The potential of numerical prediction systems to support the design of Arctic observing systems: Insights from the APPLICATE and YOPP projects

Received: 4 July 2021 | Revised: 4 October 2021 | Accepted: 5 October 2021 | Published on: 3 November 2021

DOI: 10.1002/qj.4182

Quarterly Journal of the Royal Meteorological Society RMetS

INVITED MANUSCRIPT

The potential of numerical prediction systems to support the design of Arctic observing systems: Insights from the APPLICATE and YOPP projects

Irina Sandu[1] | François Massonnet[2] | Guillian van Achter[2] | Juan C. Acosta Navarro[3] | Gabriele Arduini[1] | Peter Bauer[1] | Ed Blockley[4] | Niels Bormann[1] | Matthieu Chevallier[5] | Jonathan Day[1] | Mohamed Dahoui[1] | Thierry Fichefet[2] | Daniela Flocco[6] | Thomas Jung[7] | Ed Hawkins[6] | Stephane Laroche[8] | Heather Lawrence[1,4] | Jørn Kristiansen[9] | Eduardo Moreno-Chamarro[3] | Pablo Ortega[3] | Emmanuel Poan[8] | Leandro Ponsoni[2] | Roger Randriamampianina[9]

[1]European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK

[2]Université Catholique de Louvain, Brussels, Belgium

[3]Barcelona Supercomputing Centre, Barcelona, Spain

[4]Met Office, Exeter, UK

[5]Meteo-France, Toulouse, France

[6]University of Reading, Reading, UK

[7]Alfred Wegener Institute, Bremerhaven, Germany

[8]Environment and Climate Change, Gatineau, Quebec Canada

[9]Met Norway, Oslo, Norway

Correspondence
I. Sandu, European Centre for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, Reading, RG2 9AX, UK.
Email: irina.sandu@ecmwf.int

Funding information
European Commission, Grant/Award Number: 727862; Norges Forskningsråd, Grant/Award Number: 280573

Abstract

Numerical systems used for weather and climate predictions have substantially improved over past decades. We argue that despite a continued need for further addressing remaining limitations of their key components, numerical prediction systems have reached a sufficient level of maturity to examine and critically assess the suitability of Earth's current observing systems – remote and *in situ*, for prediction purposes; and that they can provide evidence-based support for the deployment of future observational networks. We illustrate this point by presenting recent, co-ordinated international efforts focused on Arctic observing systems, led in the framework of the Year of Polar Prediction and the H2020 project APPLICATE. The Arctic, one of the world's most rapidly changing regions, is relatively poorly covered in terms of *in situ* data but richly covered in terms of satellite data. In this study, we demonstrate that existing state-of-the-art datasets and targeted sensitivity experiments produced with numerical prediction systems can inform us of the added value of existing or even hypothetical Arctic observations, in the context of predictions from hourly to interannual time-scales. Furthermore, we argue that these datasets and experiments can also inform us how the uptake of Arctic observations in numerical prediction systems can be enhanced to maximise predictive skill. Based on these efforts we suggest that (a) conventional *in situ* observations in the Arctic play a particularly important role in initializing numerical weather forecasts during the winter season, (b) observations from satellite microwave sounders play a particularly important role during the summer season, and their enhanced usage over snow and sea ice is expected to further improve their impact on predictive skill in the Arctic region and beyond, (c) the deployment of a small number of *in situ* sea-ice thickness monitoring devices at strategic sampling sites in the Arctic could be sufficient to monitor most of the large-scale sea-ice volume variability, and (d) sea-ice thickness observations can improve the simulation of both the sea ice and near-surface air temperatures on seasonal time-scales in the Arctic and beyond.

KEYWORDS

Arctic, climate prediction, data assimilation, *in situ* measurements, numerical modelling, observing system design, satellite information, weather forecasting

1 | INTRODUCTION

Environmental changes in the Arctic open up new opportunities (e.g. new shipping routes), but also bring new challenges (e.g. environmental disasters such as oil spills). With the ever-growing interest in Arctic regions, the need to improve predictions from hours to years ahead and the need for near-real-time polar weather and climate monitoring all become more pressing than ever. In polar regions, however, producing such predictions is even more difficult than in other regions due to specific challenges related to process understanding (including those unique to the polar regions like rapid Arctic air-mass transformations: Pithan *et al.*, 2018), coupled modelling (e.g. representation of stable boundary layers, mixed-phase clouds, snow and sea ice, and their coupling with the atmosphere), data assimilation and observations (e.g. Bauer *et al.*, 2014; Bauer and Jung, 2016; Jung *et al.*, 2016).

It is often argued that better predictions will be made possible by improving the underlying numerical models. While this is correct, it should be remembered that weather and (initialized) climate predictions rely on four building blocks: a numerical model to represent the dynamical and physical processes of the Earth system; a comprehensive set of observations; a data assimilation scheme to create the best possible estimate of the state of the atmosphere, land, ocean and sea ice from which predictions are initialized, by optimally blending the model and the observations; and a methodology to generate an ensemble of simulations to reflect forecast uncertainty. Hereafter, numerical prediction systems (NPS) refer to the numerical systems relying on these four building blocks, which are used to produce weather and climate predictions.

Observations are crucial for weather predictions, due to their importance for deriving accurate initial conditions and for evaluating the performance of the weather forecasts. Improvements in the quality and coverage of observations and in their usage in NPS have undeniably contributed to the tremendous advances in numerical weather prediction capabilities which have taken place over recent decades (Bauer *et al.*, 2015). Similarly, observations have been instrumental to advance climate prediction capabilities by assisting the development of new physical components (e.g. Hunke *et al.* (2010) for sea ice modelling); the choice of parameters in physical parametrizations and the identification of systematic model errors, which has revealed increased realism of the climate models from one Coupled Model Intercomparison Project (CMIP) cycle to the next (e.g. Notz *et al.*, 2020).

To improve weather and climate predictions in the Arctic, enhancing the Arctic observing systems and further developing their use in NPS are as important as further developing the numerical models themselves to reduce remaining systematic biases. In this context, several questions related to Arctic observations necessitate urgent answers:

- To which degree do we make optimal use of currently available Arctic observations in numerical prediction systems?
- What cost-effective strategies can be used to reliably monitor the large-scale Arctic climate variability from *in situ* observations alone?
- What is the importance of the currently available Arctic observing systems for predictive skill in the Arctic and beyond from hours to years ahead?
- Are Arctic observations more beneficial for skill during certain types of weather regimes, as has been found for midlatitudes?

- What new Arctic observations would we need to further enhance predictive skill in the Arctic and beyond?

A concerted international effort to address these questions was made in recent years, in the framework of the Polar Prediction Project (PPP) of the World Meteorological Organization (WMO) and of its core activity the Year of Polar Prediction (YOPP), as well as the Horizon 2020 European project APPLICATE (www.applicate-h2020.eu). In these initiatives, NPS have played a central role. The investigations regarding the role and design of Arctic observing systems primarily relied on state-of-the-art datasets produced with NPS (e.g. analyses and reanalyses, climate historical reconstructions, initialized predictions and projections) and on targeted numerical experimentation using these systems.

This approach relies on the fact that, for the reasons detailed in the next section, NPS can now be reliably used to answer key questions related to the observing systems thanks to the advances made in the last decades (Bauer *et al.*, 2015; Zampieri *et al.*, 2018). NPS have indeed already been previously successfully used to assess the relative role of various observations on weather forecasting skill at a global scale (e.g. Thépaut and Kelly, 2007; Bauer and Radnoti, 2009; Radnoti, 2010; Radnoti *et al.*, 2010; 2012; Bormann *et al.*, 2019). They have also been used to determine the importance of certain Arctic observations for predictive skill from hours to seasons ahead (e.g. Inoue *et al.*, 2009; 2013; Day *et al.*, 2014; Massonnet *et al.*, 2015; Yamazaki *et al.*, 2015; Ono *et al.*, 2016; Sato *et al.*, 2017; Bushuk *et al.*, 2019).

The effort conducted in the framework of YOPP and APPLICATE embraced this approach, focusing specifically on guiding the design of Arctic observing systems using NPS and emerging statistical techniques. It also searched to further demonstrate the idea that NPS can be successfully used to answer such questions for the Arctic, despite remaining challenges that need to be tackled in these regions related to systematic model errors (e.g. cloud microphysics, stable boundary layers, sea-ice thickness), data assimilation and ensemble techniques, and observation usage. This effort relied on a variety of NPS-based techniques and a diversity of NPS, applied in a concerted manner employing co-ordinated protocols, and was made possible thanks to international cooperation. To our knowledge, a dedicated effort to answer questions related to the optimal design of Arctic observing systems to maximize predictive skill across time-scales has not been previously attempted.

This article gives an overview of this effort and uses its key findings to answer the questions posed above and to draw recommendations on how to enhance the Arctic observing systems and the uptake of Arctic observations in coupled NPS. First, we briefly review the available evidence suggesting that NPS can be successfully used to derive insights regarding Arctic observing systems. We then discuss the approaches used to derive these insights, before making a few recommendations on how to enhance the design, and future exploitation, of the Arctic observing systems and before presenting some conclusions.

2 | WHY AND HOW CAN NPS BE USED TO INFORM ARCTIC OBSERVING SYSTEM DESIGN?

The numerical systems used to produce weather forecasts, analyses and reanalyses have massively improved over the last decades. Advances in weather prediction represent a quiet revolution because they have resulted from a steady accumulation of progress in fundamental science on different fronts (numerical techniques, physical parametrizations, data assimilation methodologies), from the use of vast amounts of observations and from an exponential growth in supercomputing capacities (Bauer *et al.*, 2015). This quiet revolution has resulted in today's forecasts of large-scale weather patterns 6 days ahead being as good as forecasts 4 days ahead 20 years ago. It also led to considerable improvements of long-term reanalyses, which constitute the best possible reconstruction of the past atmospheric state obtained by blending a forecast model and observations through data assimilation with the same NPS used to produce weather forecasts. Modern reanalyses such as those produced by the Copernicus Climate Change Service (C3S) spanning the last 70 years (e.g. ERA5: Hersbach *et al.*, 2020) are crucial tools for assessing and monitoring the climate and the changes it experienced over recent decades.

In parallel to the weather prediction revolution, climate models have also steadily improved. Weather and climate models are sharing an increasing number of common elements (e.g. atmosphere and ocean dynamical cores, parametrizations of atmospheric processes, ocean physics, sea ice physics, land models, atmospheric composition (Brown *et al.*, 2012)). There is also an interest in using diagnostic tools typically used in numerical weather prediction to assess the realism of the representation of weather-type phenomena in climate models, also in support of judging whether the climate sensitivity produced by certain models can be considered credible (Palmer *et al.*, 2008; Hoskins, 2013; Palmer, 2020). These methods clearly emphasise the benefits of seamless thinking and the generic applicability of data assimilation methods for exploiting rich observational datasets.

The drive towards a more unified (seamless) approach for weather and climate modelling is further fuelled by similar scientific and computing challenges, but also by a growing interest for initialized predictions from sub-seasonal to seasonal and decadal scales. Similar to medium-range forecasts, predictions at sub-seasonal and seasonal time-scales have also improved considerably over the past decades (Stockdale *et al.*, 2018; Robertson and Vitart, 2019). Furthermore, important improvements start to emerge in decadal prediction (Smith *et al.*, 2019), including in the Arctic.

Given the increasing interest in Arctic regions, targeted efforts have been made to assess the quality of weather forecasts and of long-term global or regional reanalyses in polar regions (Jung and Leutbecher, 2007; Bauer *et al.*, 2014; Bromwich *et al.*, 2016; Jung and Matsueda, 2016; Batrak and Müller, 2019; Graham *et al.*, 2019; Vessey *et al.*, 2020; Renfrew *et al.*, 2021). These studies have demonstrated that despite the specific challenges (Jung *et al.*, 2016) and remaining issues that need to be addressed in polar regions in the four building blocks of NPS (Sandu *et al.*, 2021), short- and medium-range weather forecasts and reanalyses have improved over time in the Arctic (Bauer *et al.*, 2014; Jung and Matsueda, 2016). The skill of medium-range forecasts in the Arctic has for example improved at a similar pace, albeit it remains lower than in the midlatitudes (e.g. see figure 1 of Sandu *et al.* (2021)). Similarly, despite remaining challenges, the prospects for sub-seasonal to seasonal sea ice predictions in the Arctic also look bright (Blockley and Peterson, 2018; Zampieri *et al.*, 2018). Some forecasts conducted with dynamical models now outperform trivial benchmarks (climatological or anomaly persistence forecasts) and new techniques based on data-driven approaches show promising results, too (Andersson *et al.*, 2021).

These improvements in predictive skill corroborate the increased quality of NPS in Arctic regions, giving confidence that the datasets they produce, including the output from specifically designed numerical experimentation, can be used to answer questions regarding Arctic observing system design. This argument will be further substantiated by some concrete examples given below.

In the studies reviewed below, the questions posed in the Introduction have been addressed with various methods using NPS that can be categorised in two groups: (a) in-depth analyses of existing, consolidated datasets (in particular analyses, reanalyses, and CMIP5 and CMIP6 historical runs), and (b) targeted numerical experimentation. Some of these targeted experiments aimed at assessing the impact of different atmospheric observations on short- and medium-range weather forecasts (i.e. day–week time-scales), while others explored the impact of initialization of different sea ice variables through different techniques on predictions a few months ahead (i.e. sub-seasonal to seasonal time-scales). Regardless of the time-scale, it was important to ensure that the results were not specific to a given system. This is why the experimentation was performed with several NPS, and in certain cases it was co-ordinated to follow similar protocols and cover similar time periods.

In the following, we briefly summarise these efforts and point to the studies describing each of them in more detail. Figure 1 encapsulates in a nutshell the key results of these studies, used to formulate the recommendations for the enhanced Arctic observing system design and its exploitability in NPS.

3 | ANALYSIS OF EXISTING DATASETS

3.1 | Examining the (sub)optimal usage of Arctic atmospheric observing systems

A commonly made – and yet incorrect – assumption is that the Arctic is void of atmospheric observations. It is true that conventional observations, such as those gathered by national meteorological services through radiosonde launches, surface stations or deployment of buoys in the ocean or over the sea ice, are comparatively sparser north of 60°N than at lower latitudes. However, despite the lack of geostationary satellite data, polar regions are rather well covered by satellite observations compared to lower-latitude regions, thanks to the strong overlap of orbits of Low Earth Orbit (LEO; or polar-orbiting) satellites.

A lot can be learned about Arctic atmospheric observing systems by studying the analyses used to initialize numerical weather predictions (Lawrence *et al.*, 2019b). Figure 2 illustrates the point above by showing the number of atmospheric conventional and satellite observations assimilated in the ECMWF Integrated Forecasting System (IFS) for creating the initial conditions of weather forecasts in 2019. Opposing Equator–Pole gradients can indeed be seen for conventional and satellite observations, highlighting a decrease/increase of conventional/satellite observations from the Equator to the Poles. Another striking feature of the observational data distribution shown in Figure 2 is that a large number of observations are rejected (i.e. not assimilated) either because of too large model-data mismatch, or because of difficulties in treating observational uncertainties. Although this is a feature of all latitudes/seasons, this phenomenon is amplified in the Arctic.

Lawrence *et al.* (2019b) also showed that there is a reduced use of satellite radiances from channels peaking in the lower troposphere during winter in the ECMWF IFS, particularly over snow and sea ice (e.g. see their figure 2).

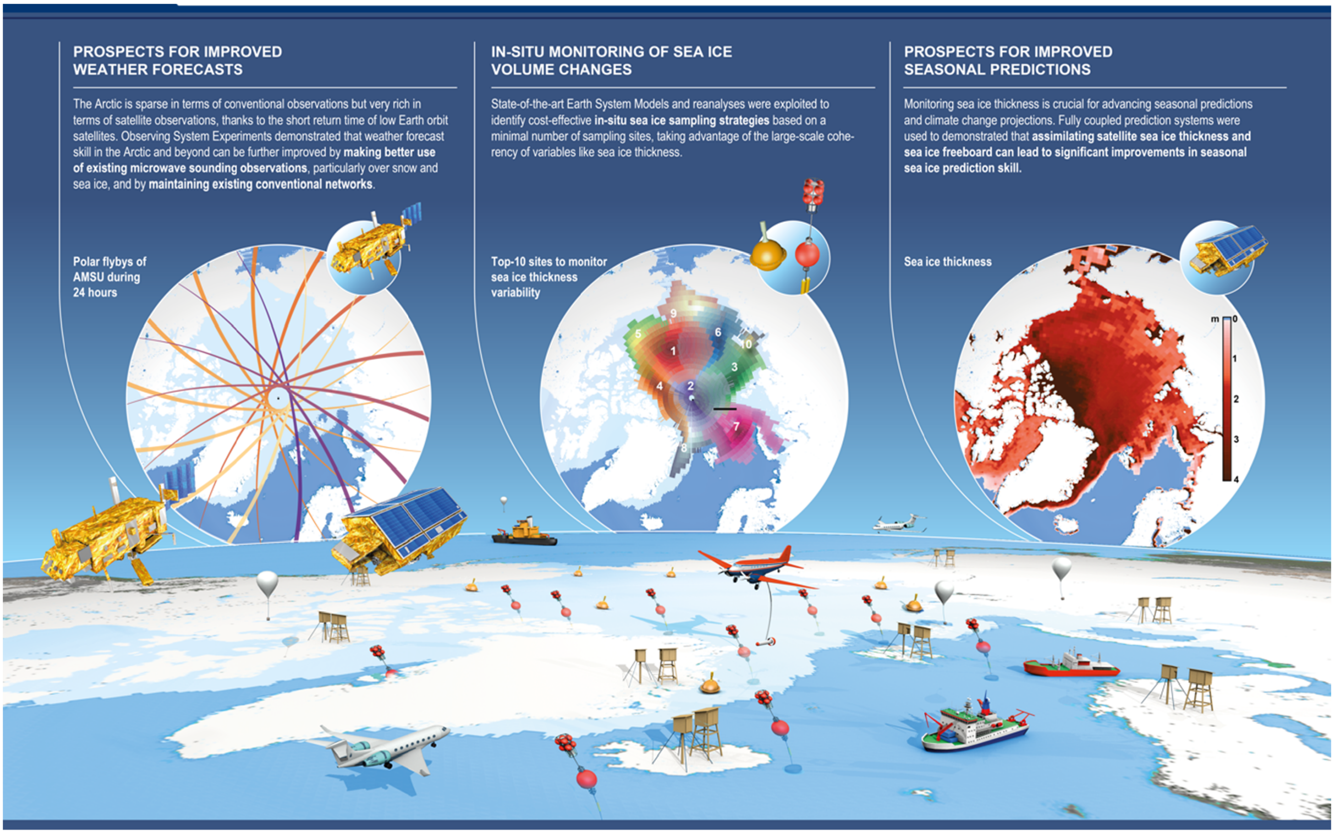

FIGURE 1 Key results of the co-ordinated efforts exploiting numerical prediction systems to inform the design and enhanced exploitability of the Arctic observing systems. [Colour figure can be viewed at wileyonlinelibrary.com]

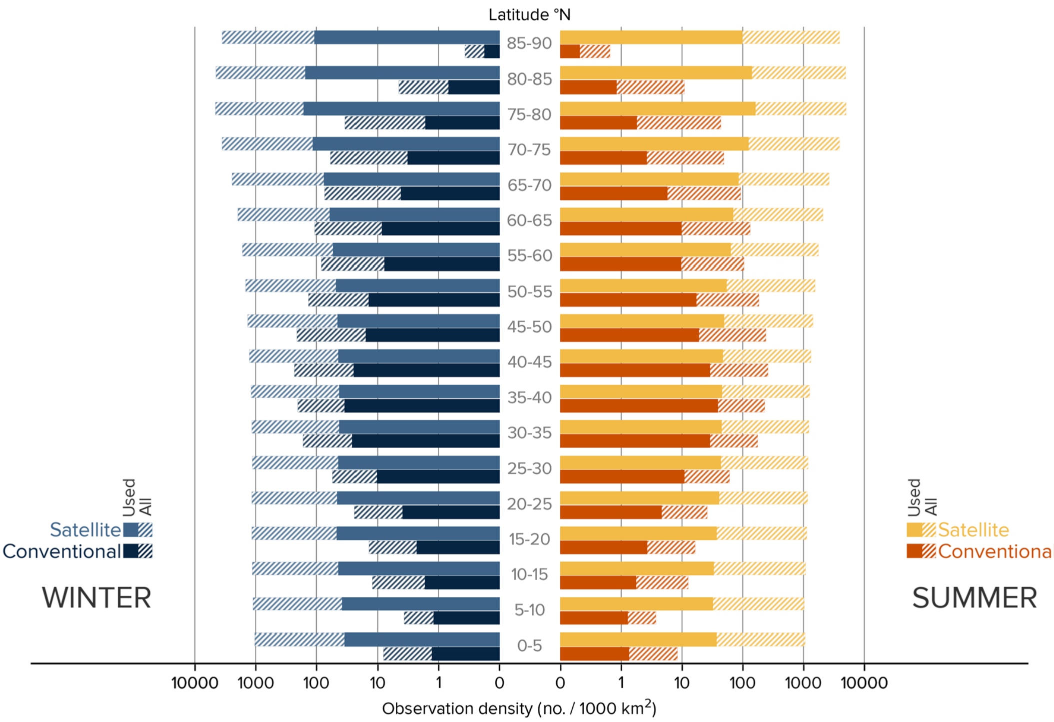

FIGURE 2 Availability and actual usage of conventional and satellite observations in the ECMWF IFS. Number of available observations (per 1,000 km^2 and per day) for different latitudes bands of the Northern Hemisphere (light shades) and the number of observations actually assimilated in the IFS (darker shades) to create the initial conditions of the weather forecasts. The data correspond to January 2019 (left) and July 2019 (right). Note the logarithmic scale. [Colour figure can be viewed at wileyonlinelibrary.com]

This is possibly related to issues in (a) the modelling of snow (Arduini *et al.*, 2019), sea ice, mixed-phase clouds and shallow stable boundary layers, (b) the assumptions regarding the surface emission and reflection over sea ice and snow, made in the radiative transfer computations used to project model variables into satellite observation space (radiances), and (c) the associated specification of background error covariances which is important for giving appropriate weights to the observations and model fields in the data assimilation. It was found, for example, that the weights given to observations in the Arctic lower troposphere and stratosphere are currently too low, which suggests that the adjustments that the observations can make in these regions when creating the initial conditions are currently limited (for more details, see Lawrence *et al.* (2019b)).

The analysis of operational diagnostics performed from the ECMWF data assimilation system, such as analysis increments, observation minus short-range forecasts, or adjoint-based techniques like the Forecast Sensitivity Observations Impact (FSOI: Cardinali, 2009) demonstrated the value of all Arctic atmospheric observations for the skill of the analyses and short-range forecasts (Lawrence *et al.*, 2019b). The FSOI analysis for example suggested that among the data available in the Arctic, the conventional observations contribute the most to reducing the global short-range forecast error during winter, while microwave observations from polar-orbiting satellites contribute the most in summer.

3.2 | Defining strategies for monitoring Arctic sea-ice volume variability

An analysis of the simulated sea-ice thicknesses in state-of-the-art climate models participating in the High Resolution Model Intercomparison Project (HighResMIP: Haarsma *et al.*, 2016) of CMIP6 has revealed that the variability of this field exhibits significant spatial auto-correlation if grid-cell averages and monthly means are considered. This finding suggests that a limited number of well-placed *in situ* monitoring stations could be sufficient to estimate the large-scale changes in sea-ice thickness and volume on interannual time-scales (Ponsoni *et al.*, 2020), especially if the *in situ* data records are complemented and cross-validated by large-scale satellite retrievals, for which large uncertainties remain (Zygmuntowska *et al.*, 2014). A proposed list of 10 sampling sites is given in Ponsoni *et al.* (2020) and is illustrated in Figure 1 (middle panel). According to their study, sea-ice thickness measurements sampled from as little as six well-placed stations are sufficient to reconstruct most (80%) of the actual sea-ice volume variability. Among these regions, they find the transition between the Beaufort, Chukchi and Central Arctic Seas (a region known as the "sea ice factory" of the Arctic), the North Pole, and the boundary between the Laptev Sea and the Central Arctic Ocean (that is, across the transpolar drift), to be top-priority sites where sea-ice thickness should be monitored.

The results should be interpreted in full awareness of the potential limitations of current general circulation models. Although NPS are our best tools for guiding observing system design, uncertainty in the decorrelation length-scales of thickness anomalies seen in coupled general circulation models (Blanchard-Wrigglesworth and Bitz, 2014) and in reanalyses (Ponsoni *et al.*, 2019) imply that the number and location of optimal sites for thickness monitoring may themselves be uncertain. This coherence might not correspond to reality for several reasons, including the lack of mechanical redistribution of sea ice in many of those models, or more simply the lack of an explicit subgrid-scale sea-ice thickness distribution. It is also worth noting that most of the sea ice models within CMIP6 models are based on the same assumptions (e.g. viscous-plastic assumption for the sea ice rheology). Such a lack of model diversity can cause an artificial robustness of the results.

This uncertainty is projected to narrow down in the future as models improve, for example, by running at higher spatial resolution, by benefiting from improved tuning of critical parameters or by accounting for more subgrid-scale processes like floe size distribution, form drag or snow. On top of that, the practicality of the Ponsoni *et al.* conclusions is limited by the fact that a measuring station at a fixed sampling site would never measure sea-ice thickness that is representative of the average conditions several dozens of km around it (which is what CMIP6 models provide), see for example Geiger *et al.* (2015).

4 | CO-ORDINATED NUMERICAL EXPERIMENTATION

4.1 | Assessing the impact of atmospheric observations on short- to medium-range predictive skill

Another important effort exploited so-called Observing System Experiments (OSEs), in which certain observations are withdrawn (denied) from data assimilation when creating the initial conditions for weather forecasts. Such experiments allow measuring the actual impact of losing certain observing systems and evaluating the influence on the medium-range forecast for a range of parameters. OSEs in which different types of atmospheric observations were denied in polar regions were performed for the first time in a co-ordinated way at several operational weather centres, including ECMWF, Environment and Climate Change Canada (ECCC), German Weather Service (DWD) and Met Norway. OSEs were performed for several seasons, among which the YOPP Special Observing Periods for the Northern Hemisphere (February to March and June to August 2018), and the analysis focused mainly on the impact of Arctic observations. The results highlighted the added value of Arctic observations for short- and medium-range forecast skill (Lawrence *et al.*, 2019a; Laroche and Poan, 2021; Randriamampianina *et al.*, 2021) by showing that:

- In global NPS, all current Arctic atmospheric observing systems increase short- and medium-range predictive skill both in polar regions and midlatitudes;
- In all the contributing global NPS, conventional Arctic observations have the largest impact in winter, while in summer the leading observing system varies from one forecasting system to another: radiances from microwave sounders play the biggest role in the ECMWF system, while conventional observations are most important at ECCC and DWD. This demonstrates that observation impacts are always subject to the sophistication/maturity of the data assimilation system, the forecast model and of the assessment and monitoring of the observations' quality;
- The use of microwave sounder observations in the ECMWF IFS is suboptimal during winter. As Lawrence *et al.* (2019b) demonstrated, fewer microwave observations are assimilated during winter than during summer, particularly over snow and sea ice. The strong positive impact of microwave observations on predictive skill in summer suggests that improving their use over snow and sea ice is likely to further improve forecasts in the Arctic and the midlatitudes, particularly during the winter season (Figure 1).
- In regional NPS (such as AROME-Arctic), there is a clear benefit in terms of short-range forecast skill from the assimilation of Arctic atmospheric observations both in the global models used to create their lateral boundary conditions, and in the regional NPS themselves (Randriamampianina *et al.*, 2021).

4.2 | Assessing the impact of sea-ice thickness initialization on seasonal forecasts

A parallel effort consisted of using numerical experimentation to explore the impacts of the sea-ice thickness initialization on predictive skill of the summer sea ice cover and atmospheric circulation. Arctic sea ice reanalyses are well constrained when it comes to their areal extent, because the assimilated datasets of sea ice concentration are available on a daily basis and at the large scale and are fairly mature. However, these reanalyses are highly scattered for thickness which is not yet routinely assimilated (Chevallier *et al.*, 2017; Uotila *et al.*, 2019). So initializing the ocean–sea-ice models from existing sea ice reanalyses might introduce initial-condition errors that will eventually translate into forecast errors.

To overcome this issue, several approaches were used in a co-ordinated manner to investigate the benefit of assimilating sea-ice thickness information. First, Blockley and Peterson (2018) assimilated sea-ice thickness, from CryoSat-2, in the Met Office GloSea coupled atmosphere–ocean–sea ice prediction system and showed that the September sea ice concentration was more successfully predicted than in experiments initialized without thickness assimilation, with a reduction in ice-edge error of around 37% (in both cases, the forecasts were initialized for a range of dates in late April and early May). These results have recently been confirmed with another coupled atmosphere–ocean–sea ice forecasting system (EC-Earth3) for the same pair of months, with the assimilation of observed sea ice freeboards employing an ensemble Kalman filter, for the year 2012. In these experiments, it was found that applying an observational (CryoSat-2) constraint on the 1 May sea ice freeboard would be sufficient to reduce the September integrated ice edge error, a measure of spatial disagreement between forecasted sea ice concentration and that of the verification dataset, by up to 25% (Massonnet *et al.*, in preparation). These advances have undeniably contributed to bridge the gap between earlier theoretical studies of sea ice predictability (e.g. Day *et al.*, 2014) that demonstrated the importance of the knowledge of spring sea-ice thickness information, and full, quasi-operational seasonal predictions with all the constraints that this implies (existence of model drift, observational errors, need to work with large ensembles). Above all, these results motivate the need for continued monitoring of radar and laser altimetry measurements of sea-ice thickness. Thin ice measurements (e.g. through passive microwave imagery from the Soil Moisture and Ocean Salinity mission from the European Space Agency (ESA)) will also be needed to initialize models in peripheral seas (Yang *et al.*, 2014).

Second, a two-model co-ordinated experiment using the Hadley Centre Global Environment Model version 3 (HadGEM3) and EC-Earth3 global coupled models was conducted to assess the role of Arctic winter sea-ice thickness information on seasonal to annual predictability (Flocco *et al.*, in preparation). By following a data-denial approach in idealised set-ups, it was shown that neglecting the initial January sea-ice thickness information in these prediction systems led to a systematic reduction in prediction skill for sea ice variables, but also for air temperature in that month (as expected) and in September (less expected). This finding supports the existence of long-range predictability mechanisms through re-emergence, that is, an increase in auto-correlation of time series after an initial decrease, confirming earlier studies (e.g. Blanchard-Wrigglesworth *et al.*, 2011; Bushuk and Giannakis, 2017). More importantly, the results obtained underlined the need to sustain large-scale measurements of sea-ice thickness with satellite campaigns during winter (Figure 1).

5 | HOW SHOULD THE ARCTIC OBSERVING SYSTEMS BE ENHANCED?

5.1 | Enhancements of the Arctic observing systems in YOPP

The OSEs performed by Lawrence *et al.* (2019a) demonstrated that removing Arctic atmospheric *in situ* or satellite observations during the data assimilation process used to create the initial conditions for the forecasts, deteriorates midlatitude synoptic forecast skill in the medium range, particularly over northern Asia. Day *et al.* (2019) further analysed these OSEs and showed that the deterioration is largest during Scandinavian blocking episodes, during which: (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 more effectively propagate from the Arctic into midlatitudes. The important role played by Scandinavian blocking in modulating the influence of the Arctic on midlatitudes is further corroborated in so-called relaxation experiments, in which the state variables are relaxed, or nudged towards an atmospheric reanalysis throughout the forecast range, and through a diagnostic analysis of the ERA5 reanalyses and reforecasts.

The idea that the influence of the Arctic on midlatitudes is flow-dependent was proposed in the studies of Jung *et al.* (2014) and Semmler *et al.* (2018) using a relaxation approach. The Day *et al.* (2019) study corroborates these results and, importantly, further demonstrates that the periods when the Arctic has a strong influence on northern Asia are also periods when the midlatitudes have a strong influence on the Arctic. In particular, during Scandinavian blocking episodes, the crests of planetary waves extend into the Arctic causing high baroclinicity along warm intrusions and associated rapid error growth. This regime also provides a mechanism for errors to be propagated out of the Arctic as well. Although Day *et al.* (2019) have focused on such patterns over Eurasia, it is likely that similar high-amplitude planetary waves in the Pacific–North-American sector would lead to a similar influence over North America, as also suggested by Yamazaki *et al.* (2021). Day *et al.* (2019) suggested that increasing the observational coverage in regions of high error growth in the European Arctic during Scandinavian blocking events should improve forecast errors, not just in this part of the Arctic, but also downstream over northern Asia. Indeed, such flow-dependent error growth suggests that a more dynamic observing network, where more observations are taken in regions and during weather conditions for which error growth is fast, might be advantageous. In fact, this is reminiscent of the targeted observation efforts carried out in THe Observing system Research and Predictability EXperiment (THORPEX) (Parsons *et al.*, 2017). It looks that the Arctic is particularly well suited to this concept (which has been largely abandoned in recent years for midlatitudes).

These results partly contributed to the change in approach that was adopted for the third period of enhanced Arctic observations conducted as part of YOPP. This took the form of a targeted observing period (TOP), which was different from the earlier special observing periods (SOPs) held in 2018, during which additional radiosondes were released around the whole Arctic every day for an extended period of time. In the TOPs, extra observations were only requested during selected meteorological situations of enhanced relevance for the Arctic. Additional radiosondes were launched from different stations situated along warm air intrusions in order to shed light on the processes governing these situations, which were shown by Day *et al.* (2019) to be particularly hard to predict. During the period of this warm air intrusion event, when the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) ice camp was located north of Svalbard, four radiosondes per day were launched at several upstream locations and seven per day on board the *Polarstern*.

5.2 | Long-term enhancements of the conventional observational networks

Results of the OSEs performed at ECMWF and other centres in the framework of YOPP, H2020 APPLICATE and Alertness (a project led by Met Norway) have demonstrated the importance of conventional observations in the Arctic, particularly for the winter season during which they were found to be the leading observing system relative to microwave radiances, infrared radiances, Global

Positioning System Radio Occultation (GPSRO) and atmospheric motion vectors (AMVs). This impact is particularly impressive given that conventional observations make up only 4–6% of all assimilated observations north of 60°N (Figure 2). Results of the OSEs suggest that radiosonde data are responsible for approximately half of the overall impact of conventional data in the ECMWF and ECCC forecasting systems, indicating that these observations are particularly important. While these observations are more expensive to obtain at high latitudes, these data are needed for reducing forecast errors in the Arctic winter and a key recommendation is that these sites should be maintained. Where possible, extending the conventional network, in particular in areas where there are currently no conventional observations, is also expected to lead to improved forecasts.

The analysis of climate model simulations has revealed the possibility of generating large-scale reconstructions of sea-ice volume from a small number of well-placed sampling devices measuring sea-ice thickness (Ponsoni *et al.*, 2020). This idea is particularly appealing, given that in the real world deploying conventional sampling sites comes at a cost (human, financial, logistical). More out-of-sample tests are required, for example, with independent sea ice reanalyses, other types of numerical simulations, higher-resolution output, to test whether the 10 stations highlighted in Figure 1 are sufficient to reconstruct the real-world sea-ice volume anomalies. Even if this result proves to be robust with other datasets, we should keep in mind that NPS cannot represent metre-scale variations of sea-ice thickness, which will provide a challenge when turning this idea of a minimal number of stations into a concrete campaign strategy. In addition, sea ice is a highly mobile medium so that mooring drifting buoys to the sea ice cover would probably not be enough to sample sea-ice thickness in a spatially representative way. There are (Eulerian) alternatives to buoys, like bottom-mounted upward-looking sonars (Figure 2) or airborne remote sensing of sea-ice thickness from low-altitude flying aircraft (e.g. NASA Operation IceBridge: Kurtz *et al.*, 2013), which could provide the desired sea-ice thickness estimates that, averaged together, would better match the model spatial scales.

6 | ENSURE UNINTERRUPTED SATELLITE MONITORING AND ENCOURAGE BACK-EXTENSIONS OF THE SATELLITE RECORD

The studies described above demonstrate the value of current polar satellite observations – both sampling the atmosphere and the sea ice – for predictive skill from hours to seasons ahead both in the Arctic and midlatitudes. The key recommendation here is to ensure the continued monitoring from space of key variables in the atmosphere, ocean and sea ice. With the scheduled end of the ICESat2, Sentinel-3 and CryoSat2 missions in 2024–2025 and the start of the ESA Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission only in 2027 at the earliest, there is likely to be a 2–3-year gap in Arctic sea-ice thickness monitoring. Even though current operational seasonal prediction systems do not assimilate sea-ice thickness information, this might well be the case in several years from now. The unavailability of such valuable thickness information could adversely affect the quality of seasonal predictions. For microwave sounding observations, we currently benefit from many old satellites that are operating well beyond their design life, and the benefit from having the present range of satellites has been highlighted by Duncan and Bormann (2020) globally as well as for the Arctic region. It is recommended to maintain or even improve the available sampling, including through initiatives such as the Arctic Weather Satellite (www.esa.int/aws).

In parallel to these efforts in sustaining the existing infrastructure, there is an increasing demand to develop innovative approaches to extend the satellite record of sea-ice thickness back in time for as long as possible. According to the pioneering work of Laxon *et al.* (2003), estimates of Arctic sea-ice thickness could be obtained as early as 1993 and the early days of radar altimetry, with the launch of the European Remote Sensing (ERS) 1 and 2 satellites on which a Ku radar altimeter was installed. Such a long-term back-extension of the sea-ice thickness data would be a significant advancement, allowing operational centres to perform seasonal hindcasts over significantly longer reforecast periods, thus allowing better estimating the lead-dependent forecast biases and in this way improve the *a posteriori* correction of forecasts. We strongly encourage future work that would contribute to producing such a back-extension of sea-ice thickness.

7 | HOW TO ENHANCE THE USE OF EXISTING OBSERVATIONS

7.1 | Improved use of available atmospheric satellite observations

The OSEs performed for atmospheric observations (e.g. Lawrence *et al.*, 2019a) also allowed identifying key areas of development for enhancing the use of atmospheric satellite observations and thereby improving forecast skill in both the Arctic itself and the midlatitudes.

While microwave radiances in summer were found to be the most important part of the observing systems in the Arctic, they have a reduced impact in winter relative to other observation types, primarily due to their suboptimal assimilation over snow and sea ice. The assimilation of microwave radiances over snow and sea ice could be improved through better modelling of snow properties (depth, density, temperature, albedo, emissivity), both in the physical model of the snow and in forward models used to represent satellite observations accurately in snow-covered regions. Building blocks to make these improvements are already being developed. These include improvements in snow models (e.g. the multi-layer snow model such as that developed by Arduini *et al.* (2019)), as well as fast and accurate radiative transfer models for snow that can simulate the full array of satellite observations available. A number of such models have been developed (Wiesmann and Mätzler, 1999; Lemmetyinen *et al.*, 2010; Picard *et al.*, 2013) and, as a first step, efforts are needed to evaluate them for use in NWP. Recently, the Helsinki University of Technology (HUT) model developed by Lemmetyinen *et al.* (2010) has been evaluated at ECMWF for low-frequency microwave observations (6–10 GHz: Hirahara *et al.*, 2020). Crucially, however, evaluation is also needed at higher frequencies (50–60 GHz, 183–190 GHz). The radiative transfer forward model over snow and sea ice, for which there are known problems with the current treatment of surface emission and reflection (as discussed by Lawrence *et al.*, 2019a), should also be improved. In operational weather prediction centres, the surface emission/reflection is usually treated as specular and the emissivity and/or skin temperature over land and sea ice is retrieved prior to assimilation from a window channel. This method is subject to higher errors over snow and sea ice than over snow-free land, leading to higher systematic differences between observations and forecasts and a suboptimal use of the data, as discussed by Lawrence *et al.* (2019a). Again, solutions such as using a representation of Lambertian surface effects are being tested at the moment and will be reported on in future studies.

Infrared radiances were also found to have a positive impact on forecasts in the Arctic at ECMWF, and improvements in the use of these observations are also likely to lead to benefits to forecasts in the Arctic and midlatitudes. At ECMWF, non-surface sensitive infrared observations were recently added over land leading to a large positive impact on short- and medium-range forecast skill (Eresmaa *et al.*, 2017). Developments in using tropospheric channels over land are therefore likely to lead to improvements in forecast skill in the Arctic. This would require accurate modelling of the surface emission and reflection for infrared frequencies, to support the addition of these channels over land. In addition, cloud detection in the infrared remains challenging over cold surfaces (Jeppesen *et al.*, 2019) as is the representation of mixed-phase clouds, and dedicated attention to these aspects is recommended.

7.2 | Improved use of sea ice observations

The EC-Earth3 and HadGEM3 coupled systems are now capable of assimilating a wealth of polar observations (sea ice concentration, seawater temperature and salinity, sea-ice thickness and sea ice freeboard) using different assimilation approaches, from nudging and flux adjustment methods to variational approaches (3D-Var) and sequential approaches (ensemble Kalman filter). Sensitivity experiments have clearly demonstrated that the uptake of sea ice observations in these climate prediction systems is beneficial for the skill in Arctic seasonal predictions, corroborating the results obtained by Blockley and Peterson (2018) with an operational seasonal prediction system, Met Office Global Seasonal (GloSea). These results demonstrate the importance of sea-ice thickness initialization for predictions up to several months ahead and pave the way for assimilating these observations in the next generation of operational seasonal prediction systems.

8 | CONCLUSIONS

The work conducted in the framework of APPLICATE and YOPP reviewed here has demonstrated that NPS and ensuing datasets can be successfully used to extract a wealth of information regarding the impacts of existing Arctic observations, and define pathways to improve their uptake in prediction systems and the design of future observing systems.

It has allowed us to answer, at least in part, the questions regarding Arctic observing system design and exploitability posed in the Introduction:

- *To which degree do we make optimal use of currently available Arctic observations in numerical prediction systems?*
  The uptake of current Arctic atmospheric and sea ice observations in NPS is limited due to remaining challenges in coupled modelling, data assimilation and ensemble techniques, and observation usage (including their quality assessment). Further developing the NPS to overcome these challenges is key for enhancing observation uptake, and ultimately for further improving prediction.
- *What cost-effective strategies can be used to reliably monitor the large-scale Arctic climate variability from* in situ *observations alone?*

A few well-placed bottom-moored buoys could allow us to reliably monitor the large-scale Arctic sea-ice volume variability. The cost of investing into, placing and recovering these buoys has not to be underestimated. Numerical models can provide guidance for optimising the spatial distribution of these buoys to retain a maximum of sea-ice volume variability.

- *What is the importance of the currently available Arctic observing systems for predictive skill in the Arctic and beyond from hours to years ahead?*
  Existing Arctic observing systems have positive and complementary impacts on predictive skill from hours to seasons ahead; with conventional observations playing a dominant role during winter and microwave satellite observations playing a dominant role during summer (in systems with a high level of maturity in terms of the use of these data in polar regions) for short- to medium-range skill; and sea-ice thickness for example playing an important role in predictive skill at sub-seasonal to seasonal time ranges.
- *Are Arctic observations more beneficial for skill during certain types of weather regimes, as has been found for midlatitudes?*
  Similar to what was previously found for midlatitudes, Arctic observations are more beneficial for predictive skill in midlatitudes for certain weather regimes (i.e. Scandinavian blocking).
- *What new Arctic observations would we need to further enhance predictive skill in the Arctic and beyond?*
  Predictive skill can both be enhanced by adding new types of Arctic observations (e.g. snow and sea ice surface temperatures) and by ensuring the continuity of existing observing systems, and by improving their exploitation in NPS.

A clear message of this work is that investment in observing systems must be carried out synergistically with the investment in NPS. Investments to further improve all key components of prediction systems (coupled modelling, use of observations, data assimilation, and ensemble prediction techniques) may be more important than investments in observations themselves, in particular in polar regions where the specific challenges posed in each of these aspects are larger than in other parts of the globe. These challenges limit the extent to which observations can contribute to creating accurate initial conditions for weather forecasts, as well as an accurate, consistent and comprehensive depiction of past conditions through long-term reanalyses. For example, improving the use of microwave observations, which is currently suboptimal over snow and sea ice, would benefit not only weather forecasts, but also future reanalyses such as those produced by the Copernicus Climate Change Service (ECMWF ReAnalysis fifth generation, ERA5; Copernicus Arctic Regional ReAnalysis, CARRA) for time periods as far back as 1979, when the first microwave sounding instrument was launched.

The quality of predictions and monitoring at high latitudes also critically depends on ensuring that all cryosphere relevant parameters and – in particular the sea ice, which has experienced and will continue to experience dramatic changes in areal coverage, thickness, extent and age – are monitored as continuously as possible and that no data gaps occur due to discontinued or postponed satellite missions. Ensuring a maximum of diversity in the type of retrievals (e.g. altimetry and passive microwave from satellites; airborne remote sensing; moorings – anchored buoys on the ice or even on the ocean floor; upward looking sonars) is key to avoiding the unfortunate possibility of data gaps that would be highly detrimental to the realisation of predictions. The availability of various observational datasets is also an advantage when it comes to independent evaluation of NPS output like sea ice reanalyses (Chevallier *et al.*, 2017), which currently are very poorly constrained for sea-ice thickness.

Moreover, models and observations should form a "healthy ecosystem" where cross-fertilisation enriches and drives the development of each effort. An increased collaboration between the observation and modelling communities is thus strongly encouraged as models benefit from observations and vice versa. Adopting a routine, model-based perspective on the monitoring and optimisation of observing systems is urgently required to ensure that the data that will be collected in future observational campaigns or through enhanced observing systems are used optimally in numerical prediction systems, and hence will result in maximised predictive skill.

Strengthening efforts towards the convergence of weather and climate modelling capabilities, and more generally resource and expertise sharing as well as a reduction in the duplication of efforts is essential. Finally, it is also important to continue to (financially) support coordination and scientific underpinning of community efforts such as those led by the WMO WWRP Polar Prediction Project, which are instrumental for defining the scientific challenges and priorities and for channelling efforts for increasing predictive skill in polar regions and beyond.

ACKNOWLEDGEMENTS

This study was supported by the APPLICATE project (727862), which was funded by the European Union's Horizon 2020 research and innovation programme. It was also supported by the Norwegian Research Council project no. 280573 "Advanced models and weather prediction in the Arctic: enhanced capacity from observations and polar process representations (ALERTNESS)". 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 co-ordinating this international research activity. The authors would also like to thank Alexander Cress for performing the observing system experiments at the German Weather Service (DWD), Martin Künsting for designing Figure 1; and John Methven, Jun Inoue and two anonymous reviewers for providing comments on the manuscript.

AUTHOR CONTRIBUTIONS

Irina Sandu: Conceptualization; writing – original draft; writing – review and editing. **Francois Massonnet:** Conceptualization; writing – original draft; writing – review and editing. **Guillian Van Achter:** Writing – original draft; writing – review and editing. **Juan Acosta Navarro:** Writing – original draft; writing – review and editing. **Gabriele Arduini:** Writing – original draft; writing – review and editing. **Peter Bauer:** Writing – original draft; writing – review and editing. **Ed Blockley:** Writing – original draft; writing – review and editing. **Niels Bormann:** Writing – original draft; writing – review and editing. **Matthieu Chevallier:** Writing – original draft; writing – review and editing. **Jonathan Day:** Writing – original draft; writing – review and editing. **Thierry Fichefet:** Writing – original draft; writing – review and editing. **Daniela Flocco:** Writing – original draft; writing – review and editing. **Thomas Jung:** Writing – original draft; writing – review and editing. **Ed Hawkins:** Writing – original draft; writing – review and editing. **Stephane Laroche:** Writing – original draft; writing – review and editing. **Heather Lawrence:** Writing – original draft; writing – review and editing. **Jørn Kristiansen:** Writing – original draft; writing – review and editing. **Eduardo Moreno-Chamarro:** Writing – original draft; writing – review and editing. **Pablo Ortega:** Writing – original draft; writing – review and editing. **Emmanuel Poan:** Writing – original draft; writing – review and editing. **Leandro Ponsoni:** Writing – original draft; writing – review and editing. **Roger Randriamampianina:** Writing – original draft; writing – review and editing.

ORCID

Irina Sandu https://orcid.org/0000-0002-1215-3288
François Massonnet https://orcid.org/0000-0002-4697-5781
Gabriele Arduini https://orcid.org/0000-0002-6564-1699
Stephane Laroche https://orcid.org/0000-0002-4886-5535
Eduardo Moreno-Chamarro https://orcid.org/0000-0002-7931-5149

REFERENCES

Andersson, T.R., Hosking, J.S., Pérez-Ortiz, M., Paige, B., Elliott, A., Russell, C., Law, S., Jones, D.C., Wilkinson, J., Phillips, T., Byrne, J., Tietsche, S., Sarojini, B.B., Blanchard-Wrigglesworth, E., Aksenov, Y., Downie, R. and Shuckburgh, E. (2021) Seasonal Arctic sea ice forecasting with probabilistic deep learning. *Nature Communications*, 12(1), 5124. https://doi.org/10.1038/s41467-021-25257-4.

Arduini, G., Balsamo, G., Dutra, E., Day, J.J., Sandu, I., Boussetta, S. and Haiden, T. (2019) Impact of a multi-layer snow scheme on near-surface weather forecasts. *Journal of Advances in Modeling Earth Systems*, 11(12), 4687–4710. https://doi.org/10.1029/2019MS001725.

Batrak, Y. and Müller, M. (2019) On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice. *Nature Communications*, 10(1), 4170. https://doi.org/10.1038/s41467-019-11975-3.

Bauer, P. and Jung, T. (2016) Editorial for the Quarterly Journal's special issue on polar prediction. *Quarterly Journal of the Royal Meteorological Society*, 142(695), 537–538. https://doi.org/10.1002/qj.2639.

Bauer, P., Magnusson, L., Thépaut, J.-N. and Hamill, T.M. (2014) Aspects of ECMWF model performance in polar areas. *Quarterly Journal of the Royal Meteorological Society*, 142(695), 583–596. https://doi.org/10.1002/qj.2449.

Bauer, P. and Radnoti, G. (2009) *Study on Observing System Experiments (OSEs) for the evaluation of degraded EPS/post-EPS instrument scenarios*. Reading: Report available from ECMWF, p. 99.

Bauer, P., Thorpe, A. and Brunet, G. (2015) The quiet revolution of numerical weather prediction. *Nature*, 525(7567), 47–55. https://doi.org/10.1038/nature14956.

Blanchard-Wrigglesworth, E., Armour, K.C., Bitz, C.M. and DeWeaver, E. (2011) Persistence and inherent predictability of Arctic sea ice in a GCM ensemble and observations. *Journal of Climate*, 24(1), 231–250. https://doi.org/10.1175/2010JCLI3775.1.

Blanchard-Wrigglesworth, E. and Bitz, C.M. (2014) Characteristics of Arctic sea-ice thickness variability in GCMs. *Journal of Climate*, 27(21), 8244–8258. https://doi.org/10.1175/JCLI-D-14-00345.1.

Blockley, E.W. and Peterson, K.A. (2018) Improving Met Office seasonal predictions of Arctic sea ice using assimilation of CryoSat-2 thickness. *The Cryosphere*, 12(11), 3419–3438. https://doi.org/10.5194/tc-12-3419-2018.

Bormann, N., Lawrence, H. and Farnan, J. (2019) Global observing system experiments in the ECMWF assimilation system. ECMWF Technical Memorandum No. 839. Available at: https://www.ecmwf.int/en/elibrary/18859-global-observing-system-experiments-ecmwf-assimilation-system.

Bromwich, D.H., Wilson, A.B., Bai, L.-S., Moore, G.W.K. and Bauer, P. (2016) A comparison of the regional Arctic system reanalysis and the global ERA-interim reanalysis for the Arctic. *Quarterly Journal of the Royal Meteorological Society*, 142(695), 644–658. https://doi.org/10.1002/qj.2527.

Brown, A., Milton, S., Cullen, M.J.P., Golding, B., Mitchell, J. and Shelly, A. (2012) Unified modeling and prediction of weather and climate: a 25-year journey. *Bulletin of the American Meteorological Society*, 93(12), 1865–1877. https://doi.org/10.1175/BAMS-D-12-00018.1.

Bushuk, M. and Giannakis, D. (2017) The seasonality and interannual variability of Arctic sea ice reemergence. *Journal of Climate*, 30(12), 4657–4676. https://doi.org/10.1175/JCLI-D-16-0549.1.

Bushuk, M., Yang, X., Winton, M., Msadek, R., Harrison, M., Rosati, A. and Gudgel, R. (2019) The value of sustained ocean observations for sea ice predictions in the Barents Sea. *Journal of Climate*, 32(20), 7017–7035. https://doi.org/10.1175/JCLI-D-19-0179.1.

Cardinali, C. (2009) Monitoring the observation impact on the short-range forecast. *Quarterly Journal of the Royal Meteorological Society*, 135(638), 239–250. https://doi.org/10.1002/qj.366.

Chevallier, M., Smith, G.C., Dupont, F., Lemieux, J.-F., Forget, G., Fujii, Y., Hernandez, F., Msadek, R., Peterson, K.A., Storto, A., Toyoda, T., Valdivieso, M., Vernieres, G., Zuo, H., Balmaseda, M., Chang, Y.-S., Ferry, N., Garric, G., Haines, K., Keeley, S., Kovach, R.M., Kuragano, T., Masina, S., Tang, Y.M., Tsujino, H. and Wang, X.C. (2017) Intercomparison of the Arctic sea ice cover in global ocean–sea ice reanalyses from the ORA-IP project. *Climate Dynamics*, 49(3), 1107–1136. https://doi.org/10.1007/s00382-016-2985-y.

Day, J.J., Hawkins, E. and Tietsche, S. (2014) Will Arctic sea ice thickness initialization improve seasonal forecast skill? *Geophysical Research Letters*, 41(21), 7566–7575. https://doi.org/10.1002/2014GL061694.

Day, J.J., Sandu, I., Magnusson, L., Rodwell, M.J., Lawrence, H., Bormann, N. and Jung, T. (2019) Increased Arctic influence on the midlatitude flow during Scandinavian blocking episodes. *Quarterly Journal of the Royal Meteorological Society*, 145(725), 3846–3862. https://doi.org/10.1002/qj.3673.

Duncan, D. and Bormann, N. (2020) On the addition of microwave sounders and NWP skill, including assessment of FY-3D sounders. ECMWF Report No. 55. Available at: https://www.ecmwf.int/en/elibrary/19760-addition-microwave-sounders-and-nwp-skill-including-assessment-fy-3d-sounders

Eresmaa, R., Lupu, C. and McNally, A.P. (2017) *Assimilation of tropospheric-sensitive infrared radiances over land*. Presentation at ITSC-21, Darmstadt, Germany, 1 December. Available at: https://cimss.ssec.wisc.edu/itwg/itsc/itsc21/program/1december/1400_10.01_Eresmaa_ITSC21_IR_Over_Land.pdf

Geiger, C., Müller, H.-R., Samluk, J.P., Bernstein, E.R. and Richter-Menge, J. (2015) Impact of spatial aliasing on sea-ice thickness measurements. *Annals of Glaciology*, 56(69), 353–362. https://doi.org/10.3189/2015AoG69A644.

Graham, R.M., Cohen, L., Ritzhaupt, N., Segger, B., Graversen, R.G., Rinke, A., Walden, V.P., Granskog, M.A. and Hudson, S.R. (2019) Evaluation of six atmospheric reanalyses over Arctic sea ice from winter to early summer. *Journal of Climate*, 32(14), 4121–4143. https://doi.org/10.1175/JCLI-D-18-0643.1.

Haarsma, R.J., Roberts, M.J., Vidale, P.L., Senior, C.A., Bellucci, A., Bao, Q., Chang, P., Corti, S., Fučkar, N.S., Guemas, V., von Hardenberg, J., Hazeleger, W., Kodama, C., Koenigk, T., Leung, L.R., Lu, J., Luo, J.-J., Mao, J., Mizielinski, M.S., Mizuta, R., Nobre, P., Satoh, M., Scoccimarro, E., Semmler, T., Small, J. and von Storch, J.-S. (2016) High resolution model intercomparison project (HighResMIP v1.0) for CMIP6. *Geoscientific Model Development*, 9(11), 4185–4208. https://doi.org/10.5194/gmd-9-4185-2016.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.-N. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Hirahara, Y., de Rosnay, P. and Arduini, G. (2020) Evaluation of a microwave emissivity module for snow covered area with CMEM in the ECMWF integrated forecasting system. *Remote Sensing*, 12(18), 2946. https://doi.org/10.3390/rs12182946.

Hoskins, B. (2013) The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science. *Quarterly Journal of the Royal Meteorological Society*, 139(672), 573–584. https://doi.org/10.1002/qj.1991.

Hunke, E.C., Lipscomb, W.H. and Turner, A.K. (2010) Sea-ice models for climate study: retrospective and new directions. *Journal of Glaciology*, 56(200), 1162–1172. https://doi.org/10.3189/002214311796406095.

Inoue, J., Enomoto, T. and Hori, M.E. (2013) The impact of radiosonde data over the ice-free Arctic Ocean on the atmospheric circulation in the Northern Hemisphere. *Geophysical Research Letters*, 40(5), 864–869. https://doi.org/10.1002/grl.50207.

Inoue, J., Enomoto, T., Miyoshi, T. and Yamane, S. (2009) Impact of observations from Arctic drifting buoys on the reanalysis of surface fields. *Geophysical Research Letters*, 36(8), 864–869. https://doi.org/10.1029/2009GL037380.

Jeppesen, J.H., Jacobsen, R.H., Inceoglu, F. and Toftegaard, T.S. (2019) A cloud detection algorithm for satellite imagery based on deep learning. *Remote Sensing of Environment*, 229, 247–259. https://doi.org/10.1016/j.rse.2019.03.039.

Jung, T., Gordon, N.D., Bauer, P., Bromwich, D.H., Chevallier, M., Day, J.J., Dawson, J., Doblas-Reyes, F., Fairall, C., Goessling, H.F., Holland, M., Inoue, J., Iversen, T., Klebe, S., Lemke, P., Losch, M., Makshtas, A., Mills, B., Nurmi, P., Perovich, D., Reid, P., Renfrew, I.A., Smith, G., Svensson, G., Tolstykh, M. and Yang, Q.H. (2016) Advancing polar prediction capabilities on daily to seasonal time scales. *Bulletin of the American Meteorological Society*, 97(9), 1631–1647. https://doi.org/10.1175/BAMS-D-14-00246.1.

Jung, T., Kasper, M.A., Semmler, T. and Serrar, S. (2014) Arctic influence on subseasonal midlatitude prediction. *Geophysical Research Letters*, 41(10), 3676–3680. https://doi.org/10.1002/2014GL059961.

Jung, T. and Leutbecher, M. (2007) Performance of the ECMWF forecasting system in the Arctic during winter. *Quarterly Journal of the Royal Meteorological Society*, 133(626), 1327–1340. https://doi.org/10.1002/qj.99.

Jung, T. and Matsueda, M. (2016) Verification of global numerical weather forecasting systems in polar regions using TIGGE data. *Quarterly Journal of the Royal Meteorological Society*, 142(695), 574–582. https://doi.org/10.1002/qj.2437.

Kurtz, N.T., O'Farrell, S.L., Studinger, M., Galin, N., Harbeck, J.P., Lindsay, R., Onana, V.D., Panzer, B. and Sonntag, J.G. (2013) Sea ice thickness, freeboard, and snow depth products from operation IceBridge airborne data. *The Cryosphere*, 7(4), 1035–1056. https://doi.org/10.5194/tc-7-1035-2013.

Laroche, S. and Poan, E. (2021) Impact of terrestrial and satellite observations over the Arctic on the ECCC global weather forecasts during the YOPP Special Observing Periods. In preparation.

Lawrence, H., Bormann, N., Sandu, I., Day, J., Farnan, J. and Bauer, P. (2019a) Use and impact of Arctic observations in the ECMWF numerical weather prediction system. *Quarterly Journal of the Royal Meteorological Society*, 145(725), 3432–3454. https://doi.org/10.1002/qj.3628.

Lawrence, H., Farnan, J., Sandu, I., Bormann, N., Bauer, P. and Magnusson, L. (2019b) *An assessment of the use of observations in the Arctic at ECMWF*. ECMWF Technical Memorandum 845.

Laxon, S., Peacock, N. and Smith, D. (2003) High interannual variability of sea ice thickness in the Arctic region. *Nature*, 425(6961), 947–950. https://doi.org/10.1038/nature02050.

Lemmetyinen, J., Pulliainen, J., Rees, A., Kontu, A., Qiu, Y. and Derksen, C. (2010) Multiple-layer adaptation of HUT snow emission model: comparison with experimental data. *IEEE Transactions on Geoscience and Remote Sensing*, 48(7), 2781–2794. https://doi.org/10.1109/TGRS.2010.2041357.

Massonnet, F., Fichefet, T. and Goosse, H. (2015) Prospects for improved seasonal Arctic sea ice predictions from multivariate data assimilation. *Ocean Modelling*, 88, 16–25. https://doi.org/10.1016/j.ocemod.2014.12.013.

Notz, D., Dörr, J., Bailey, D.A., Blockley, E.W., Bushuk, M., Debernard, J.B., Dekker, E., DeRepentigny, P., Docquier, D., Fučkar, N.S., Fyfe, J.C., Jahn, A., Holland, M., Hunke, E., Iovino, D., Khosravi, N., Massonnet, F., Madec, G., O'Farrell, S.P. and Vancoppenolle, M. (2020) Arctic sea ice in CMIP6. *Geophysical Research Letters*, 47(10), e2019GL086749. https://doi.org/10.1029/2019GL086749.

Ono, J., Inoue, J., Yamazaki, A., Dethloff, K. and Yamaguchi, H. (2016) The impact of radiosonde data on forecasting sea-ice distribution along the Northern sea route during an extremely developed cyclone. *Journal of Advances in Modeling Earth Systems*, 8(1), 292–303. https://doi.org/10.1002/2015MS000552.

Palmer, T.N. (2020) Short-term tests validate long-term estimates of climate change. *Nature*, 582(7811), 185–186. https://doi.org/10.1038/d41586-020-01484-5.

Palmer, T.N., Doblas-Reyes, F.J., Weisheimer, A. and Rodwell, M.J. (2008) Toward seamless prediction: calibration of climate change projections using seasonal forecasts. *Bulletin of the American Meteorological Society*, 89(4), 459–470. https://doi.org/10.1175/BAMS-89-4-459.

Parsons, D.B., Beland, M., Burridge, D., Bougeault, P., Brunet, G., Caughey, J., Cavallo, S.M., Charron, M., Davies, H.C., Niang, A.D., Ducrocq, V., Gauthier, P., Hamill, T.M., Harr, P.A., Jones, S.C., Langland, R.H., Majumdar, S.J., Mills, B.N., Moncrieff, M., Nakazawa, T., Paccagnella, T., Rabier, F., Redelsperger, J.-L., Riedel, C., Saunders, R.W., Shapiro, M.A., Swinbank, R., Szunyogh, I., Thorncroft, C., Thorpe, A.J., Wang, X., Waliser, D., Wernli, H. and Toth, Z. (2017) THORPEX research and the science of prediction. *Bulletin of the American Meteorological Society*, 98(4), 807–830. https://doi.org/10.1175/BAMS-D-14-00025.1.

Picard, G., Brucker, L., Roy, A., Dupont, F., Fily, M., Royer, A. and Harlow, C. (2013) Simulation of the microwave emission of multi-layered snowpacks using the dense media radiative transfer theory: the DMRT-ML model. *Geoscientific Model Development*, 6(4), 1061–1078. https://doi.org/10.5194/gmd-6-1061-2013.

Pithan, F., Svensson, G., Caballero, R., Chechin, D., Cronin, T.W., Ekman, A.M.L., Neggers, R., Shupe, M.D., Solomon, A., Tjernström, M. and Wendisch, M. (2018) Role of air-mass transformations in exchange between the Arctic and mid-latitudes. *Nature Geoscience*, 11(11), 805–812. https://doi.org/10.1038/s41561-018-0234-1.

Ponsoni, L., Massonnet, F., Docquier, D., Van Achter, G. and Fichefet, T. (2020) Statistical predictability of the Arctic sea ice volume anomaly: identifying predictors and optimal sampling locations. *The Cryosphere*, 14(7), 2409–2428. https://doi.org/10.5194/tc-14-2409-2020.

Ponsoni, L., Massonnet, F., Fichefet, T., Chevallier, M. and Docquier, D. (2019) On the timescales and length scales of the Arctic sea ice thickness anomalies: a study based on 14 reanalyses. *The Cryosphere*, 13(2), 521–543. https://doi.org/10.5194/tc-13-521-2019.

Radnoti, G. (2010) *Study on Observing System Experiments (OSEs) for the evaluation of degraded European radiosonde and AMDAR scenarios for the EUCOS Operational Programme – Upper-air network redesign*. Study Report, ECMWF, Shinfield Park, Reading RG2 9AX, UK.

Radnoti, G., Bauer, P., McNally, A.P., Cardinali, C., Healy, S. and de Rosnay, P. (2010) *ECMWF study on the impact of future developments of the space-based observing system on Numerical Weather Prediction*. ECMWF Technical Memorandum No. 638, 117 pp. European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK.

Radnoti, G., Bauer, P., McNally, A.P. and Horani, A. (2012) *ECMWF study to quantify the interaction between terrestrial and space-based observing systems on Numerical Weather Prediction skill*. ECMWF Technical Memorandum No. 679.

Randriamampianina, R., Bormann, N., Køltzow, M.A.Ø., Lawrence, H., Sandu, I. and Wang, Z.Q. (2021) Relative impact of observations on a regional Arctic numerical weather prediction system. *Quarterly Journal of the Royal Meteorological Society*, 147(737), 2212–2232. https://doi.org/10.1002/qj.4018.

Renfrew, I.A., Barrell, C., Elvidge, A.D., Brooke, J.K., Duscha, C., King, J.C., Kristiansen, J., Cope, T.L., Moore, G.W.K., Pickart, R.S., Reuder, J., Sandu, I., Sergeev, D., Terpstra, A., Våge, K. and Weiss, A. (2021) An evaluation of surface meteorology and fluxes over the Iceland and Greenland seas in ERA5 reanalysis: the impact of sea ice distribution. *Quarterly Journal of the Royal Meteorological Society*, 147(734), 691–712. https://doi.org/10.1002/qj.3941.

Robertson, A.W. and Vitart, F. (2019) *Sub-Seasonal to Seasonal Prediction: The gap between weather and climate forecasting*. Amsterdam, The Netherlands: Elsevier.

Sandu, I., Arduini, G., Day, J., Magnusson, L., Lawrence, H., Bormann, N., Bauer, P., Balsamo, G. and Haiden, T. (2021) *How APPLICATE contributed to ECMWF core activities*. ECMWF Newsletter No. 168. https://www.ecmwf.int/en/newsletter/168/meteorology/how-applicate-contributed-ecmwf-core-activities

Sato, K., Inoue, J., Yamazaki, A., Kim, J.-H., Maturilli, M., Dethloff, K., Hudson, S.R. and Granskog, M.A. (2017) Improved forecasts of winter weather extremes over midlatitudes with extra Arctic observations. *Journal of Geophysical Research: Oceans*, 122(2), 775–787. https://doi.org/10.1002/2016JC012197.

Semmler, T., Jung, T., Kasper, M.A. and Serrar, S. (2018) Using NWP to assess the influence of the Arctic atmosphere on midlatitude weather and climate. *Advances in Atmospheric Sciences*, 35(1), 5–13. https://doi.org/10.1007/s00376-017-6290-4.

Smith, D.M., Eade, R., Scaife, A.A., Caron, L.-P., Danabasoglu, G., DelSole, T.M., Delworth, T., Doblas-Reyes, F.J., Dunstone, N.J., Hermanson, L., Kharin, V., Kimoto, M., Merryfield, W.J., Mochizuki, T., Müller, W.A., Pohlmann, H., Yeager, S. and Yang, X. (2019) Robust skill of decadal climate predictions. *Npj Climate and Atmospheric Science*, 2(1), 1–10. https://doi.org/10.1038/s41612-019-0071-y.

Stockdale, T., Balmaseda, M., Johnson, S., Ferranti, L., Molteni, F., Magnusson, L., Tietsche, S., Vitart, F., Decremer, D., Weisheimer, A., Roberts, C., Balsamo, G., Keeley, S., Mogensen, K., Zuo, H., Mayer, M. and Monge-Sanz, B.M. (2018) *SEAS5 and the future evolution of the long-range forecast system*. ECMWF Technical Memorandum No. 835.

Thépaut, J.-N. and Kelly, G. (2007) *Relative contributions from various terrestrial observing systems in the ECMWF NWP system*. Final ECMWF report of the EUCOS Space Terrestrial Study. EUCOS.

Uotila, P., Goosse, H., Haines, K., Chevallier, M., Barthélemy, A., Bricaud, C., Carton, J., Fučkar, N., Garric, G., Iovino, D., Kauker, F., Korhonen, M., Lien, V.S., Marnela, M., Massonnet, F., Mignac, D., Peterson, K.A., Sadikni, R., Shi, L., Tietsche, S., Toyoda, T., Xie, J.P. and Zhang, Z.R. (2019) An assessment of ten ocean reanalyses in the polar regions. *Climate Dynamics*, 52(3), 1613–1650. https://doi.org/10.1007/s00382-018-4242-z.

Vessey, A.F., Hodges, K.I., Shaffrey, L.C. and Day, J.J. (2020) An inter-comparison of Arctic synoptic scale storms between four global reanalysis datasets. *Climate Dynamics*, 54(5), 2777–2795. https://doi.org/10.1007/s00382-020-05142-4.

Wiesmann, A. and Mätzler, C. (1999) Microwave emission model of layered snowpacks. *Remote Sensing of Environment*, 70(3), 307–316. https://doi.org/10.1016/S0034-4257(99)00046-2.

Yamazaki, A., Inoue, J., Dethloff, K., Maturilli, M. and König-Langlo, G. (2015) Impact of radiosonde observations on forecasting summertime Arctic cyclone formation. *Journal of Geophysical Research: Atmospheres*, 120(8), 3249–3273. https://doi.org/10.1002/2014JD022925.

Yamazaki, A., Miyoshi, T., Inoue, J., Enomoto, T. and Komori, N. (2021) EFSO at different geographical locations verified with observing-system experiments. *Weather and Forecasting*, 36(4), 1219–1236. https://doi.org/10.1175/WAF-D-20-0152.1.

Yang, Q., Losa, S.N., Losch, M., Tian-Kunze, X., Nerger, L., Liu, J., Kaleschke, L. and Zhang, Z. (2014) Assimilating SMOS sea ice thickness into a coupled ice-ocean model using a local SEIK filter. *Journal of Geophysical Research: Oceans*, 119(10), 6680–6692. https://doi.org/10.1002/2014JC009963.

Zampieri, L., Goessling, H.F. and Jung, T. (2018) Bright prospects for Arctic sea ice prediction on subseasonal time scales. *Geophysical Research Letters*, 45(18), 9731–9738. https://doi.org/10.1029/2018GL079394.

Zygmuntowska, M., Rampal, P., Ivanova, N. and Smedsrud, L.H. (2014) Uncertainties in Arctic sea ice thickness and volume: new estimates and implications for trends. *The Cryosphere*, 8(2), 705–720. https://doi.org/10.5194/tc-8-705-2014.

How to cite this article: (2021) The potential of numerical prediction systems to support the design of Arctic observing systems: Insights from the APPLICATE and YOPP projects. *Quarterly Journal of the Royal Meteorological Society*, 147(741), 3863–3877. Available from: https://doi.org/10.1002/qj.4182