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The Year of Polar Prediction (YOPP): Achievements, Impacts, and Lessons Learnt

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ABSTRACT: The Year of Polar Prediction (YOPP), an international research initiative organized by the World Meteorological Organization's (WMO) World Weather Research Program from 2013 to 2022, aimed to markedly enhance environmental prediction capabilities in the polar regions and beyond, particularly in the context of a rapidly changing climate. YOPP achieved this through a concerted effort in observation, modeling, verification, user engagement, and educational activities. This article offers a comprehensive overview of YOPP's key outcomes and impacts, using a dual approach that merges qualitative success stories with quantitative metrics. Scientifically, the focus is on the role of polar observations in improving prediction accuracy, enhanced understanding of processes to support model development, advancements in forecast verification, particularly in sea ice prediction, an improved understanding of the interconnections between polar and midlatitude regions, and effective user engagement. This paper also discusses how these scientific discoveries have been converted into practical applications, emphasizing the route from science to services. Additionally, it summarizes the education, communication, outreach, and coordination efforts employed to maximize YOPP's impact. Finally, the article provides a series of recommendations for future research, informed by the insights gained from YOPP's experiences and recent radical developments in technology.

SIGNIFICANCE STATEMENT: The Year of Polar Prediction (YOPP) was a landmark initiative aimed at enhancing our ability to predict environmental changes in the polar regions, areas that are increasingly affected by climate change. By integrating global efforts in observation, modeling, and data analysis, YOPP has significantly contributed to improve the accuracy of weather and climate forecasts in these critical zones, and beyond. These advancements matter because they provide crucial insights into polar processes along with their remote impacts, enhance global prediction models, and inform stakeholders about predictive capabilities. The project's focus on user engagement and education ensures that these scientific achievements translate into practical benefits. The collaborative spirit of YOPP exemplifies how international scientific cooperation can address some of the most pressing environmental challenges of our time.

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1. Introduction

In the 2000s, the world witnessed a rising interest in the polar regions. This surge was predominantly driven by the amplification of anthropogenic climate change effects in these areas, especially the Arctic (e.g., Moritz et al. 2002; Arctic Climate Impact Assessment 2005). The polar regions, traditionally perceived as remote and less relevant to people, began to emerge as focal points of concern due to their sensitivity to climate change and their significant role in Earth's climate system. Simultaneously, there was a noticeable increase in planned economic and transportation activities in these regions. This development brought about an unprecedented demand for comprehensive and integrated observational and predictive information regarding weather and climate to manage the opportunities and risks that came with increased activities but also the challenges for local communities to manage day-to-day lives in a rapidly changing world (Goessling et al. 2016b).

At the same time, it became increasingly evident that there existed substantial gaps in our understanding and predictive capabilities. The polar regions, often overshadowed by a focus on lower- and midlatitudes in international research efforts, suffered from a lack of predictive capacity across time scales (Bauer et al. 2016b; Jung et al. 2016). This deficiency posed significant challenges for reliable decision-making, impacting not only local but also nonlocal activities in lower latitudes.

In light of these challenges and the growing global significance of the polar regions, and as a contribution to the legacy to the International Polar Year (IPY) 2007/08 (e.g., Renfrew and Kristjánsson 2009; Kristjánsson and Kolstad 2011), the World Meteorological Organization recognized the urgent need for focused and coordinated action. In 2013, the WMO made a decisive move to address these gaps by launching the Polar Prediction Project (PPP). Originally one of several priorities under the PPP, the Year of Polar Prediction (YOPP) swiftly

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became the project's focal point, underscoring the urgent need to enhance environmental prediction in the polar regions and beyond (Goessling et al. 2016b; Bromwich et al. 2020).

Central to YOPP's mission was enabling a significant improvement in environmental prediction capabilities for the polar regions and beyond (Fig. 1). This involved coordinating a period of intensive observing, modeling, verification, user-engagement, and educational activities. By bringing together researchers, forecasters, and stakeholders, YOPP aimed not only to advance scientific understanding but also to foster a more comprehensive approach to polar prediction. This included engaging users of polar forecasts in the endeavor to ensure

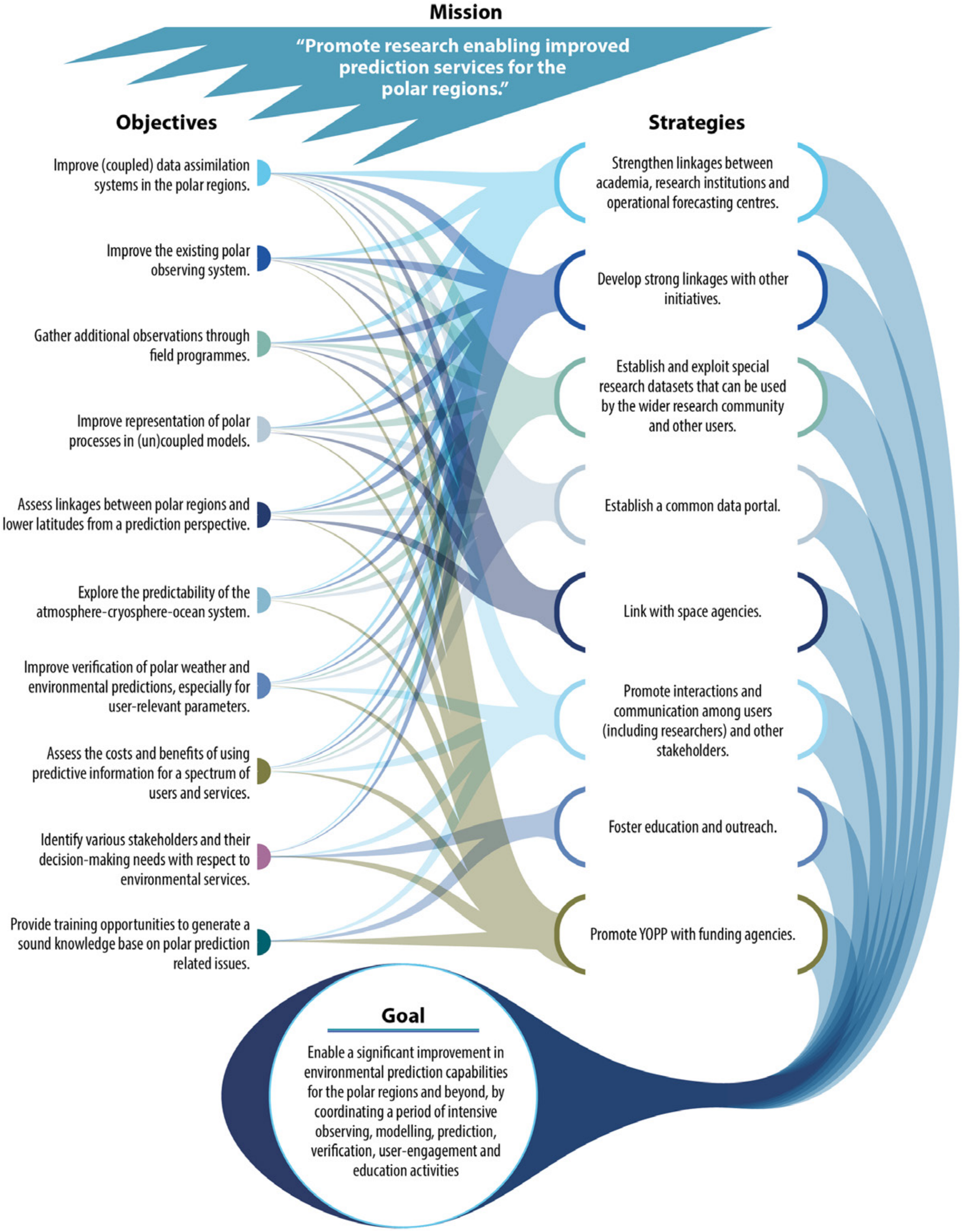

Fig. 1. Overarching goal of YOPP along with specific objectives and strategies to achieve the objectives. The success of YOPP can be evaluated based on the progress made toward its overarching goal and the achievement of its more specific objectives.

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the practical applicability of research findings, at times to coproduce research and to promote education and awareness about the polar regions' significance in the global climate system. YOPP, thus, stands as a pivotal initiative in transforming our abilities to provide environmental forecasts in polar regions and beyond.

In this article, we provide a summary of important accomplishments and impacts of YOPP, both qualitatively and quantitatively [a comprehensive discussion of quantitative accomplishments is given in Jung and Wilson (2022)]. We will outline the significant advancements made in environmental prediction capabilities, highlighting the successes and challenges encountered. Additionally, we will explore the various ways in which YOPP has influenced user engagement and education in the realm of polar prediction. Alongside documenting these achievements, we will offer explanations for why YOPP can be considered a success, analyzing the factors and strategies that contributed to its effectiveness. Drawing from these insights, we will also provide recommendations for future endeavors similar to YOPP, including important emerging themes that have not been sufficiently addressed.

2. User perspective and needs

From the beginning of the planning process, it was considered crucial to involve forecast users to guarantee that their requirements and potential contributions would be incorporated into YOPP. To achieve this, user representatives were invited to join and contribute to YOPP conferences and workshops. In addition, from 2015, the Polar Prediction Project's Societal and Economic Research and Applications (PPP-SERA) Task Team was in place, a team of social scientists and service delivery specialists, aimed at carrying out and coordinating research projects contributing to a more nuanced understanding of the diverse needs of key users of polar environmental forecasts. The team also showcased the need for transdisciplinary collaborations and coproduction approaches to ensure long-term societal benefits from improved environmental forecasting abilities (Thoman et al. 2017). PPP-SERA undertook a thorough analysis of the actor-scape of various user groups and service providers in the polar regions, the activities and mobilities of user groups, their information needs, and their current and preferred methods of accessing services and products (Dawson et al. 2017; Stewart et al. 2020; Haavisto et al. 2020). We further explore the social-science outcomes below.

3. Scientific outcomes

a. Observations and their impacts on prediction. In planning YOPP, it became clear that answering the following questions was essential for enhancing forecasting abilities in the polar regions and beyond:

- How significantly do current polar observations impact forecast accuracy, and do we utilize existing polar observations to their fullest potential?
- What new observations are required to further improve forecast accuracy in these regions?
- What should an optimal future polar observation system look like?

To tackle these questions, YOPP implemented a multifaceted approach (e.g., Bromwich et al. 2020; Sandu et al. 2021; Jung et al. 2023; Bromwich et al. 2024). This included two special observing periods (SOPs) in the Arctic and the Antarctic and targeted observing periods (TOPs), one in the Arctic and seven in the Antarctic. Reports of model performance during these SOPs are being published (e.g., Casati et al. 2023; Renfrew et al. 2021). Additionally, a series of coordinated observing system experiments (OSEs) using both global and limited area numerical weather prediction (NWP) systems were integral to the strategy.

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Before the SOPs and TOPs, a cost-effective radiosonde frequency was experimentally proposed based on OSEs (e.g., Inoue et al. 2015). Overall, YOPP saw the launch of over 10 000 additional radiosondes and 250 buoys deployed in both hemispheres.

During YOPP, it was found that although conventional observations are scarce in the Arctic compared to the high density of data from polar-orbiting satellites, both observation types significantly enhance forecast accuracy. Conventional data improve forecast skill by up to 5%, particularly in winter, due to their ability to capture vertical structure, while satellite data, especially microwave radiances, play a dominant role in other seasons (Fig. 2). Withholding atmospheric motion vectors (AMVs), infrared, and global positioning system radio occultation (GPSRO) observations appears to lead to improved forecast skill beyond 5 days. Whether this is due to sampling uncertainty at longer lead times or issues in the uptake of the observation by the forecasting system remains to be seen.

For global NWP systems like the one used at the European Centre for Medium-Range Weather Forecasts (ECMWF), the Arctic atmospheric observing system notably improves short- and medium-range forecast skill, not only in polar regions but also in midlatitudes (Lawrence et al. 2019). Similarly, in regional NWP systems, such as AROME-Arctic, assimilating Arctic atmospheric observations significantly benefits short-range forecasts. This improvement is due to two factors, enhanced skill of the global model (Lawrence et al. 2019), which is used for providing lateral boundary conditions to the regional NWP system, and improved skill within the regional domain (Randriamampianina et al. 2021).

The influence of polar observations on midlatitude weather, and vice versa, was found to be closely tied to the behavior of the large-scale circulation (Day et al. 2019). A strongly meandering jet stream enhances these interconnections, while a more zonal flow tends to weaken them (Jung et al. 2014; Semmler et al. 2016, 2018; Day et al. 2019). This insight, along with findings from OSEs that deny additional observations, underscores the importance of flow-dependent, targeted observing periods so-called TOPs. With the aid of extra radiosondes in the Arctic region, the flow-dependent approach targeting potential vorticity was also applied to each weather type in the midlatitudes, e.g., cold spells, hurricanes, and typhoons (Sato et al. 2017, 2018, 2020).

The utilization of microwave sounder observations during winter, especially over snow and ice, was shown not to be optimal. In the lower troposphere, for instance, fewer microwave

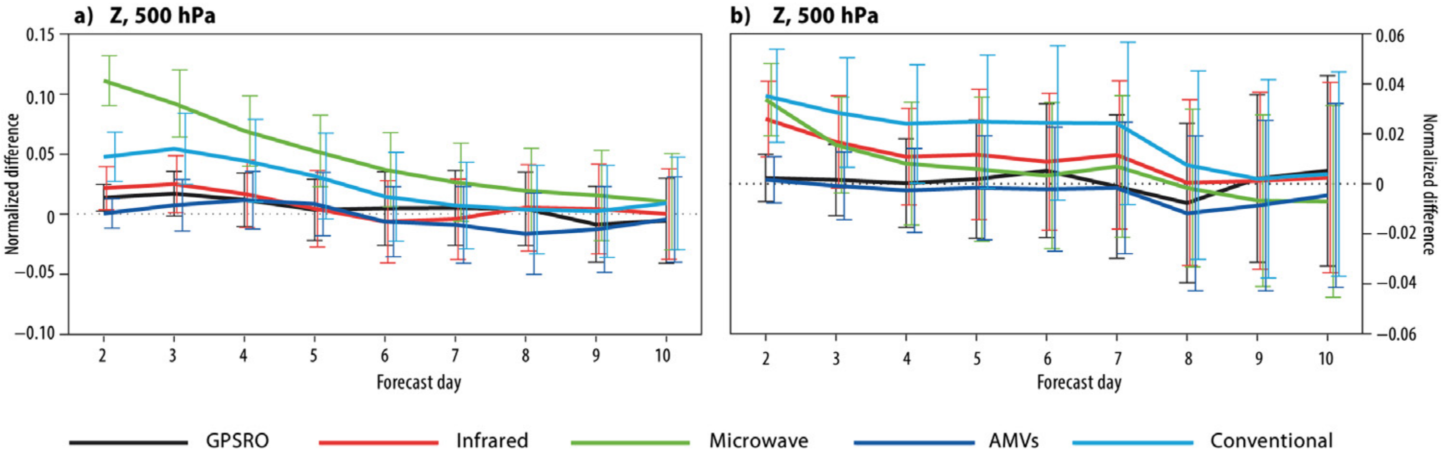

Fig. 2. Impact of removing different components of the observing system on Arctic forecast skill in the ECMWF IFS. The change in the standard deviation of forecast error (difference between forecast and observations), normalized by values for the control experiment (no observations removed), for geopotential height at 500 hPa over the Arctic region (north of 60°N) during (a) summer and (b) winter. Different lines give results from different OSEs in which certain observation types are removed when creating the initial conditions for the forecasts (GPS radio occultation bending angles, infrared radiances, microwave radiance, atmospheric motion vectors, and all conventional observations). A value of 0.05, for example, means that forecast errors increase by 5% with data from a certain component of the Arctic observing system withheld. After Lawrence et al. (2019).

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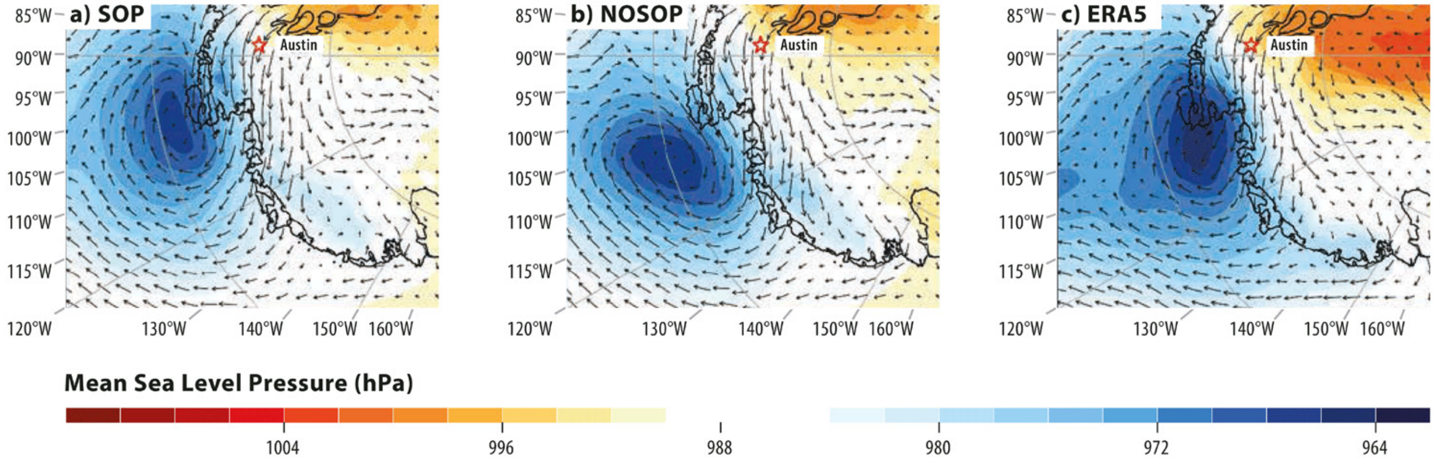

Fig. 3. Impact of extra observations during the SOP around Antarctica on a 2-day forecast of a low pressure system along the data-sparse coast of West Antarctica during the summer. Sea level pressure (shaded; hPa; scale below figures) and surface winds (vectors) from 48-h (a) forecast using all available observations and (b) forecast with all observations, except for the additional YOPP SOP radiosondes, and (c) the ERA5 global reanalysis ("truth"), valid 0000 UTC 18 Jan 2019. Having the extra radiosondes included in the forecast leads to a better prediction of the low pressure system. The Austin automatic weather station (AWS) is marked for which time series of different meteorological parameters is shown in Bromwich et al. (2020). Adapted from Bromwich et al. (2020).

observations were assimilated in the winter than in the summer within the ECMWF system, partly as a result of deficiencies in radiative-transfer modeling over snow and sea ice surfaces for temperature and humidity-sounding radiances. Development of a Lambertian formulation of surface scattering at ECMWF has increased the use of observations over snow-covered surfaces and the skill of forecasts (Bormann 2022).

For the Antarctic, it was found that the impact of adding extra observations to the existing conventional observing system during the SOP adds additional value (Bromwich et al. 2020). This value is demonstrated in Fig. 3 for the case of an intense extratropical cyclone in Antarctica (Bromwich et al. 2022). This is in contrast to the Arctic, where adding extra observations has a smaller impact, presumably due to the more comprehensive existing baseline observing system. During the time of writing, the data from the Antarctic TOPs are still being analyzed. In this context, the possibility of additional existing observing systems instead of radiosondes was also assessed (Sato et al. 2022).

Finally, through OSEs, it was shown that on subseasonal to seasonal time scales, the accuracy of sea ice forecasts can be enhanced significantly by integrating the winter sea ice thickness information for initialization, both in the Arctic (Blockley and Peterson 2018; Yang et al. 2019, 2023) and in the Antarctic (Luo et al. 2021). Furthermore, assimilating the newly developed *CryoSat-2* summer sea ice thickness observations (Landy et al. 2022) has the potential to further improve the prediction (Min et al. 2023). It should be also noted that, to make the best use of the historical sea ice observations in the data assimilation and prediction, optimizing the model-dependent parameters in the current sea ice data assimilation systems is strongly required (e.g., Luo et al. 2023).

b. Process understanding in support of model development. Process understanding, a critical aspect of YOPP, played a fundamental role in supporting improved prediction through model development. In this context, outcomes in three key areas will be highlighted for their significant contributions: YOPP Model Intercomparison and Improvement Project (MIIP), the YOPP–Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) link, and innovative approaches to model evaluation.

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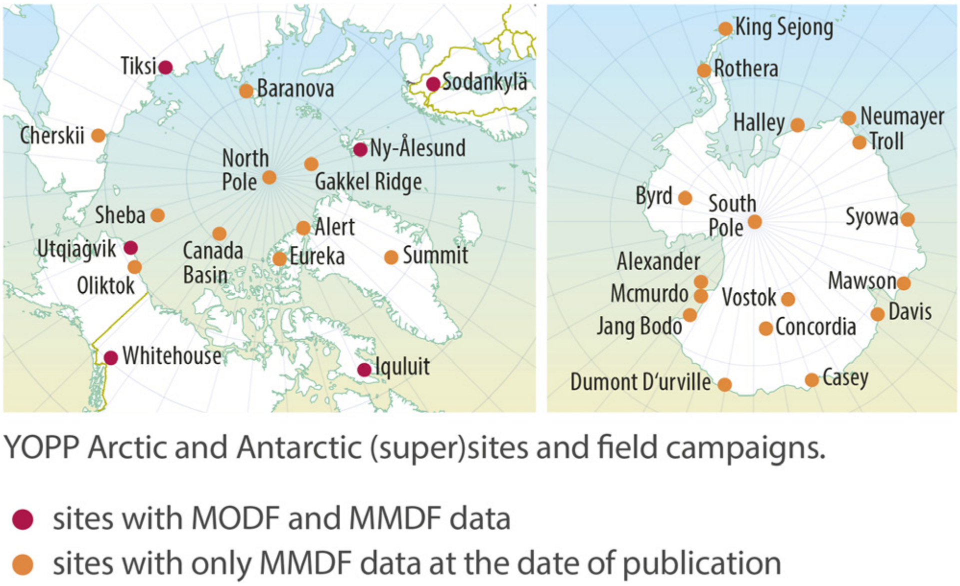

Fig. 4. **YOPP Arctic and Antarctic (super)sites. MODF and MMDF correspond to merged observatory data file and merged model data file. These are new file formats based on NETcdf designed to allow direct comparison of observed and model data for evaluation and process purposes. Further details are given later in this paper.**

1) YOPP MIIP. To improve the capabilities of environmental prediction models in polar regions, it is necessary to increase the understanding and model representation of the complex processes and interactions in the coupled atmosphere–ocean–sea ice–land system. The YOPP MIIP has coordinated the activities to improve process representation, involving observational groups and modelers, including scientists from operational forecast centers (Arduini et al. 2019; Batrak and Müller 2019; Elvidge et al. 2021; Tjernström et al. 2020).

An important element of the MIIP was the MOSAiC near-real-time verification (NRV) Project, which was focused on evaluating the simulation of the Arctic atmospheric boundary layer and surface energy budget in short-term forecasts of the coupled ocean–atmosphere–sea ice system from state-of-the-art operational and experimental forecast systems. Using observations taken during the MOSAiC campaign (Solomon et al. 2023), it was found that, among other challenges, limitations in the representation of clouds and the snow/ice thermal properties affect the models' ability to accurately represent energy partitioning at the surface.

Much of the progress on process representation resulted from coordinated efforts during a few specific time periods: the two Northern Hemisphere SOPs and the MOSAiC year (see below) that includes the YOPP Arctic TOP in mid-April 2020 (Svensson et al. 2023a).

Another important aspect underpinning success was the focus on several "supersite observatories" (Fig. 4) well-instrumented locations on land or at sea with sustained observations that were matched by corresponding high-resolution, high-frequency model output (see the section on YOPPsiteMIP).

2) The YOPP–MOSAiC Connection. One important partner program for YOPP was the MOSAiC expedition (Shupe et al. 2020). For most of the year of September 2019–October 2020, the research vessel Polarstern drifted with the central Arctic sea ice along the Transpolar Drift, serving as a platform for intensive science in a rapidly changing region.

More than simply sharing a goal to improve model predictions in the Arctic, both YOPP and MOSAiC recognized the importance of coupled-system processes and their manifestation in all

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seasons (Jung et al. 2016; Goessling et al. 2016b). Both programs sought to promote process understanding and ultimately process representation in models. Specific processes of shared focus included mixed-phase clouds, stable boundary layers, ice–ocean dynamics, organized large-scale atmospheric systems, and much more. MOSAiC has obtained an unprecedented dataset that can feed model development work in all of these areas (Nicolaus et al. 2022; Rabe et al. 2022; Shupe et al. 2022).

Building on these scientific foundations, the close collaboration with YOPP contributed significantly to MOSAiC's design and field implementation, ensuring that the obtained observations effectively meet modeling needs. For example, the YOPP community explicitly called for information on scaling, which contributed to the design of MOSAiC's "Distributed Network" of autonomous observing systems (Rabe et al. 2024). The result was a drifting constellation of observations, sometimes called drifting model grid cells, representing many scales out to multiple tens of kilometers from the Polarstern, with the ability to capture modes of variability in the atmosphere, sea ice, and ocean (i.e., ocean eddies at different scales, intra-floe variability in sea ice properties, heterogeneity in atmospheric radiative forcing, and more). Through observational design and coordination, the MOSAiC observations have also been placed solidly within the pan-Arctic context established by the network of existing Arctic ground observatories (Uttal et al. 2016; Inoue et al. 2015) and extensive satellite observations (Nicolaus et al. 2022).

During the MOSAiC field year, quasi-operational modeling products produced by the YOPP community (e.g., SIDFEx sea ice drift forecasts) helped guide field operations in real time. Last, the drifting MOSAiC site participated in YOPP's TOP in 2020 by increasing radiosonde frequency during impactful events in coordination with other stations. The TOP was successful in capturing a major mid-April warm air intrusion event that triggered a change from a winter regime toward the spring and summer and has served as a focus for many observational and modeling analyses (Svensson et al. 2023a; Dada et al. 2022; Kirbus et al. 2023; Schneirstien et al. 2024).

While still in the early stages, the MOSAiC observations are already feeding a wide range of model-centric activities. Merged Observatory Data Files (MODFs) (Uttal et al. 2024) that combine many different measurements in a uniform manner have been developed following the protocols established via the PPP for efficient comparison with Merged Model Data Files (MMDF) of similar design. Numerous other activities are underway to refine, combine, and enhance observational products to support model forcing and assessment across many types and scales of models (e.g., Hames et al. 2022; Shaddy et al. 2023; Solomon et al. 2023; Heinemann et al. 2022, 2023; Herrmannsdörfer et al. 2023; Pithan et al. 2023; Aue et al. 2023; Zampieri et al. 2023; Cummins et al. 2023; Liu et al. 2024; Bazile et al. 2020).

Finally, reaching beyond science, the programs shared goals in outreach and education via, for example, coordination on the MOSAiC field school wherein a collection of international graduate students received comprehensive lectures on board a vessel in the Arctic sea ice and participated in the initial installation of MOSAiC field observations.

Overall, the YOPP–MOSAiC partnership was a resounding success. It further justified and strengthened each program, leading to amplified outcomes on both sides.

3) Novel approaches for model evaluation. During YOPP, it was demonstrated that nudging the large-scale atmospheric circulation in coupled climate models to reanalysis data enables an effective direct comparison with observations from field campaigns on specific days (Pithan et al. 2023). This results from the fact that nudging, a simple form of data assimilation, aligns the evolution of simulated large-scale weather patterns in the coupled model with the one observed during the campaign. A major source of model-observation differences over shorter time periods, that is entirely different weather patterns, has thus been

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removed. This approach was applied during the Arctic TOP in April 2020 when a warm air intrusion event was observed by the MOSAiC expedition in the central Arctic. It was found, for example, that some of the coupled models failed to capture the diurnal surface temperature cycle due to simplistic snowpack temperature assumptions. Additionally, model discrepancies in cloud cover and radiation during cold, dry periods with thin mixed-phase clouds were observed. These findings show that nudging enhances the relevance of short-term observational campaigns for model evaluation, offering a streamlined approach to model refinement and broadening the scope of useful observational data.

The use of fully coupled atmosphere–ocean single-column models (Hartung et al. 2018) allows to decouple local small-scale from large-scale processes to hence investigate model performance in controlled experiments where the interaction between the atmosphere and ocean is particularly important. The tool, that is, a column of EC-Earth or ECMWF's IFS, has been applied to Eulerian simulations for an observed case of extreme warm air advection over sea ice. The summary diagnostics, developed to analyze a large number of perturbations, clearly map sensitivities of the model results due to changes in physical and model properties as well as to the large-scale tendencies (Hartung et al. 2022). The tool was also used to analyze airmass transformation in cases of warm air intrusions, such as the one observed during the NH TOP, in a Lagrangian framework as suggested in Pithan et al. (2018).

c. Polar–midlatitude linkages. Understanding possible two-way linkages between the polar regions and lower latitudes has been a priority theme in YOPP from the outset fueled by some influential studies linking Arctic sea ice decline to extreme weather events in midlatitudes (e.g., Francis and Vavrus 2012; Inoue et al. 2012; Cohen et al. 2020).

1) LINKAGES ON CLIMATE TIME SCALES. YOPP has made significant contributions to comprehending the impact of sea ice decline on midlatitude extreme events over climate time scales, notably through its role in shaping and implementing the Polar Amplification Model Intercomparison Project (PAMIP; Smith et al. 2019), and analyzing the data (Smith et al. 2022). Data analysis suggests that the actual effect in the real world might be stronger than what most models predict (Smith et al. 2022). However, even with this stronger effect, the impact of sea ice loss on lower-latitude weather is still relatively small. For example, changes in North Atlantic weather patterns due to sea ice loss are similar to those caused by increasing greenhouse gases but would only explain about 10% of the year-to-year weather changes.

Recent work has also shown that the way Arctic sea ice affects weather patterns has been changing over time. Recently, the observed connection between sea ice and atmospheric circulation has weakened (Blackport and Screen 2020). This means that results from observations are now more in line with what the models have been suggesting (i.e., a robust but weak midlatitude response).

2) LINKAGES ON WEATHER TO SEASONAL TIME SCALES. Research carried out in the context of YOPP demonstrates that the dynamics of daily to seasonal linkages, crucial for weather prediction, differ fundamentally from those on climate time scales (see Fig. 5 for a synthesis). Studies show that during certain periods, the jet stream's meandering enhances linkages between high and lower latitudes (e.g., Jung et al. 2014; Semmler et al. 2018; Day et al. 2019). For instance, southerly and northerly flows in the jet stream bring midlatitude and Arctic weather influences to the Arctic and midlatitudes, respectively (see Jung and Leutbecher 2007; Jung et al. 2014). One prominent phenomenon identified is Scandinavian blocking (Fig. 5b) leading to enhanced transport of North Atlantic air masses into the Arctic, which involves challenging to simulate processes such as airmass transformations (e.g., Pithan et al. 2018), interaction of the atmospheric flow with topography (e.g., Jung and Rhines

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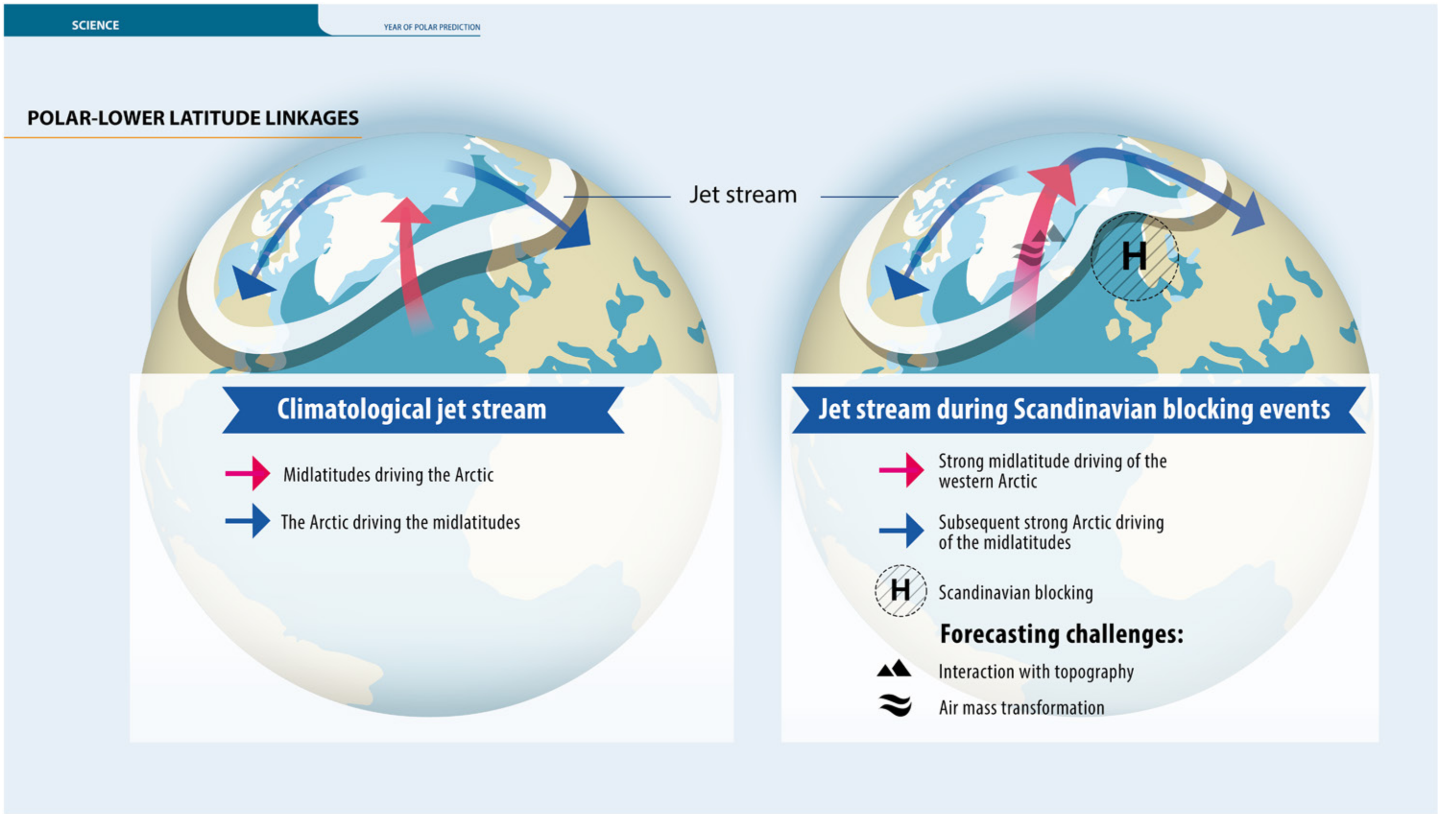

Fig. 5. Schematic indicating key pathways of polar–midlatitude linkages from a prediction perspective on daily to seasonal time scales. (left) The "average" picture and (right) episodes of particularly strong connections in the North Atlantic–European–Asian region associated with a meandering jet stream. This synthesis is from the YOPP-endorsed EU-project APPLICATE (https://applicate-h2020.eu/).

2007), and strong air–sea interaction in the Barents Sea (e.g., Bailey et al. 2021); the same air is then later strongly impacting weather further downstream in Eurasia (Day et al. 2019).

In the Southern Hemisphere, polar–midlatitude linkages exist but are less prominent than in the Northern Hemisphere, likely due to reduced planetary wave activity, which leaves the flow more zonal (Semmler et al. 2016; Bromwich et al. 2022; Choi et al. 2023). These insights are robust, supported by various methodologies including observing system experiments, nudging, and adjoint sensitivities. Sea surface temperature anomalies, e.g., ocean heat waves, influence planetary wave activity and regional warming and cooling in the Antarctic region (Sato et al. 2021).

d. Verification. In the planning of YOPP, verification emerged as an important element, since it provides crucial information on forecast quality, aiding users in decision-making and offering valuable feedback for forecasters to refine their methods. In the following, we highlight some accomplishments and insights with an emphasis on sea ice prediction, which has become one of the foci of YOPP.

As part of YOPP, the development of innovative metrics to assess the accuracy of sea ice predictions has experienced significant advancement. The integrated ice edge error (IIEE; Goessling et al. 2016a) and the spatial probability score (SPS; Goessling and Jung 2018), along with other methodologies (e.g., Dukhovskoy et al. 2015), have emerged as pioneering tools in this domain. These scores, particularly IIEE and SPS, have gained widespread recognition and are now used as headline scores, similar to 500-hPa geopotential height in midlatitudes, for routinely verifying sea ice forecast accuracy.

Another notable breakthrough has been the determination of the predictability of linear kinematic features (LKFs) in sea ice, such as leads (Mohammadi-Aragh et al. 2020).

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It was found that the predictability of LKFs drops quickly, with predictability on average being lost after 4–8 days. This is in contrast to quantities such as sea ice concentration or the location of the ice edge, which retain high levels of predictability throughout the full 10-day forecast period.

Moreover, there has been a comprehensive evaluation of the effectiveness of operational sea ice concentration and thickness predictions on subseasonal time scales in both the Arctic and Antarctic regions (Zampieri et al. 2018, 2019; Xiu et al. 2022) using data from the subseasonal to seasonal prediction project (Vitart et al. 2017). These assessments revealed that while some of the then operational prediction systems exhibited considerable accuracy, there was still a significant potential for improvement. This finding underscored the need for and potential of ongoing research and development in sea ice forecasting.

The Sea Ice Prediction Network South (SIPN South) project, launched in 2017 and building on the Arctic Sea Ice Prediction Network, has enhanced understanding of Antarctic sea ice forecast accuracy. Through the aggregation of data from various contributors, SIPN South's collective forecast, based on six summer seasons of data from DJF 2017–18 through 2022–23, surpasses the accuracy of most singular predictions on both circumpolar and regional scales (Massonnet et al. 2023). This underscores the effectiveness of merging predictions to mitigate errors unique to individual models.

e. PPP-SERA. Another important element of YOPP has been to stimulate social science research focused on understanding the information needs of key user groups, as well as the role of various environmental service users and data providers in the process of coproducing improved polar forecasts and services. An important legacy as well as area of future development relates to linking innovations in forecasts and services with user needs and to ensure that scientific advances translate into salient services.

Four conclusions from PPP-SERA's work stand out as follows:

1) We need to better understand user needs in a diversity of highly specific user contexts.
2) Tailoring actionable environmental services for user groups in the polar regions requires inclusive transdisciplinary approaches to co-production.
3) New or enhanced environmental services generate intended, as well as unintended, societal impacts in the polar regions, which we need to assess.
4) Investments and dedicated funding are needed to involve the social sciences in research and tailoring processes across all the polar regions (Lamers et al. 2024).

As the distinction between creators and users of environmental information becomes less clear, with some users starting to produce their required information, the diverse needs of various groups remain significant (e.g., Jeuring and Lamers 2022). For instance, Indigenous communities in the Arctic and commercial enterprises such as shipping and tourism in polar regions have vastly different requirements. Additionally, the capacity to manage uncertainty varies greatly among these user groups, particularly between the Arctic and Antarctic, underscoring the inefficacy of a universal service approach. People in polar areas depend on environmental predictions for planning and safety, using platforms like windy.com, but often face a gap between available services and their specific needs. This mismatch hampers the effective use of weather information, suggesting a need for user-inclusive design and continuous feedback to refine these services. The widespread use of portals like windy.com shows the importance of accessible, intuitive, and locally relevant information.

Identifying key environmental factors like wind speed, visibility, and sea ice conditions is crucial for real-time decision-making and future planning in both polar regions. Timely access to these data is essential for users facing diverse challenges, from immediate weather

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conditions to long-term planning. Integration of these services into essential systems, particularly for the shipping industry, could streamline operations and reduce the burden on personnel. Engaging users in the design and feedback process is critical to addressing concerns about data accuracy and reliability, similar to those in midlatitude regions.

Some of the important lessons learnt from PPP-SERA regarding user perspectives and environmental information needs are graphically summarized in Fig. 6. It contrasts the current "service landscape" with a future vision. Presently, generating relevant information is an uphill battle, leading to the idea that "more information is always better." This results in users being flooded with undifferentiated information that does not meet their specific needs. In the future vision, a more nuanced and tailored approach to information production and delivery is envisioned.

The YOPP-endorsed European Enhancing the Saliency of Climate Services for Marine Mobility Sectors in European Arctic Seas (SALIENSEAS) project is a prime example of the more nuanced and tailored approach. In SALIENSEAS, an international, multidisciplinary team has coproduced customized services for subseasonal-to-seasonal (S2S) sea ice forecasts (time scales from 2 weeks to 3 months) for maritime sectors and users in the European Arctic. The time scales from 2 weeks to 3 months correspond to forecasts initialized at different months using the spatial probability score (SPS) verification score. The forecasts starting on 1 June have skill for about 3 months, while the forecasts starting in December/January have skill for about 2 weeks. These sea ice forecasts [from the fifth generation seasonal forecasts from ECMWF (SEAS5)] are skillful for about 5 weeks on average (Palerme et al. 2019). This project utilized innovative user engagement methods, including participatory mapping and serious gaming (as detailed on salienseas.com), to develop services that are more aligned with the specific needs of its users. The project developed and tested a novel, transdisciplinary coproduction approach that combined socioeconomic scenarios and participatory, research-driven simulation gaming to test a

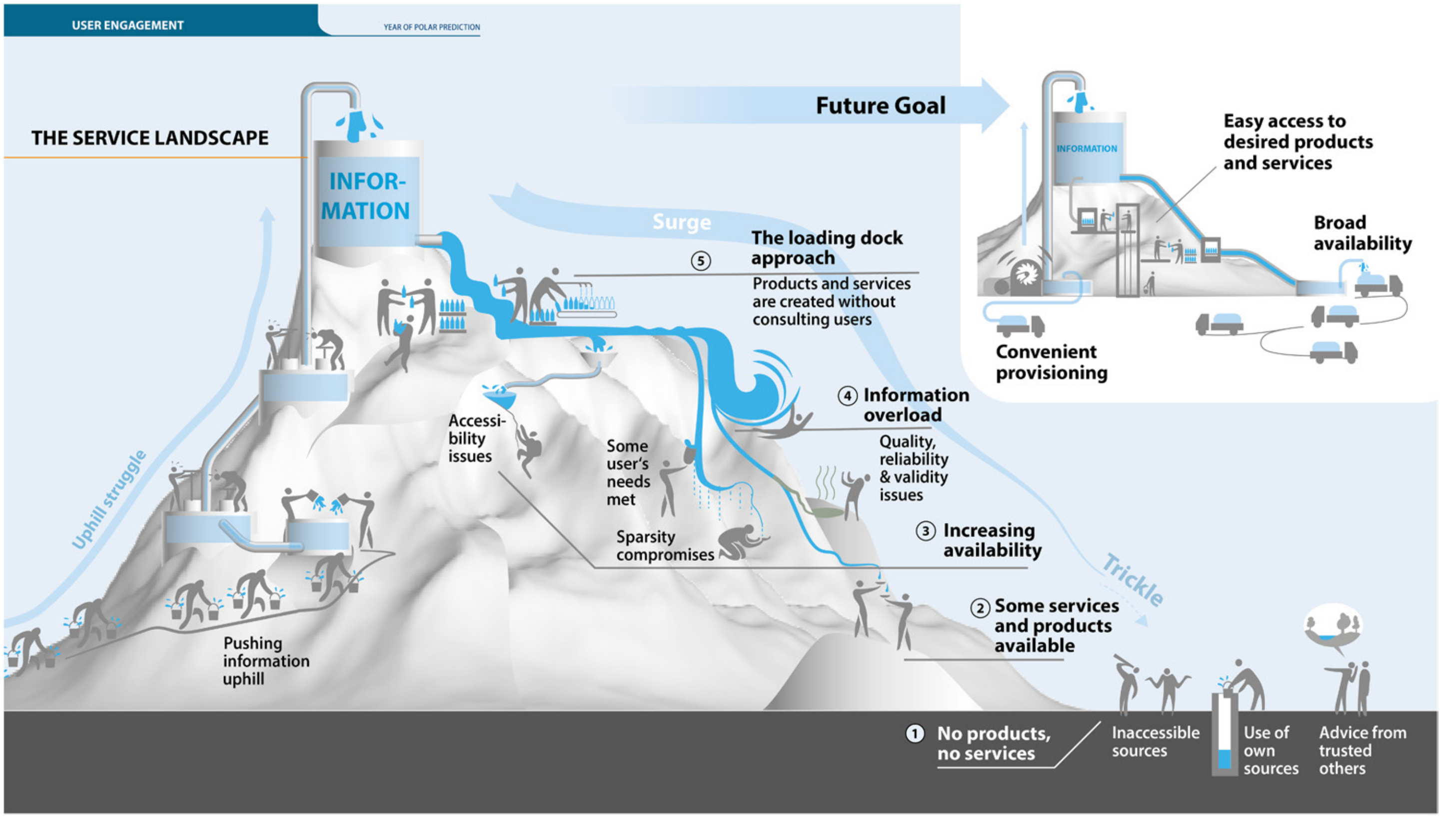

Fig. 6. Schematic of the service landscape today and as envisioned for the future (Heinrich et al. 2024).

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new S2S sea ice forecast system with experienced mariners in the cruise tourism sector. The custom-developed computerized simulation game known as “ICEWISE” integrated sea ice parameters, forecast technology, and human factors as a participatory environment for stakeholder engagement. Through the coproduction approach, the project explored the value of application-relevant S2S sea ice prediction and linked uncertainty information (Blockley and Peterson 2018).

f. Publications. Publishing the plans and results of YOPP has been a vital part of the strategy to maximize its impact. In the following, some notable achievements will be highlighted. For effective planning and resource allocation, a Science Plan was published in 2013, followed by four versions of the PPP/YOPP Implementation Plans in 2013, 2014, 2016, and 2019. The project has also achieved significant academic recognition, with more than 265 peer-reviewed publications and an overall Google Scholar h-index of 55. The Google Scholar shows a h-index of 52 for papers published since 2019 indicating the development of publications as the project matured (https://scholar.google.de/citations?hl=en&user=tbR5tOAAAAAJ&view_op=list_works&sortby=pubdate). These numbers indicate a high level of influence in the scientific community. There have been five special issues in reputable journals, showcasing the wide range of YOPP research: “Polar Prediction” in the Quarterly Journal of the Royal Meteorological Society (Bauer and Jung 2016), “Towards improving understanding and prediction of Arctic change and its linkage with Eurasian midlatitude weather and climate” in Advances in Atmospheric Sciences (Zhang et al. 2018), “Societal Values of Improved Forecasting” in Polar Geography (Lamers and Liggett 2020), “Impacts of Polar Observations on Predictive Skill” in the Quarterly Journal of the Royal Meteorological Society (Jung et al. 2023), and “Antarctic Meteorology and Climate: Past, Present and Future” in Advances in Atmospheric Sciences (Liu et al. 2020). Another special issue, bridging the MIIPs between YOPP and its follow-on project, is in preparation (https://gmd.copernicus.org/articles/special_issue1284.html).

Key publications are also accessible online (https://www.polarprediction.net). The breadth of these publications is wide, covering not only natural sciences but also social sciences (Dawson et al. 2017), data descriptions (Bauer et al. 2020), education (Day et al. 2017), and project description and management (Bauer et al. 2016b; Pasqualetto et al. 2022; Werner et al. 2019).

4. YOPP data

Early on in the planning, it was recognized that a “Data Portal” approach for YOPP would be the best way forward. The YOPP Data Portal, and more recently the YOPP Site Model Intercomparison Project (YOPPSiteMIP), both of which will be described in more detail below, turned out to be integral parts to the project’s success. Other success stories include the ECMWF-YOPP dataset (Bauer et al. 2020) covering the period 2017–20, including the MOSAiC campaign, to enhance model forecast evaluations and climate impact studies in polar regions. This comprehensive dataset, covering initial conditions and forecasts up to 15 days, including process tendencies, is available on the YOPP Data Portal, serving as a crucial tool for researchers and meteorologists.

a. YOPP Data Portal. During YOPP, partners generated and gathered petabytes of data. Recognizing the importance of open data access and the need to acknowledge data providers, the Norwegian Meteorological Institute (Met Norway) leveraged recent technological advances to create a comprehensive data portal. This portal, known as the YOPP Data Portal, serves as a centralized access point where users can discover and (subject to the data owner’s access and copyright requirements) view, compare, and download data. The portal is accessible online (https://yopp.met.no/).

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The YOPP Data Portal connects to various data repositories. Some, like the WMO WIS connection, act as gateways to other systems that exchange metadata. Others, such as the Arctic Data Center (ADC) managed by Met Norway, are repositories for a broader range of Arctic data. This centralized metadata catalog enables users to search across multiple repositories from a single access point. Additionally, individuals and institutions can manually upload metadata for their observations and forecasts, especially if their data repositories are not automatically integrated with the YOPP data servers.

Met Norway plans to maintain the YOPP Data Portal as a separate entity at least until the end of 2025. When a hardware update is necessary, the YOPP Data Portal Catalog will be integrated into the ADC.

As of February 2024, the YOPP Data Portal has cataloged metadata for 602 parent datasets. This number is down from a peak of just over 1100 in May 2022 as a result of ongoing maintenance and cleaning of records, and a number of remote repositories have modified their system interfaces resulting in loss of connection. Work is continuing to reconnect to these repositories so the number of parent datasets is expected to increase from the 602 level with time. From January 2020 to May 2022, the portal recorded over 21 000 visitors, with monthly peaks surpassing 1500 unique visits. In 2023/24, the average monthly visitors were around 900.

b. YOPPSiteMIP. Enhancing our understanding and modeling of critical processes in polar regions necessitates integrating the best available observations for investigating parameterized processes in contemporary models. This integration is complex due to the distribution of data across various archives, each employing different naming conventions, file formats, and attributes. To streamline this process, YOPP, in the context of MIIP, has introduced the YOPPsiteMIP concept (Fig. 7). YOPPSiteMIP significantly simplifies the use of observational and modeling data from diverse sources, facilitating more efficient process-oriented model evaluation and expediting model improvements.

YOPPsiteMIP combines high-frequency, multivariable observations from supersite observatories with corresponding model outputs from native grids at these locations. This initiative has already seen contributions from seven observational Arctic sites (see Mariani et al. 2024), offering comprehensive measurements from critical polar observatories equipped with a variety of long-term monitoring instruments. Major NWP centers have provided model output for these sites (see Day et al. 2024), contributing to both the YOPPsiteMIP and its sister project, the MOSAiC-Near-Real-Time Verification Project (Solomon et al. 2023). This collaboration allows for a detailed evaluation of small-scale processes crucial for atmosphere–sea ice interactions.

A critical aspect of this effort is the adoption of a common file format and semantics (netCDF with CF naming convention) for both models and observations, adhering to Findability, Accessibility, Interoperability, and Reusability (FAIR) principles. This has resulted in the creation of merged data files (MDFs), including both MMDF and MODF (Uttal et al. 2024), along with tools for their analysis (Tjernström et al. 2024). These files are accessible through the YOPP Data Portal, making these data readily available for research and analysis.

5. Science to services

PPP/YOPP aimed not only to facilitate cutting-edge research within the polar research community and the publication of findings. YOPP also sought to transform scientific discoveries into practical operations and services that could aid decision-making. Notable examples of this include the following:

- The development of the innovative AROME-Arctic system by Met Norway, with support from YOPP-endorsed projects such as APPLICATE, ALERTNESS, and Nansen Legacy.

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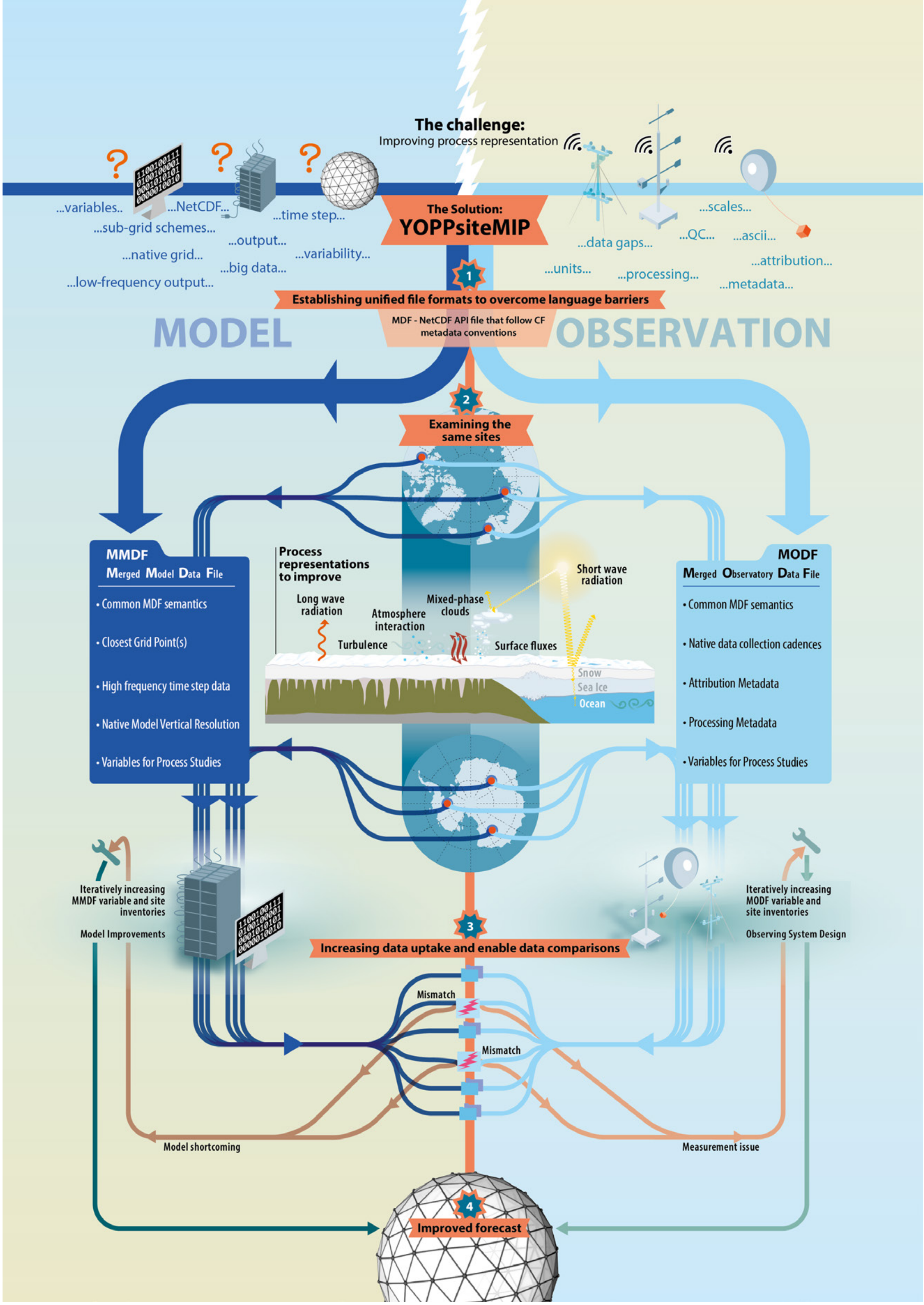

Fig. 7. Schematic of YOPPSiteMIP and its components.

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This system significantly improves weather forecasts in the complex Arctic environment (Køltzow et al. 2019), including temperature predictions over sea ice (Batrak and Müller 2019; Batrak et al. 2024). It is now used operationally and forms the core of the Copernicus Arctic Regional Reanalysis (Schyberg et al. 2020).
- At ECMWF, a new multilevel snow scheme was developed (Arduini et al. 2019, 2022), which ECMWF implemented in 2023 in operations, offering a much more accurate representation of critical processes in polar regions. This led to improved scores in polar regions (Haiden et al. 2023).

These initiatives illustrate YOPP's commitment to applying scientific research to practical applications, thereby contributing to more effective and informed decision-making in polar regions.

6. Education

Training the next generation of polar scientists was a pivotal goal of YOPP. Central to this objective were the YOPP schools, which provided a platform for graduate students to delve into aspects of polar prediction, fostering discussions and enabling valuable networking opportunities with experienced polar scientists. Feedback from more than half of the YOPP endorsed projects and the PPP steering committee indicates more than 200 graduate students used YOPP data in their MSc and PhD dissertations and more than 160 students participated in YOPP endorsed projects.

School participants received comprehensive training in environmental prediction specific to polar regions (Day et al. 2017; Tummon et al. 2018). This training included a blend of lectures, hands-on modeling assignments, and field observation collection and analysis. Since YOPP's inception, two summer schools have been hosted at the Abisko Scientific Research Station in northern Sweden, in 2016 and 2018. These sessions were attended by nearly 60 PhD students and early career scientists.

The YOPP Education, Communication, and Outreach Task Team has also been actively involved in organizing and participating in various workshops. These have been held in conjunction with conferences such as the Arctic Science Summit Week in March 2021 and meetings of the Association of Polar Early Career Scientists (APECS) Oceania in August 2020.

Further enhancing its educational and outreach initiatives, YOPP strategically collaborated with APECS. This partnership was a significant step in integrating early career perspectives into the program's decision-making processes. An APECS member was included in the steering group overseeing the planning and implementation of YOPP, thus ensuring that the interests and insights of emerging polar scientists were represented at a high level. This collaboration extended to funded projects like APPLICATE, which provided APECS with the resources to employ staff. These strategic moves not only strengthened the YOPP's commitment to education and capacity building but it also reinforced APECS' role in shaping the future of polar science. This synergy between established and emerging scientists fostered a more inclusive and dynamic environment for polar research and prediction.

7. Communication and outreach

Outreach and communication were key elements of YOPP, aimed at connecting and engaging the diverse members of the polar prediction community. To this end, a variety of communication channels were utilized, including direct email, email lists, the polar prediction website, social media, and newsletters. The polar prediction mailing list, with nearly 700 subscribers, served as a major channel for communicating with the YOPP community.

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From October 2016 to 2021, 19 editions of the PolarPredictNews newsletter were published. This newsletter highlighted research results, featured articles about scientists, summarized major activities, and showcased engagement with stakeholder groups involved in YOPP. Later issues of PolarPredictNews expanded to over 25 pages and even included a unique "Art and Science" section.

YOPP actively engaged with social media to connect with a broader audience. On Twitter, YOPP amassed over 2000 followers, with posts averaging around 900 impressions per day from January 2020 to April 2022. Additionally, YOPP boasts over 1000 followers on Instagram. The utilization of social media platforms enabled YOPP to engage with a wider and, potentially, younger audience compared to email lists.

The Polar Prediction Matters initiative was launched as a nonpeer reviewed forum to bridge the gap between researchers, developers, providers of polar environmental forecasts, and users who rely on these forecasts for socioeconomic decision-making. Hosted by the German Helmholtz Association as part of their science blog (https://blogs.helmholtz.de/polarpredictionmatters/), the initiative facilitated valuable dialogue and resulted in an electronic booklet (Goessling and Werner 2023).

One of the standout outreach initiatives of YOPP was the podcast series "The IcePod," which debuted in September 2019 (Werner and Pasqualetto 2021, https://open.spotify.com/show/0uNGiEiVxPZGfb1dtzmoof). This podcast, themed "The Podcast about Polar Science and the People," successfully ran for two seasons. The first season centered around MOSAiC, while the second season shifted focus to the users of polar environmental services. "The IcePod" has achieved considerable success, with over 11 000 downloads of its episodes. It has also ranked within the top 30 Apple Podcasts during 2021 and 2022 for Earth Sciences in several countries, including Germany, Great Britain, Canada, and Australia, reflecting its wide-reaching impact and popularity in the field of polar science communication.

8. Coordination, planning, and resource mobilization

a. Structure and governance. YOPP was a core endeavor of WWRP from 2013 to 2022 with a dedicated governance and management structure (Fig. 8). Central to PPP was its Steering Group, comprising over 20 international experts from different fields. Their efforts were bolstered by various Task Teams and the International Coordination Office (ICO), housed at the Alfred Wegener Institute. Coordination was further enhanced through regular reporting and engagement with high-level WMO groups.

b. Community building. Right from the start, it was understood that for YOPP to succeed, effective community building would be crucial. This initiative specifically aimed to connect various groups, including weather and climate scientists, modelers and

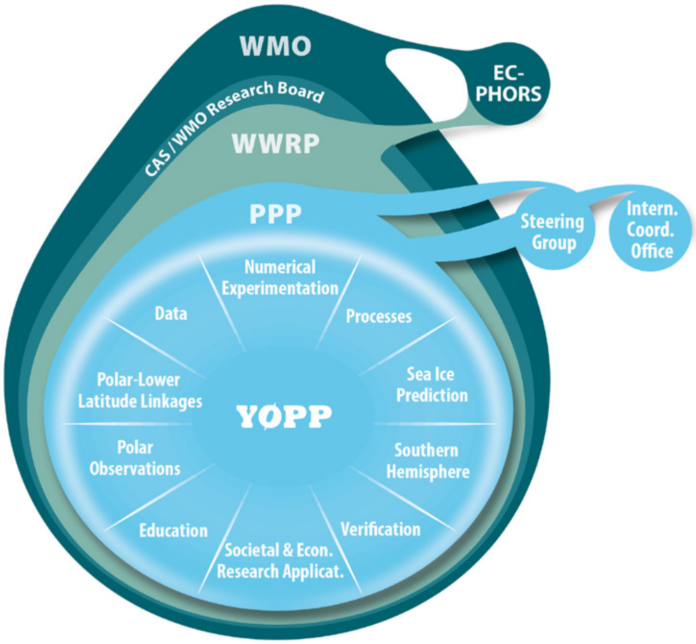

Fig. 8. Structure and governance of the YOPP. The innermost circle represents the YOPP Task Teams.

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observationalists, experts in midlatitude and polar meteorology and oceanography, academia, research institutions, operational forecasting centers, and developers and users of polar environmental services.

YOPP has been instrumental in fostering this community. YOPP's efforts included organizing two summits (Goessling et al. 2016b; Wilson et al. 2023), over 10 workshops, and holding nearly 20 face-to-face planning meetings. These varied activities played a significant role in building and maintaining a vibrant and engaged community focused on polar environmental prediction.

c. YOPP endorsement. At the first YOPP Summit in 2015 in Geneva, the broad interest in YOPP from various stakeholders led to the launch of an endorsement process by the PPP steering group and the ICO. This process aimed to organize activities by detailing "who does what and by when," while also recognizing contributors' efforts to help them secure funding and increase their projects' visibility and recognition. In fact, the YOPP endorsement process guided funding agencies to invest in globally recognized research. The PPP Steering Group oversaw the endorsements, resulting in 102 out of 130 requests being approved.

A mid-April 2022 survey of over 90 endorsed projects yielded responses from more than half. The feedback revealed that YOPP-endorsed projects had amassed over USD 53 million in funding and involved more than 950 people (see below).

d. Resource mobilization. Resource mobilization for YOPP can be considered a success story (Fig. 9). It focused on three areas: i) financial support for coordination activities through the PPP Trust Fund; ii) in kind contributions from partners (e.g., weather services running experiments); and iii) third-party funding, often secured through calls for proposals that align with the goals of YOPP. The financial figures used in Fig. 9 were collated by the PPP International Coordination Office in June 2022. They are based on direct reports from the PPP Steering Group and the International Coordination Office. They are an underestimate of the

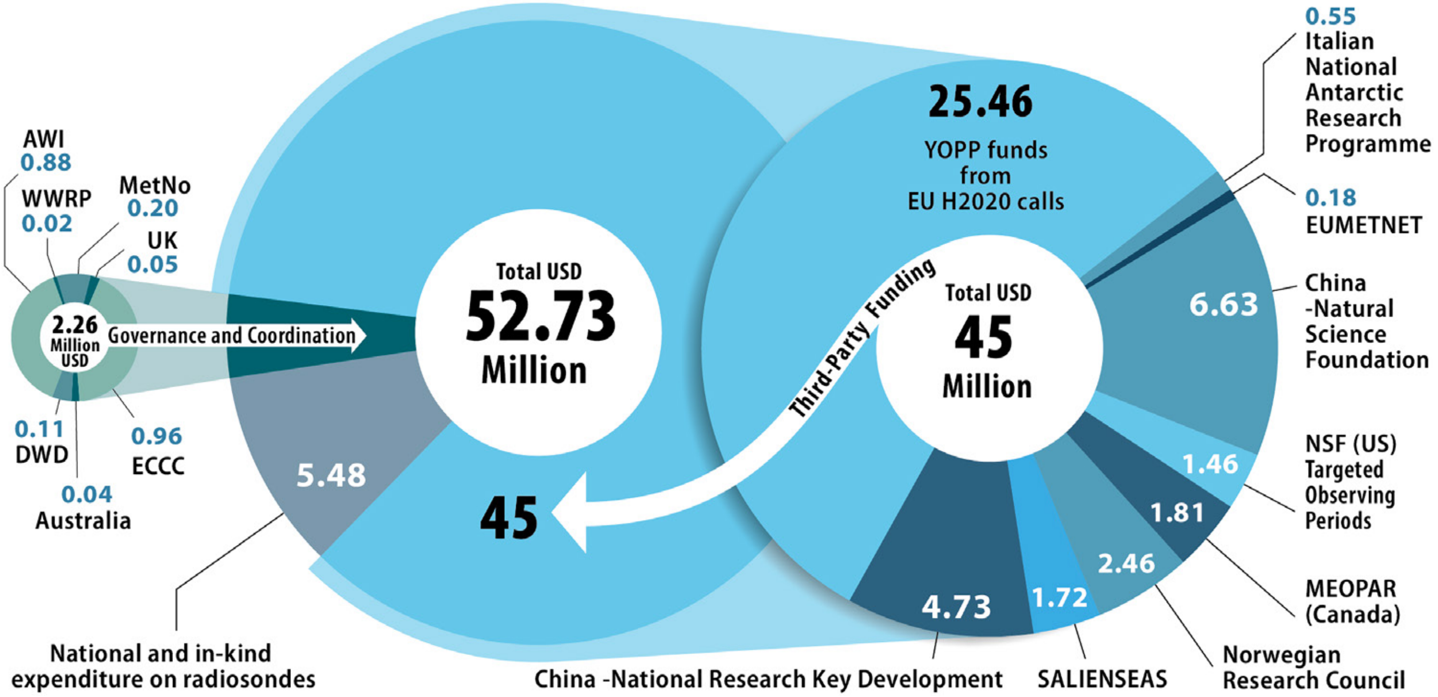

Fig. 9. Resource mobilization in support of YOPP. A total of USD 2.26 million for governance and coordination leveraged USD 45 million in third-party funding from various contributors worldwide. In addition to these figures, the YOPP endorsed projects reported funding of in excess of USD 53 million but these figures have not been included due to inconsistency in how they were reported.

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total YOPP-related funding as many of the endorsed projects were not able to provide explicit YOPP-related budget figures or did not respond to questions on their budget expenditure. As noted earlier, the YOPP endorsed projects that did respond to the questionnaire included funding information totalling more than USD 52 million; however, as they were not consistent with how they calculated their funding (some included logistics, others salary, others just grants), it has not been used in Fig. 9. In other cases such as MOSAiC, it is difficult to ascribe what portion of the total MOSAiC budget is YOPP related, so it has not been included specifically in these figures.

The Trust Fund received substantial contributions, totaling approximately USD 1.4 million from 2011 to 2022, with donations from Environment and Climate Change Canada (ECCC), the Met Norway, the German Meteorological Service (Deutscher Wetterdienst, DWD), the Australian Bureau of Meteorology (BoM), and the U.K. Met Office (Met Office). In-kind contributions were equally impressive, including support from the Alfred Wegener Institute for hosting the International Coordination Office; time and effort from individuals in the PPP Steering Group and its Task Teams; provision of staff, equipment, and materials for Special and Targeted Observing Periods in the Arctic and Antarctic; and the extensive work in curating, quality controlling, analyzing, and publishing data from these periods.

Dedicated third-party funding was a clear indicator of YOPP's success. Notable contributors included the European Commission, the Norwegian Research Council, and the Canadian Marine Environmental Observation Prediction and Response (MEOPAR) network. Support also enabled the deployment of over 10 000 additional radiosondes and 200–250 buoys during targeted observation periods in 2018 and 2019 by various countries and organizations, including the European Meteorological Network (EUMETNET) and the Russian Arctic and Antarctic Research Institute (AARI).

9. Discussion

Reflecting on the conclusion of the 10-yr YOPP initiative, our discussion begins by acknowledging its significant achievements. YOPP has successfully united a broad network of scientists, practitioners, and stakeholders, significantly boosting observational capabilities and user engagement. This collaboration has led to a wealth of scientific publications, enhanced model predictions, and a deeper understanding of polar–midlatitude interactions. The development of advanced models promises to improve forecasting, while YOPP's effective communication strategies have raised awareness and interest in polar prediction. These accomplishments highlight YOPP's comprehensive impact, from fostering community to advancing operational forecasting.

Building on YOPP's endeavors, two clusters were delineated to address and finalize tasks that remained incomplete at the close of 2022, extending the project's work into 2023 and beyond. Cluster 1, YOPP-SH, was set to conclude the analysis and documentation of the targeted observation periods (TOPs) from the Antarctic winter of 2022 focusing on atmospheric rivers. Simultaneously, Cluster 2, known as the Model Intercomparison and Improvement Project (MIIP), undertook several tasks into 2023. This included the refinement and curation of MMDF and MODF files. Utilizing these formats, the cluster also brought to completion the incorporation of data from the MOSAiC expedition into the YOPP MIIP framework. Another essential part of their 2023 agenda was to provide a thorough analysis and report on the Arctic TOP and SOP field campaigns (Svensson et al. 2023a,b), thereby wrapping up critical research initiatives from the previous year.

What made YOPP a success? At the heart of YOPP's success was the selection of an important and timely topic—polar prediction—which addressed significant knowledge and capacity gaps in the field of weather and environmental prediction. The vision to embark on YOPP set the stage for a well-coordinated international response to a pressing

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global challenge. What truly made the difference was the strategic establishment of three distinct phases: preparation, core, and consolidation. The preparation phase was critical, allowing for detailed planning and resource mobilization. This foresight ensured that the core phase was underpinned by a robust and strategic framework ready to capitalize on the intense period of data collection and analysis. The consolidation phase was of equal importance; it provided further opportunity to conduct in-depth research with the data gathered during the core phase, solidify the findings, and importantly, integrate them into operational prediction systems.

Building on the significant progress made by YOPP, WMO Congress in 2023 approved the Polar Coupled Analysis and Prediction for Services (PCAPS) project as a direct successor. Acknowledging that a decade-long program like YOPP could not possibly resolve all challenges, PCAPS aims to continue this work, addressing remaining and emerging issues in polar environmental prediction and focusing on enhancing the relevance and connection of the latter to services that are meaningfully enhancing human and environmental safety in the polar regions.

The last few years of YOPP have witnessed significant developments that were not anticipated in its original planning, many emerged by groundbreaking technological advancements (e.g., Bauer et al. 2021; Wedi et al. 2022). The emergence of advanced hardware, such as GPUs and pre-exascale computing systems, for example, has catalyzed a shift toward higher-resolution modeling, enabling global simulations at the kilometer scale. Additionally, the concept of "digital twins" high-fidelity virtual representations of the Earth system has gained traction (Hoffmann et al. 2023), potentially offering unprecedented interactivity and simulation capabilities. These digital twins have become instrumental in refining our predictive models and allowing a new level of interactivity. The field has also been significantly impacted by the advent of artificial intelligence (AI). AI technologies have revolutionized both the methodology of weather and sea ice forecasting (Bauer et al. 2023; refs; Dong et al. 2024) and the dissemination of weather and climate information (e.g., Koldunov and Jung 2024). The integration of machine learning and deep learning techniques in predictive models has led to more accurate and efficient forecasts (e.g., Lam et al. 2023). Moreover, novel ideas and methods have emerged that bring weather and climate closer together (Shepherd 2019; Pithan et al. 2023; Sánchez-Benítez et al. 2022). From the viewpoint of additional observing systems, using uncrewed aircraft systems (UASs) is an emerging field considered in WMO. The WMO UAS demonstration campaign has taken place from March to September 2024 in midlatitudes to Arctic regions (see WMO 2023, for planning details). Frequent and high-accuracy data acquisition (e.g., Inoue 2021; Inoue and Sato 2022) are desired shortly to fill the sparse observing networks in polar regions.

These emerging technologies and methodologies hold immense potential to elevate the field of polar prediction. As we look toward future international collaborations, these advancements should be at the forefront of our strategic planning, ensuring that we leverage these innovations to enhance our understanding and predictive capabilities of the weather and climate in polar regions and beyond.

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Data availability statement. The observational and model data used in the YOPPsiteMIP activities are available through the Year of Polar Prediction Data Portal (https://yopp.met.no/) developed and maintained by the Meteorological Institute of Norway.

Sea Ice Drift Forecast Experiment (SIDFEx)

SIDFEx is a collaborative project that was initiated as part of YOPP and that aims at gathering and analyzing sea ice drift forecasts over periods ranging from a few days to a year. SIDFEx responds to the growing need for accurate forecasting of the future positions of equipment and assets drifting primarily in the Arctic sea ice. One of its goals is to systematically evaluate the current capabilities in drift forecasting, which will enhance our understanding of sea ice dynamics and help identify and address gaps in existing models.

Since its inception in 2017, SIDFEx has seen significant participation, with 14 groups regularly contributing drift forecasts for buoys associated with the International Arctic Buoy Program (IABP) and some other assets. These forecasts are primarily derived using diagnostic Lagrangian tracking methods based on the predicted drift fields. Additionally, some groups provide ensembles of potential drift trajectories, and several contribute their forecasts in near–real time, ensuring timely and relevant data for ongoing research and operational needs.

Due to SIDFEx, the accuracy of satellite image ordering during the MOSAiC expedition improved significantly, with a hit rate of about 80%–85%. Without SIDFEx, experts like Suman Singha from the German Aerospace Center estimated the likelihood of the research vessel Polarstern being captured within the ordered imagery would have been below 50%. SIDFEx has also contributed to the recent discovery of Shackleton's Endurance that sank underneath the ice in the Antarctic Weddell Sea a century ago—highlighting the impact that SIDFEx had on enhancing the precision of operational tasks in polar expeditions.

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References

Arctic Climate Impact Assessment, 2005: *Arctic Climate Impact Assessment – ACIA Overview Report.* Cambridge University Press, 1020 pp.

Arduini, G., G. Balsamo, E. Dutra, J. J. Day, I. Sandu, S. Boussetta, and T. Haiden, 2019: Impact of a multi-layer snow scheme on near-surface weather forecasts. *J. Adv. Model. Earth Syst.*, **11**, 4687–4710, https://doi.org/10.1029/2019MS001725.

——, S. Keeley, J. J. Day, I. Sandu, L. Zampieri and G. Balsamo, 2022: On the importance of representing snow over sea-ice for simulating the Arctic boundary layer. *J. Adv. Model. Earth Syst.*, **14**, e2021MS002777, https://doi.org/10.1029/2021MS002777.

Aue, L., L. Roentgen, W. Dorn, P. Uotila, T. Vihma, G. Spreen, and A. Rinke, 2023: Impact of three intense winter cyclones on the sea ice cover in the Barents Sea: A case study with a coupled regional climate model. *Front. Earth Sci.*, **11**, 1112467, https://doi.org/10.3389/feart.2023.1112467.

Bailey, H., A. Hubbard, E. S. Klein, K.-R. Mustonen, P. D. Akers, H. Marttila, and J. M. Welker, 2021: Arctic sea-ice loss fuels extreme European snowfall. *Nat. Geosci.*, **14**, 283–288, https://doi.org/10.1038/s41561-021-00719-y.

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

——, B. Cheng, and V. Kallio-Myers, 2024: Sea ice cover in the Copernicus Arctic Regional Reanalysis. *Cryosphere*, **18**, 1157–1183, https://doi.org/10.5194/tc-18-1157-2024.

Bauer, P., and T. Jung, 2016: Editorial for the Quarterly Journal's special issue on polar prediction. *Quart. J. Roy. Meteor. Soc.*, **142**, 537–538. https://doi.org/10.1002/qj.2639.

——, and Coauthors, 2016a: WWRP Polar Prediction Project Implementation Plan for the Year of Polar Prediction (YOPP). World Meteorological Organisation, WWRP/PPP 4, 68 pp., https://library.wmo.int/idurl/4/55195.

——, L. Magnusson, J.-N. Thépaut, and T. M. Hamill, 2016b: Aspects of ECMWF model performance in polar areas. *Quart. J. Roy. Meteor. Soc.*, **142**, 583–596, https://doi.org/10.1002/qj.2449.

——, I. Sandu, L. Magnusson, R. Mladek, and 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.

——, P. D. Dueben, T. Hoefler, T. Quintino, T. C. Schulthess, and N. P. Wedi, 2021: The digital revolution of Earth-system science. *Nat. Comput. Sci.*, **1**, 104–113, https://doi.org/10.1038/s43588-021-00023-0.

——, P. Dueben, M. Chantry, F. Doblas-Reyes, T. Hoefler, A. McGovern, and B. Stevens, 2023: Deep learning and a changing economy in weather and climate prediction. *Nat. Rev. Earth Environ.*, **4**, 507–509, https://doi.org/10.1038/s43017-023-00468-z.

Bazile, E., N. Azouz, A. Napoli and C. Loo, 2020: Impact of the 1D sea-ice model GELATO in the global model ARPEGE. WCRP Rep. 12/2020, Research Activities in Earth System Modelling Rep. 50, 2 pp., https://wgne.net/bluebook/uploads/2020/docs/06_Bazile_Eric_sea_ice_model_in_ARPEGE.pdf.

Blackport, R., and J. A. Screen, 2020: Weakened evidence for mid-latitude impacts of Arctic warming. *Nat. Climate Change*, **10**, 1065–1066, https://doi.org/10.1038/s41558-020-00954-y.

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

Bormann, N., 2022: Accounting for Lambertian reflection in the assimilation of microwave sounding radiances over snow and sea-ice. *Quart. J. Roy. Meteor. Soc.*, **148**, 2796–2813, https://doi.org/10.1002/qj.4337.

Bromwich, D. H., and Coauthors, 2020: The Year of Polar Prediction in the Southern Hemisphere (YOPP-SH). *Bull. Amer. Meteor. Soc.*, **101**, E1653–E1676, https://doi.org/10.1175/BAMS-D-19-0255.1.

——, J. G. Powers, K. W. Manning, and X. Zou, 2022: Antarctic data impact experiments with Polar WRF during the YOPP-SH summer special observing period. *Quart. J. Roy. Meteor. Soc.*, **148**, 2194–2218, https://doi.org/10.1002/qj.4298.

——, and Coauthors, 2024: Winter targeted observing periods during the Year of Polar Prediction in the Southern Hemisphere (YOPP-SH). *Bull. Amer. Meteor. Soc.*, **105**, E1662–E1684, https://doi.org/10.1175/BAMS-D-22-0249.1.

Casati, B., and Coauthors, 2023: Performance of the Canadian Arctic Prediction System during the YOPP Special Observing Periods. *Atmos.–Ocean*, **61**, 246–272, https://doi.org/10.1080/07055900.2023.2191831.

Choi, Y., S.-J. Kim, D. H. Bromwich, J. G. Powers, H. Kwon, and S.-J. Park, 2023: Effects of assimilation of YOPP-SH additional radiosonde observations on analyses and forecasts over Antarctica in austral summer. *Quart. J. Roy. Meteor. Soc.*, **149**, 2719–2741, https://doi.org/10.1002/qj.4528.

Cohen, J., and Coauthors, 2020: Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. *Nat. Climate Change*, **10**, 20–29, https://doi.org/10.1038/s41558-019-0662-y.

Cummins, D. P., V. Guemas, M. R. Gallagher, C. J. Cox, and M. D. Shupe, 2023: Surface turbulent fluxes from the MOSAiC campaign predicted by machine learning. *Geophys. Res. Lett.*, **50**, e2023GL105698, https://doi.org/10.1029/2023GL105698.

Dada, L., and Coauthors, 2022: A central arctic extreme aerosol event triggered by a warm air-mass intrusion. *Nat. Commun.*, **13**, 5290, https://doi.org/10.1038/s41467-022-32872-2.

Dawson, J., and Coauthors, 2017: Navigating weather, water, ice and climate information for safe polar mobilitires. WWRP/PPP 5, 84 pp.,http://www.polarprediction.net/fileadmin/user_upload/www.polarprediction.net/Home/Organization/Task_Teams/PPP-SERA/WWRP_PPP_No_5_2017_11_OCT.pdf.

Day, J. J., and Coauthors, 2017: The Abisko Polar Prediction School. *Bull. Amer. Meteor. Soc.*, **98**, 445–447, https://doi.org/10.1175/BAMS-D-16-0119.1.

——, I. Sandu, L. Magnusson, M. J. Rodwell, H. Lawrence, N. Bormann, and T. Jung, 2019: Increased Arctic influence on the midlatitude flow during Scandinavian Blocking episodes. *Quart. J. Roy. Meteor. Soc.*, **145**, 3846–3862, https://doi.org/10.1002/qj.3673.

——, and Coauthors, 2024: The Year of Polar Prediction site Model Intercomparison Project (YOPPsiteMIP) phase 1: project overview and Arctic winter forecast evaluation. *Geosci. Model Dev.*, **17**, 5511–5543, https://doi.org/10.5194/gmd-17-5511-2024.

Dong, X., Y. Nie, J. Wang, H. Luo, Y. Gao, Y. Wang, J. Liu, D. Chen, and Q. Yang, 2024: Deep learning shows promise for seasonal prediction of Antarctic sea ice in a rapid decline scenario. *Adv. Atmos. Sci.*, **41**, 1569–1573, https://doi.org/10.1007/s00376-024-3380-y.

Dukhovskoy, D. S., J. Ubnoske, E. Blanchard-Wrigglesworth, H. R. Hiester, and A. Proshutinsky, 2015: Skill metrics for evaluation and comparison of sea ice models. *J. Geophys. Res. Oceans*, **120**, 5910–5931, https://doi.org/10.1002/2015JC010989.

Elvidge, A. D., I. A. Renfrew, I. M. Brooks, P. Srivastava, M. J. Yelland, and J. Prytherch, 2021: Surface heat and moisture exchange in the marginal ice zone: Observations and a new parameterization scheme for weather and climate models. *J. Geophys. Res. Atmos.*, **126**, e2021JD034827, https://doi.org/10.1029/2021JD034827.

Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.*, **39**, L06801, https://doi.org/10.1029/2012GL051000.

Goessling, H. F., S. Tietsche, J. J. Day, E. Hawkins, and T. Jung, 2016a: Predictability of the Arctic sea ice edge. *Geophys. Res. Lett.*, **43**, 1642–1650, https://doi.org/10.1002/2015GL067232.

——, and Coauthors, 2016b: Paving the way for the Year of Polar Prediction. *Bull. Amer. Meteor. Soc.*, **97**, ES85–ES88, https://doi.org/10.1175/BAMS-D-15-00270.1.

Goessling, H., and K. Werner, 2023: Year of the Polar Prediction: Foresting dialogue—To guide decision making. World Meteorological Organisation, World Weather Research Project Publication, 36 pp., https://library.wmo.int/idurl/4/68185.

Unauthenticated | Downloaded 04/07/26 05:14 PM UTC

Goessling, H. F., and T. Jung, 2018: A probabilistic verification score for contours: Methodology and application to Arctic ice-edge forecasts. *Quart. J. Roy. Meteor. Soc.*, **144**, 735–743, https://doi.org/10.1002/qj.3242.

Haavisto, R., M. Lamers, R. Thoman, D. Liggett, J. Carrasco, J. Dawson, G. Ljubicic, and E. Stewart, 2020: Mapping weather, water, ice and climate (WWIC) information providers in Polar Regions: Who are they and who do they serve? *Polar Geogr.*, **43**, 120–138, https://doi.org/10.1080/1088937X.2019.1707320.

Haiden, T., M. Janousek, F. Vitart, Z. Ben-Bouallegue, and F. Prates, 2023: Evaluation of ECMWF forecasts, including the 2023 upgrade. ECMWF Tech. Memo. 911, 60 pp., https://www.ecmwf.int/en/elibrary/81389-evaluation-ecmwf-forecasts-including-2023-upgrade.

Hames, O., and Coauthors, 2022: Modeling the small-scale deposition of snow onto structured Arctic sea ice during a MOSAiC storm using snowBedFoam 1.0. *Geosci. Model Dev.*, **15**, 6429–6449, https://doi.org/10.5194/gmd-15-6429-2022.

Hartung, K., G. Svensson, H. Struthers, A.-L. Deppenmeier, and W. Hazeleger, 2018: An EC-Earth coupled atmosphere–ocean single-column model (AOSCM. v1_EC-Earth3) for studying coupled marine and polar processes. *Geosci. Model Dev.*, **11**, 4117–4137, https://doi.org/10.5194/gmd-11-4117-2018.

——, ——, J. Holt, A. Lewinschal, and M. Tjernström, 2022: Exploring the dynamics of an Arctic sea ice melt event using a coupled atmosphere-ocean single-column model. *J. Adv. Model. Earth Syst.*, **14**, e2021MS002593, https://doi.org/10.1029/2021MS002593.

Heinemann, G., L. Schefczyk, S. Willmes, and M. D. Shupe, 2022: Evaluation of simulations of near-surface variables using the regional climate model CCLM for the MOSAiC winter period. *Elementa Sci. Anthropocene*, **10**, 00033, https://doi.org/10.1525/elementa.2022.00033.

——, ——, R. Zentek, I. M. Brooks, S. Dahlke, and A. Walbröl, 2023: Evaluation of vertical profiles and atmospheric boundary layer structure using the regional climate model CCLM during MOSAiC. *Meteorology*, **2**, 257–275, https://doi.org/10.3390/meteorology2020016.

Heinrich, V. J., and Coauthors, 2024: The use of weather, water, ice, and climate (WWIC) information in the Polar Regions: What is known after the decade-long Polar Prediction Project? *Wea. Climate Soc.*, **16**, 369–387, https://doi.org/10.1175/WCAS-D-23-0105.1.

Herrmannsdörfer, L., M. Mueller, M. D. Shupe, and P. Rostosky, 2023: Surface temperature comparison of the Arctic winter MOSAiC observations, ERA5 reanalysis, and MODIS satellite retrieval. *Elementa*, **11**, 00085, https://doi.org/10.1525/elementa.2022.00085.

Hoffmann, J., P. Bauer, I. Sandu, N. Wedi, T. Geenen, and D. Thiemert, 2023: Destination Earth–A digital twin in support of climate services. *Climate Serv.*, **30**, 100394, https://doi.org/10.1016/j.cliser.2023.100394.

Inoue, J., 2021: Review of forecast skills for weather and sea ice in supporting Arctic navigation. *Polar Sci.*, **27**, 100523, https://doi.org/10.1016/j.polar.2020.100523.

——, and K. Sato, 2022: Toward sustainable meteorological profiling in polar regions: Case studies using an inexpensive UAS on measuring lower boundary layers with quality of radiosondes. *Environ. Res.*, **205**, 112468, https://doi.org/10.1016/j.envres.2021.112468.

——, M. E. Hori, and K. Takaya, 2012: The role of Barents Sea ice in the wintertime cyclone track and emergence of a warm-Arctic cold-Siberian anomaly. *J. Climate*, **25**, 2561–2568, https://doi.org/10.1175/JCLI-D-11-00449.1.

——, A. Yamazaki, J. Ono, K. Dethloff, M. Maturilli, R. Neuber, P. Edwards, and H. Yamaguchi, 2015: Additional Arctic observations improve weather and sea-ice forecasts for the Northern Sea Route. *Sci. Rep.*, **5**, 16868, https://doi.org/10.1038/srep16868.

Jeuring, J., and M. Lamers, 2022: Towards useful forms of co-production in met-ocean services for the European Arctic. Report from PPP-SERA Special Services Workshop Online meeting. Zenodo, 32 pp., https://zenodo.org/record/7483419#.Y6ltnBVBzrc.

Jung, T., and M. Leutbecher, 2007: Performance of the ECMWF forecasting system in the Arctic during winter. *Quart. J. Roy. Meteor. Soc.*, **133**, 1327–1340, https://doi.org/10.1002/qj.99.

——, and P. B. Rhines, 2007: Greenland's pressure drag and the Atlantic storm track. *J. Atmos. Sci.*, **64**, 4004–4030, https://doi.org/10.1175/2007JAS2216.1.

——, and J. Wilson, 2022: Year of Polar Prediction – Achievements and Impacts. Zenodo. 48 pp., https://doi.org/10.5281/zenodo.7355088.

——, M. A. Kasper, T. Semmler, and S. Serrar, 2014: Arctic influence on subseasonal midlatitude prediction. *Geophys. Res. Lett.*, **41**, 3676–3680, https://doi.org/10.1002/2014GL059961.

——, and Coauthors, 2016: Advancing polar prediction capabilities on daily to seasonal time scales. *Bull. Amer. Meteor. Soc.*, **97**, 1631–1647, https://doi.org/10.1175/BAMS-D-14-00246.1.

——, F. Massonnet, and I. Sandu, 2023: Editorial: Special collection—Impact of polar observations on predictive skill. *Quart. J. Meteor. Soc.*, **149**, 1135–1137, https://doi.org/10.1002/qj.4458.

Kirbus, B., and Coauthors, 2023: Surface impacts and associated mechanisms of a moisture intrusion into the Arctic observed in mid-April 2020 during MOSAiC. *Front. Earth Sci.*, **11**, 1147848, https://doi.org/10.3389/feart.2023.1147848.

Koldunov, N., and T. Jung, 2024: Local climate services for all, courtesy of large language models. *Commun. Earth. Environ.*, **5**, 13, https://doi.org/10.1038/s43247-023-01199-1.

Køltzow, M., B. Casati, E. Bazile, T. Haiden, and T. Valkonen, 2019: An NWP model intercomparison of surface weather parameters in the European Arctic during the Year of Polar Prediction special observing period northern hemisphere 1. *Wea. Forecasting*, **34**, 959–983, https://doi.org/10.1175/WAF-D-19-0003.1.

Kristjánsson, J. E., and E. W. Kolstad, 2011: IPY-THORPEX. *Quart. J. Roy. Meteor. Soc.*, **137**, 1657–1658, https://doi.org/10.1002/qj.965.

Lam, R., and Coauthors, 2023: Learning skillful medium-range global weather forecasting. *Science*, **382**, 1416–1421, https://doi.org/10.1126/science.adi2336.

Lamers, M., and D. Liggett, 2020: Generating societal value from improved weather, water & ice forecasts in the Polar Regions. *Polar Geogr.*, **43**, 89–94, https://doi.org/10.1080/1088937X.2020.1766594.

——, and Coauthors, 2024: Tailored investments needed to support weather, water, ice, and climate services in the polar regions. *Bull. Amer. Meteor. Soc.*, **105**, E645–E650, https://doi.org/10.1175/BAMS-D-23-0159.1.

Landy, J. C., and Coauthors, 2022: A year-round satellite sea-ice thickness record from CryoSat-2. *Nature*, **609**, 517–522, https://doi.org/10.1038/s41586-022-05058-5.

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

Liu, C., and Coauthors, 2024: The role of non-local effects on surface sensible heat flux under different types of thermal structures over the Arctic sea-ice surface. *Geophys. Res. Lett.*, **51**, e2023GL106753, https://doi.org/10.1029/2023GL106753.

Liu, J., D. Bromwich, D. Chen, R. Cordero, T. Jung, M. Raphael, J. Turner, and Q. Yang, 2020: Preface to the special issue on Antarctic Meteorology and Climate: Past, present and future. *Adv. Atmos. Sci.*, **37**, 421–422, https://doi.org/10.1007/s00376-020-2001-7.

Luo, H., Q. Yang, L. Mu, X. Tian-Kunze, L. Nerger, M. Mazloff, L. Kaleschke, and D. Chen, 2021: DASSO: A Data Assimilation System for the Southern Ocean that utilizes both sea-ice concentration and thickness observations. *J. Glaciol.*, **67**, 1235–1240, https://doi.org/10.1017/jog.2021.57.

——, ——, M. Mazloff, L. Nerger, and D. Chen, 2023: The impacts of optimizing model-dependent parameters on the Antarctic sea ice data assimilation. *Geophys. Res. Lett.*, **50**, e2023GL105690, https://doi.org/10.1029/2023GL105690.

Mariani, Z., and Coauthors, 2024: Special observing period (SOP) Data for the Year of Polar Prediction site Model Intercomparison Project (YOPPsiteMIP). *Earth Syst. Sci. Data*, **16**, 3083–3124, https://doi.org/10.5194/essd-16-3083-2024.

Unauthenticated | Downloaded 04/07/26 05:14 PM UTC

Massonnet, F., and Coauthors, 2023: SIPN South: Six years of coordinated seasonal Antarctic sea ice predictions. *Front. Mar. Sci.*, **10**, 1148899, https://doi.org/10.3389/fmars.2023.1148899.

Min, C., Q. Yang, H. Luo, D. Chen, T. Krumpen, N. Mamnun, X. Liu, and L. Nerger, 2023: Improving Arctic sea-ice thickness estimates with the assimilation of CryoSat-2 summer observations. *Ocean-Land-Atmos. Res.*, **2**, 0025, https://doi.org/10.34133/olar.0025.

Mohammadi-Aragh, M., M. Losch, and H. F. Goessling, 2020: Comparing Arctic Sea ice model simulations to satellite observations by multiscale directional analysis of linear kinematic features. *Mon. Wea. Rev.*, **148**, 3287–3303, https://doi.org/10.1175/MWR-D-19-0359.1.

Moritz, R. E., C. M. Bitz, and E. J. Steig, 2002: Dynamics of recent climate change in the Arctic. *Science*, **297**, 1497–1502, https://doi.org/10.1126/science.1076522.

Nicolaus, M., and Coauthors, 2022: Overview of the MOSAiC Expedition: Snow and sea ice. *Elementa*, **10**, 000046, https://doi.org/10.1525/elementa.2021.000046.

Palerme, C., M. Müller, and A. Melsom, 2019: An intercomparison of verification scores for evaluating the sea ice edge position in seasonal forecasts. *Geophys. Res. Lett.*, **46**, 4757–4763, https://doi.org/10.1029/2019GL082482.

Pasqualetto, S., L. Cristini, and T. Jung, 2022: How to get your message across: Designing an impactful knowledge transfer plan in a European project. *Geosci. Comm*, **5**, 87–100, https://doi.org/10.5194/gc-5-87-2022.

Pithan, F., and Coauthors, 2018: Role of air-mass transformations in exchange between the Arctic and mid-latitudes. *Nat. Geosci.*, **11**, 805–812, https://doi.org/10.1038/s41561-018-0234-1.

——, and Coauthors, 2023: Nudging allows direct evaluation of coupled climate models with in situ observations: A case study from the MOSAiC expedition. *Geosci. Model Dev.*, **16**, 1857–1873, https://doi.org/10.5194/gmd-16-1857-2023.

Rabe, B., and Coauthors, 2022: Overview of the MOSAiC expedition: Physical oceanography. *Elementa*, **10**, 00062, https://doi.org/10.1525/elementa.2021.00062.

——, and Coauthors, 2024: The MOSAiC Distributed Network: Observing the coupled Arctic system with multidisciplinary, coordinated platforms. *Elementa*, **12**, 00103, https://doi.org/10.1525/elementa.2023.00103.

Randriamampianina, R., N. Bormann, M. A. Ø. Køltzow, H. Lawrence, I. Sandu, and Z. Q. Wang, 2021: Relative impact of observations on a regional Arctic numerical weather prediction system. *Quart. J. Roy. Meteor. Soc.*, **147**, 2212–2232, https://doi.org/10.1002/qj.4018.

Renfrew, I. A., and J. E. Kristjánsson, 2009: The Greenland Flow Distortion experiment. *Quart. J. Roy. Meteor. Soc.*, **135**, 1917–1918, https://doi.org/10.1002/qj.534.

——, and Coauthors, 2021: An evaluation of surface meteorology and fluxes over the Iceland and Greenland Seas in ERA5 reanalysis: The impact of sea ice distribution. *Quart. J. Roy. Meteor. Soc.*, **147**, 691–712, https://doi.org/10.1002/qj.3941.

Sánchez-Benítez, A., H. Goessling, F. Pithan, T. Semmler, and T. Jung, 2022: The July 2019 European heat wave in a warmer climate: Storyline scenarios with a coupled model using spectral nudging. *J. Climate*, **35**, 2372–2390, https://doi.org/10.1175/JCLI-D-21-0573.1.

Sandu, I., and Coauthors, 2021: The potential of numerical prediction systems to support the design of Arctic observing systems: Insights from the APPLICATE and YOPP projects. *Quart. J. Roy. Meteor. Soc.*, **147**, 3863–3877, https://doi.org/10.1002/qj.4182.

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

——, ——, ——, ——, A. Makshtas, V. Kustov, M. Maturilli, and K. Dethloff, 2018: Impact on predictability of tropical and mid-latitude cyclones by extra Arctic observations. *Sci. Rep.*, **8**, 12104, https://doi.org/10.1038/s41598-018-30594-4.

——, ——, and ——, 2020: Performance of forecasts of hurricanes with and without upper-level troughs over the mid-latitudes. *Atmosphere*, **11**, 702, https://doi.org/10.3390/atmos11070702.

——, ——, I. Simmonds, and I. Rudeva, 2021: Antarctic Peninsula warm winters influenced by Tasman Sea temperatures. *Nat. Commun.*, **12**, 1497, https://doi.org/10.1038/s41467-021-21773-5.

——, ——, A. Yamazaki, Y. Tomikawa, and K. Sato, 2022: Reduced error and uncertainty in analysis and forecasting in the Southern Hemisphere through assimilation of PANSY radar observations from Syowa Station: A midlatitude extreme cyclone case. *Quart. J. Roy. Meteor. Soc.*, **148**, 3115–3130, https://doi.org/10.1002/qj.4347.

Schneirstien, N., J. Chylik, M. D. Shupe, and R. A. J. Neggers, 2024: Standardized daily high-resolution large-eddy simulations of the Arctic boundary layer and clouds during the complete *MOSAiC* drift. *J. Adv. Model. Earth Syst.*, **16**, e2024MS004296, https://doi.org/10.1029/2024MS004296.

Schyberg, H., and Coauthors, 2020: Arctic regional reanalysis on single levels from 1991 to present. Copernicus Climate Change Service (C3S) Climate Data store, accessed 1 July 2023, https://doi.org/10.24381/cds.713858f6.

Semmler, T., M. A. Kasper, T. Jung, and S. Serrar, 2016: Remote impact of the Antarctic atmosphere on the southern mid-latitudes. *Meteor. Z.*, **25**, 71–77, https://doi.org/10.1127/metz/2015/0685.

——, T. Jung, M. A. Kasper, and S. Serrar, 2018: Using NWP to assess the influence of the Arctic atmosphere on midlatitude weather and climate. *Adv. Atmos. Sci.*, **35**, 5–13, https://doi.org/10.1007/s00376-017-6290-4.

Shaddy, A., and Coauthors, 2023: Modelling the coupled mercury-halogen-ozone cycle in the central Arctic during spring. *Elementa*, **11**, 00129, https://doi.org/10.1525/elementa.2022.00129.

Shepherd, T. G., 2019: Storyline approach to the construction of regional climate change information. *Proc. Roy. Soc. USA.*, **475A**, 20190013, https://doi.org/10.1098/rspa.2019.0013.

Shupe, M. D., and Coauthors, 2020: The MOSAiC expedition: A year drifting with the Arctic sea ice. NOAA Arctic Report Card 2020, 8 pp., https://doi.org/10.25923/9g3v-xh92.

——, and Coauthors, 2022: Overview of the MOSAiC Expedition: Atmosphere. *Elementa*, **10**, 00060, https://doi.org/10.1525/elementa.2021.00060.

Smith, D. M., and Coauthors, 2019: The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: Investigating the causes and consequences of polar amplification. *Geosci. Model Dev.*, **12**, 1139–1164, https://doi.org/10.5194/gmd-12-1139-2019.

——, and Coauthors, 2022: Robust but weak winter atmospheric circulation response to future Arctic sea ice loss. *Nat. Commun.*, **13**, 727, https://doi.org/10.1038/s41467-022-28283-y.

Solomon, A., and Coauthors, 2023: The winter central Arctic surface energy budget: A model evaluation using observations from the MOSAiC campaign. *Elementa*, **11**, 00104, https://doi.org/10.1525/elementa.2022.00104.

Stewart, E. J., D. Liggett, M. Lamers, G. Ljubicic, J. Dawson, R. Thoman, R. Haavisto, and J. Carrasco, 2020: Characterizing polar mobilities to understand the role of weather, water, ice and climate (WWIC) information. *Polar Geogr.*, **43**, 95–119, https://doi.org/10.1080/1088937X.2019.1707319.

Svensson, G., and Coauthors, 2023a: Warm air intrusions reaching the MOSAiC expedition in April 2020—The YOPP targeted observing period (TOP). *Elementa*, **11**, 00016, https://doi.org/10.1525/elementa.2023.00016.

——, M. D. Shupe and F. Pithan, 2023b. Model Intercomparison and Improvement Projects (MIIPs) for the polar regions and beyond (GMD/ESSD inter-journal SI) (GMD/ESSD inter-journal SI). https://www.earth-system-science-data.net/articles_and_preprints/scheduled_sis.html.

Thoman, R. L., J. Dawson, D. Liggett, M. Lamers, E. Stewart, G. Ljubicic, M. Knol, and W. Hoke, 2017: Understanding the creation and use of polar weather and climate information. *Bull. Amer. Meteor. Soc.*, **98**, ES3–ES5, https://doi.org/10.1175/BAMS-D-16-0195.1.

Unauthenticated | Downloaded 04/07/26 05:14 PM UTC

Tjernström, J., and Coauthors, 2024: Accelerating research through community open source software for a standardized file format to improve process representation in numerical weather prediction models. EGUsphere, 2024-2088 https://doi.org/10.5194/egusphere-2024-2088.

Tjernström, M., G. Svensson, L. Magnusson, I. M. Brooks, J. Prytherch, J. Vüllers, and G. Young, 2020: Central Arctic Weather Forecasting: Confronting the ECMWF IFS with observations from the Arctic Ocean 2018 expedition. *Quart. J. Roy. Meteor. Soc.*, **147**, 1278–1299, https://doi.org/10.1002/qj.3971.

Tummon, F., J. Day, and G. Svensson, 2018: Training early-career polar weather and climate researchers. *Eos*, **99**, https://doi.org/10.1029/2018EO103475.

Uttal, T., and Coauthors, 2016: International Arctic systems for observing the atmosphere: An international polar year legacy consortium. *Bull. Amer. Meteor. Soc.*, **97**, 1033–1056, https://doi.org/10.1175/BAMS-D-14-00145.1.

——, and Coauthors, 2024: Merged Observatory Data Files (MODFs): An integrated observational data product supporting process-oriented investigations and diagnostics. *Geosci. Model Dev.*, **17**, 5225–5247, https://doi.org/10.5194/gmd-17-5225-2024.

Vitart, F., and Coauthors, 2017: The Subseasonal to Seasonal (S2S) prediction project database. *Bull. Amer. Meteor. Soc.*, **98**, 163–173, https://doi.org/10.1175/BAMS-D-16-0017.1.

Wedi, N., and Coauthors, 2022: Destination Earth: High-performance computing for weather and climate. *Comput. Sci. Eng.*, **24**, 29–37, https://doi.org/10.1109/MCSE.2023.3260519.

Werner, K., and S. Pasqualetto, 2021: The IcePod—Official podcast for the Year of Polar Prediction to support MOSAiC ice drift. *Polarforschung*, **89**, 85–87, https://doi.org/10.5194/polf-89-85-2021.

——, Y. Zaika, A. K. Pavlov, S. Lidström, A. Pope, R. Badhe, M. Brückner, and L. Cristini, 2019: Project and community management in polar sciences—Challenges and opportunities. *Adv. Geosci.*, **46**, 25–43, https://doi.org/10.5194/adgeo-46-25-2019.

Wilson, J., and Coauthors, 2023: The YOPP final summit: Assessing past and forecasting future polar prediction research. *Bull. Amer. Meteor. Soc.*, **104**, E660–E665, https://doi.org/10.1175/BAMS-D-22-0282.1.

WMO, 2023: Global demonstration campaign for evaluating the use of uncrewed aircraft systems in operational meteorology: White paper, WMO 1318, 40 pp., https://library.wmo.int/idurl/4/66308.

Xiu, Y., H. Luo, Q. Yang, S. Tietsche, J. Day, and D. Chen, 2022: The challenge of Arctic sea ice thickness prediction by ECMWF on subseasonal time scales. *Geophys. Res. Lett.*, **49**, e2021GL097476, https://doi.org/10.1029/2021GL097476.

Yang, Q., L. Mu, X. Wu, J. Liu, F. Zheng, J. Zhang, and C. Lib, 2019: Improving Arctic sea ice seasonal outlook by ensemble prediction using an ice-ocean model. *Atmos. Res.*, **227**, 14–23, https://doi.org/10.1016/j.atmosres.2019.04.021.

——, and Coauthors, 2023: Better synoptic and subseasonal sea ice thickness predictions are urgently required: A lesson learned from the YOPP data validation. *Environ. Res. Lett.*, **18**, 071002, https://doi.org/10.1088/1748-9326/acdcaa.

Zampieri, L., H. F. Goessling, and T. Jung, 2018: Bright prospects for Arctic sea ice prediction on subseasonal time scales. *Geophys. Res. Lett.*, **45**, 9731–9738, https://doi.org/10.1029/2018GL079394.

——, ——, and ——, 2019: Predictability of Antarctic sea ice edge on subseasonal time scales. *Geophys. Res. Lett.*, **46**, 9719–9727, https://doi.org/10.1029/2019GL084096.

——, G. Arduini, M. Holland, S. P. E. Keeley, K. Mogensen, M. D. Shupe, and S. Tietsche, 2023: A machine learning correction model of the winter clear-sky temperature bias over the Arctic sea ice in atmospheric reanalyses. *Mon. Wea. Rev.*, **155**, 1443–1458, https://doi.org/10.1175/MWR-D-22-0130.1.

Zhang, X., T. Jung, M. Wang, Y. Luo, T. Semmler, and A. Orr, 2018: Preface to the special issue: Towards improving understanding and prediction of Arctic change and its linkage with Eurasian mid-latitude weather and climate. *Adv. Atmos. Sci.*, **35** (1), 1–4, https://doi.org/10.1007/s00376-017-7004-7.

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