3b). This can be due to challenges in the representation of upward water vapor fluxes in the presence of large vertical temperature gradients in snowpack models. The forecasts at t+120 hours show a slight degradation compared to the analysis, in particular in the topmost layer, which can be partly associated with errors in the atmospheric forcing at this lead time (Figure 3c,d).

The impact of the ML snow scheme in these pilot data assimilation experiments on near-surface meteorological variables is evaluated using 2-metre temperature (T2m) observations from the SYNOP network. The T2m biases over Eurasia are reduced by about 1 K compared to SL experiments, confirming the results presented in Arduini et al. (2019). The root-mean-square error (RMSE) of T2m increases in the ML experiments over certain regions, for instance in Alaska and West Scandinavia (not shown). This can be partly due to an increase in variability associated with errors in other variables and processes, like cloud cover and/ or cloud microphysics, to which the new scheme is more exposed, as described in Arduini et al. (2019).

The increase in forecast variability can have a positive effect in an ensemble framework through an increase in spread. Figure 5 shows that using the ML snow scheme in ensemble forecasts generally improves the continuous ranked probability score (CRPS) of 2-metre temperature over the northern hemisphere, with some negative impact located over northwest America, the Alps, and east Asia.

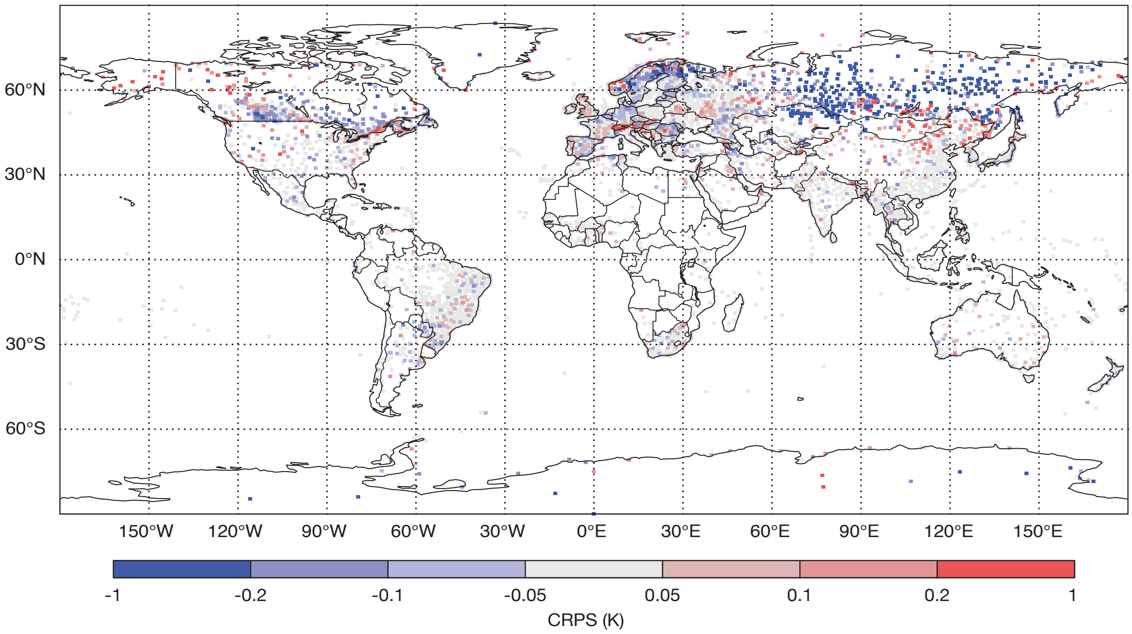


Figure 5 Difference between the continuous ranked probability score (CRPS) of 2-metre temperature of ensemble forecasts at a lead time of t+120 hours using the multi-layer (ML) and single-layer (SL) snow schemes and initialised from a consistent analysis using a multi-layer and single-layer snow scheme, respectively, from December 2019 to February 2020. Each ensemble consists of eight perturbed members. The differences are generally small in the southern hemisphere.

Coupled sea-ice–atmosphere modelling

Ocean and sea-ice models are still a fairly recent addition to NWP systems, while they have been an integral component of climate models for some time. Until recently it was assumed that sea-ice–ocean fields change so slowly that it is acceptable to keep them fixed, or to use climatological anomalies, for the period covered by global medium-range forecasts. However, coupled systems have been found to improve forecast skill in the tropics, and in certain situations errors in the position of the sea ice can lead to degradations in the skill of atmospheric forecasts. For example, during marine cold-air outbreaks, the geometry and position of the sea-ice edge exerts a strong control on turbulent exchange and can strongly influence boundary layer development hundreds of kilometres downstream of the sea ice. It can thus influence the track and intensity of hazardous polar lows on short and medium-range forecast timescales.

ECMWF's ensemble forecasts have been coupled with the ocean since 2013 and with sea ice since 2016, and ECMWF's deterministic high-resolution forecasts became coupled during the APPLICATE project (July 2018). This means that the NEMO and LIM2 ocean and sea-ice models are now used in all forecasts to evolve the ocean and sea-ice properties (Keeley & Mogensen, 2018). During APPLICATE, it was shown that a warm bias in atmospheric boundary layer temperature, downstream of the sea-ice edge during marine cold-air outbreaks, was corrected when using an interactive sea-ice model. This is because the sea-ice model accounts for the southward expansion of the sea ice in those situations. Such an expansion in sea ice can be seen in the case shown in Figure 6.

 doi: 10.21957/ir5fk44das

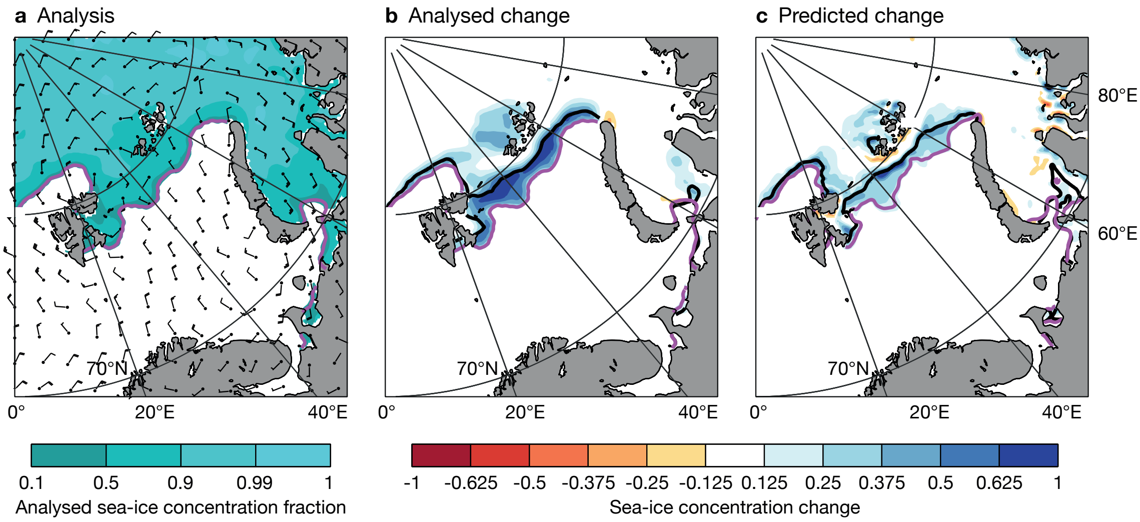


Figure 6 The plots show (a) the analysed sea-ice concentration and 10-metre wind on 28 December 2017, (b) 3-day change in analysed sea-ice concentration and the sea-ice edge between 25 December 2017 (black) and 28 December 2017 (pink), and (c) 3-day change in sea-ice concentration and the sea-ice edge in the first 3 days of an HRES forecast initialised on 25 December 2017.

Improved use of observations and data assimilation

Given how crucial the accuracy of the initial conditions is for the quality of weather forecasts, and how expensive it is to ensure the monitoring of the Earth system both from ground-based observing networks and from space, it is important to regularly assess the value extracted from current observing systems. This is even more important for the Arctic, given that the harsh meteorological conditions in this region make the maintenance of observing networks more difficult and costly than in other parts of the globe.

The value of Arctic observations

A novel aspect of APPLICATE, in which ECMWF took a leading role, consisted in examining for the first time the impact of current atmospheric Arctic observing systems on predictive skill. This was done by performing observing system experiments, in which different observing systems were removed from the data assimilation system when creating the initial conditions of weather forecasts. This type of numerical experimentation is regularly done at weather centres on a global scale to quantify the value of observations for short- and medium-range weather forecasts. The novelty in APPLICATE was to do this exercise with a particular focus on Arctic observations, and to do it in coordination with other weather centres in the framework of both APPLICATE and YOPP. Coordinated experiments were thus performed at ECMWF, ECCC and DWD with their global forecasting systems, and at Met Norway with the regional forecasting system AROME Arctic. Different types of atmospheric observations, from conventional networks (such as radiosondes, buoys, SYNOP observations) and from satellites (microwave and infrared sounders, atmospheric motion vectors and radio occultation) were removed north of 60°N for different winter and summer periods.

It was demonstrated that all Arctic observing systems have complementary positive impacts on the skill of ECMWF forecasts, both in the Arctic and in the mid-latitudes (Lawrence et al., 2019b). The impact in the mid-latitudes was shown to be primarily associated with certain flow regimes which favour the propagation of air masses from the Arctic towards the mid-latitudes. For example, removing Arctic in-situ or satellite observations during winter leads to a deterioration in forecast skill in the medium range over northern Asia during Scandinavian blocking episodes (Day et al., 2019). This is due to the fact that during such blocking episodes (a) error growth is enhanced in the European Arctic, as a result of increased baroclinicity in the region, and (b) high-amplitude planetary waves allow errors to propagate efficiently from the Arctic into the mid-latitudes.

The observing system experiments performed at ECMWF showed that conventional in-situ observations play the most important role during winter, emphasizing the need to maintain and further develop conventional observational networks, which are sparse and costly to maintain in polar regions (Figure 7a). These experiments have also shown that satellite microwave observations play the most important role during summer (Figure 7b), while for winter the use of these observations is not found to be optimal due to issues with their assimilation, in particular over snow and sea ice.

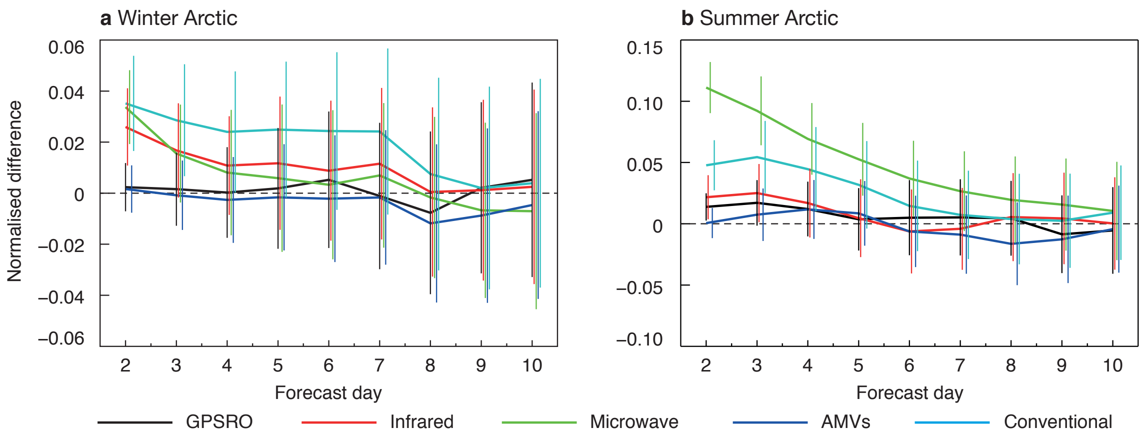


Figure 7 Normalised change in the standard deviation of forecast error for geopotential height at 500 hPa over the Arctic region (north of 60°N) during (a) winter and (b) summer. Different lines give results from observing system experiments in which certain observation types are removed when creating the initial conditions for the forecasts, with the observing systems indicated in the legend (GPSRO: bending angles from radio occultation; Infrared: radiances from hyperspectral infrared sensors; Microwave: radiances from passive microwave instruments; AMVs: Atmospheric Motion Vectors; Conventional: all in-situ observations, such as radiosondes, SYNOP observations, aircraft data, etc.). Note that forecast errors are verified against the ECMWF high-resolution operational analysis. Values are given as fractions. The intervals show a 95% confidence level. Figure from Lawrence et al. (2019b), CC BY 4.0 (*https://creativecommons.org/licenses/by/4.0/*).

Enhancing the uptake of microwave observations

The strong positive impact of microwave observations on predictive skill in summer suggests that improving their use over snow and sea ice, which is currently not optimal, is likely to further improve forecasts in the Arctic and mid-latitudes. For this to be achieved, investments are needed in all key components of NWP systems, i.e. coupled modelling, ensemble and data assimilation techniques and use of observations.

As discussed by Lawrence et al. (2019b), the uptake of microwave radiances over snow and sea ice can be enhanced through better modelling of snow, sea ice, mixed-phase clouds and shallow stable boundary layers. It can also be enhanced through a better representation of surface characteristics over sea ice and snow in the forward modelling, i.e. the radiative transfer computations used to project model variables into satellite observation space (radiances). For the forward modelling of surface-sensitive microwave radiances, improvements to the representation of surface emission/reflection are expected to be made for some instruments in IFS Cycle 48r1. In addition, the representation of skin temperature currently neglects surface penetration effects, which can be significant over snow and sea ice at microwave frequencies. This practice also contributes to systematic errors in the forward modelling. Methods for an enhanced treatment of skin temperature during the assimilation are currently being tested.

Moreover, the assumed background error covariances are important for the use of all observations, since they determine the weight given to them in the analysis, but they also play a particular role for satellite radiances. This is because they affect the vertical structure of the increments as well as the separation of radiance signals into different geophysical variables. This is particularly important where the vertical structure may not be well captured by the background. It would be interesting to further investigate how to improve the spread of the EDA in the lower troposphere, where it is currently underestimated, and to see how this may lead to a larger impact of the observations. This could be done, for example, in the context of planned developments of model uncertainty representation and ensemble resolution increases.

doi: 10.21957/ir5fk44das

Outlook

In summary, the work done in APPLICATE at ECMWF, in collaboration with many colleagues from Member and Co-operating States and beyond, has enabled progress on many aspects which are central to ECMWF's core activities and strategy for the next decade. Advances have been made in terms of coupled modelling, the use of observations and novel diagnostics, which are all key for further improving the quality of ECMWF forecasts. Avenues for further progress in these directions were also identified.

Coupled modelling: Systematic errors in the Arctic can be further reduced by taking into account snow over sea ice and by improving the thermodynamical coupling between snow, sea ice and atmosphere. Preliminary experiments indicated that accounting for snow over sea ice can improve the forecasting of strong radiative cooling events during clear skies. They also highlighted the impact of compensating errors among snow and cloud processes on the Arctic surface energy balance and the need to further improve the representation of mixed phase clouds. The research done in APPLICATE indicated that a more holistic approach, considering improvements in snow processes, mixed-phase clouds representation and turbulent mixing in stably stratified conditions, is required in the future to further improve the representation of the Arctic boundary layer in NWP systems.

Use of observations: APPLICATE further demonstrated the need to improve the uptake of microwave radiances from polar satellites over snow and sea ice. This should lead to better forecasts and also to better reanalyses, such as those produced by the EU-funded Copernicus Climate Change Service provided by ECMWF. Given that microwave sounding observations are one of the most important observation types for the quality of the initial conditions, this finding triggered a lot of interest both from the NWP community and satellite agencies. Increasing the uptake of satellite data over all surfaces (as well as in all-sky conditions) in the Integrated Forecasting System is identified as one of the priorities highlighted in the ECMWF Strategy for 2021–2030. Enhancing the uptake of satellite observations at high latitudes was recently discussed in a workshop organised by EUMETSAT and during the ESA European Polar Science week in 2020.

Novel diagnostics: Such a holistic approach to the development of coupled models requires further development in techniques to diagnose the causes of error in coupled systems which take into account the additional degrees of freedom in the coupled system. Such work will continue at ECMWF as part of the INTERACTIII project, which will utilise Arctic research station data for this purpose, and in ECMWF's ongoing contribution to YOPP.

Another important ECMWF contribution to YOPP in the framework of APPLICATE is the ECMWF YOPP dataset (Bauer et al., 2020). This freely available dataset covers the period from mid-2017 until the end of the MOSAiC field campaign in autumn 2020. This dataset also includes tendencies from model dynamics and individual physical processes, which are essential for characterising the contribution of individual processes to model state evolution and, hence, for diagnosing sources of model error. It opens thus many research opportunities with colleagues in ECMWF Member and Co-operating States and beyond.

The work described in this paper has received funding from the European Union's Horizon 2020 Research & Innovation programme through grant agreement No. 727862 APPLICATE. The content of the paper is the sole responsibility of the authors and it does not represent the opinion of the European Commission; neither is the Commission responsible for any use that might be made of the information contained herein.

This is a contribution to the Year of Polar Prediction (YOPP), a flagship activity of the Polar Prediction Project (PPP), initiated by the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO). We acknowledge the WMO WWRP for its role in coordinating this international research activity.

Further reading

Arduini, **G.**, **G. Balsamo**, **E. Dutra**, **J.J. Day**, **I. Sandu**, **S. Boussetta et al.**, 2019: Impact of a multi-layer snow scheme on near-surface weather forecasts. *Journal of Advances in Modeling Earth Systems*, **11**, 4687–4710. *https://doi.org/10.1029/2019MS001725*.

Bauer, **P.**, **I. Sandu**, **L. Magnusson**, **R. Mladek** & **M. Fuentes**, 2020: ECMWF global coupled atmosphere, ocean and sea-ice dataset for the Year of Polar Prediction 2017–2020. *Sci Data*, **7** (427). *https://doi.org/10.1038/s41597-020-00765-y*.

Day, **J.J.**, **I. Sandu**, **L. Magnusson**, **M.J. Rodwell**, **H. Lawrence**, **N. Bormann et al.**, 2019: Increased Arctic influence on the midlatitude flow during Scandinavian Blocking episodes. *Q J R Meteorol Soc.*, **145**, 3846– 3862. *https://doi.org/10.1002/qj.3673*.

Day, **J.J.**, **G. Arduini**, **I. Sandu**, **L. Magnusson**, **A. Beljaars**, **G. Balsamo et al.**, 2020: Measuring the impact of a new snow model using surface energy budget process relationships. *Journal of Advances in Modeling Earth Systems*, **12**, *https://doi.org/10.1029/2020MS002144*.

Dutra, **E.**, **P. Viterbo**, **P.M. Miranda** & **G. Balsamo**, 2012: Complexity of snow schemes in a climate model and its impact on surface energy and hydrology. *Journal of Hydrometeorology*, **13**(2), 521– 538.

Keeley, **S.** & **K. Mogensen**, 2018: Dynamic sea ice in the IFS, *ECMWF Newsletter* **No. 156**, 23–29.

Lang, **S.**, **E. Hólm**, **M. Bonavita** & **Y. Trémolet**, 2019: A 50-member Ensemble of Data Assimilations, *ECMWF Newsletter* **No. 158**, 27–29.

Lawrence, **H.**, **J. Farnan**, **I. Sandu**, **N. Bormann**, **P. Bauer**, & **L. Magnusson**, 2019a: An assessment of the use of observations in the Arctic at ECMWF, *ECMWF Technical Memorandum* **No. 845**.

Lawrence, **H.**, **N. Bormann**, **I. Sandu**, **J. Day**, **J. Farnan**, & **P. Bauer**, 2019b: Use and impact of Arctic observations in the ECMWF Numerical Weather Prediction system. *Q J R Meteorol Soc.*, **145**: 3432–3454. *https://doi.org/10.1002/qj.3628*.

 doi: 10.21957/ir5fk44das