Reducing Risks in Arctic Marine Operations: Coproducing Subseasonal-to-Seasonal (S2S) Sea-Ice Predictions Using Simulation-Gaming and Scenarios

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Climate services, S2S forecast, Sea ice predictions, Co-production, Arctic marine operations, Participatory simulation, resilience, Foresight, Socioeconomic scenarios, debriefing

Abstract

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The Arctic ice pack is fast becoming seasonal. Rapidly-changing sea ice facilitates increased activities, but it also poses increased hazards for marine sectors, which already operate in an extreme decision environment. The need is growing for forecasts of sea-ice evolution for several months ahead. Sub-seasonal to seasonal (S2S) sea-ice predictions can be of considerable potential socioeconomic value for a diverse range of marine sectors and for local community supply logistics, but such forecasts represent a significant technical challenge. Translating user needs into scientifically sound statements, manageable procedures and robust user confidence requires collaboration among a range of stakeholders. Here we present a novel, transdisciplinary co-production approach that combined socioeconomic scenario development and participatory, research-driven simulation-gaming to test a new S2S sea-ice forecast system with experienced sea-ice captains. Our custom-developed computerized simulation-game ICEWISE integrated natural parameters (sea-ice variation), the forecast technology (seasonal sea-ice risk) and human/social parameters (individual risk perception; socio-economic scenarios). The value of applications-relevant S2S sea-ice prediction is explored, and the opportunities and constraints that govern end-user buy-in are highlighted. We discuss the social benefit of applications-relevant S2S sea-ice prediction, which currently is most evident in schedule-dependent sectors. The usefulness of S2S outlooks is expected to increase however, due to anticipated changes in the physical environment and continued growth in Arctic operations. Our insights into the performance of the combined foresight/simulation coproduction model in brokering knowledge across a range of domains demonstrates promise. We conclude with an overview of the potential contributions from S2S sea-ice predictions and from experiential co-production models to the development of decision-driven and science-informed climate services.

Contribution to the field

In this article we report on a novel transdisciplinary approach in which we engaged potential end-users (sea-ice captains) to test a new S2S forecast of sea-ice probabilities. Direct questioning via surveys and interviews about perceived risks and uncertainties during marine operations does not always lend itself well to conducting research into a complex nexus of factors. This is especially true when those factors arise from different domains (biophysical, social, and human behavior) and create extreme decision environments for forecast users. As an alternative, immersive/experiential research approaches such as participatory and computerized simulation are able to provide a rich and reliable environment that also facilitates three basic goals of research: experimentation, replication and learning. Our framework integrates into the simulation key social-economic-technological scenarios that represent current and future socio-material dimensions and also biophysical parameters, such as projections of sea ice conditions. Our aim was to design a foresight-based framework for the coproduction of climate/weather/metocean forecast services to consider not only the current, but also expected future drivers that will shape the meaning of salient services in different user contexts. We combine anticipatory methods such as scenario development, with participatory simulation and a custom-developed computerized game and report on the implications of our approach for brokering effective partnerships in the development of decision-driven and science-informed climate services.

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1. Introduction

1.1 Background

The Arctic region is arguably the place where the effects of climate change are most dramatically on display. A recent IPCC report has highlighted accelerating climate-change trends in the region (Pörtner et al., 2019): The Arctic is warming twice as fast as the rest of the planet. Drastic impacts from rapid warming are evident on land and at sea alike. Permafrost thaw, coastal erosion, changing freeze and thaw cycles, and climate-related extreme events are just some of the challenges with which Arctic communities and industries are confronted. Over the past 40 years, rapid warming has pushed sea ice into a melting and thinning trend, and Arctic sea-ice extent has decreased for all months of the year.

These rapid changes have profound socio-economic consequences. Climatic changes in the Arctic are propelling growth in shipping, tourism and fisheries (ArcticCouncil, 2009) and this trend is likely to continue in the foreseeable future (Aksenov et al., 2017). For example, researchers already observe shifts in the Svalbard cruising season, pushing seasons both earlier in spring and later in the autumns (Stocker et al., 2020). Such operational trends increase the demand for salient This increases the demand for salient Arctic weather and climate predictions at different time scales, which in turn places expectations on our current global and regional forecasting systems. Improving access to, and quality of, climate-relevant information is particularly pertinent to those operating in remote and dynamic polar-marine environments. Improved services can help reduce the risks and vulnerabilities associated with activities in ice-infested and dynamic Arctic-marine environments. For example, they help to serve the needs of (often remote) Arctic communities whose economies depend on marine activities and sectors. Safe maritime waterways play an important role both in Arctic regional economies, and at the global scale with 80% of global trade in goods being transported by ship (Berle et al., 2011). Increased accessibility of Arctic shipping lanes has global influence -both positive and negative.

These environmental changes are increasing the dynamics and complexities of the decision context for Arctic mariners. For example, as sea ice is becoming thinner and more fragmented, the influence of surface waves increases, causing significant shifts in the dynamic and thermodynamic properties of sea ice (Aksenov et al., 2017). Yet it is often unclear at what time scale environmental information is needed, what constitutes real salience for stakeholders, or why existing climate information often remains unused (Lemos et al., 2012). In this regard, research is needed that considers the situated context of Arctic marine activities for better provision and dissemination of credible products and services to increase the safety and resilience of marine operations.

Under the project Enhancing the Saliency of Climate Services for Marine Mobility Sectors in European Arctic Seas (SALIENSEAS), a multinational consortium of scientists has coproduced improved services for sub seasonal-to-seasonal (S2S) sea-ice forecast. The project involved natural and social scientists and end-users to collaborate to explore ways in which forecast services can reduce uncertainties for stakeholders. S2S forecasting represents one of the central components of seamless weather and climate prediction. Seamless predictive systems aim to fill the gap between weather and climate forecasting in order to take into account the spatial-temporal continuum of the dynamics between scales (Brunet et al., 2010). In contrast with other, more user-centric models of innovation such as the 'climate services' approach (White et al., 2017), S2S prediction can be categorized as applied research (scientific discovery driving innovation); and for which demand is increasing (e.g. Scott et al., 2011; Vaughan et al., 2018; Parker and Lusk, 2019). Our transdisciplinary consortium integrated a user-focused climate services approach into the development of a S2S prediction of sea-ice probabilities, in an effort to extend Arctic marine actors' time horizon for planning.

1.2 Objectives

In this article we report on a novel approach in which we engaged potential end-users to test a new S2S forecast of sea-ice probabilities developed by project partners at the Norwegian Meteorological Institute (MET Norway). Our approach served the following objectives:

- Explore the usability of the product both under current conditions and under future conditions in light of the expected dynamic changes of the next 15 years [Objective 1].
- Test the product's potential to reduce uncertainties in the users' decision environment and to explore users' levels of confidence in S2S forecasting [Objective 2].
- Gain insight into the use of participatory computerized simulation as a method for researching complex interrelations among a nexus of three domains: natural phenomena (e.g. sea-ice variation), forecast technologies (e.g. used for assessment of seasonal sea-ice risk) and human factors (e.g. perceptions and levels of trust and confidence), especially with regard to achieving the first two objectives [Objective 3].

Individual, social and cultural factors in the context within which a product is used as well as the specific attributes of the product itself, all influence user engagement (Arhippainen and Tähti, 2003; O'Brien and Toms, 2008). For this reason we were particularly interested in socio-economic scenarios (i.e. anticipated social, economic, political, cultural and technological changes) because as sea-ice conditions and dynamics in the Arctic Ocean are projected to change drastically by 2035 (Wang and Overland, 2012), the specifics of the technologies used (ships and other equipment), the demand for Arctic marine transport and the intensity and patterns of traffic are also likely to change. These factors and their interactions create distinct sociomaterial (linked human-technological) settings in which weather and sea ice services are used in distinct ways (Lamers et al., 2018a). It is therefore important in the development of products and services that they anticipate, and are resilient to, upcoming changes in the physical environment and in the users' operational contexts. In order to facilitate a simulation-game in which players can both engage with the forecast service under current conditions, and also experiment 'in the future,' we adopted a simulation time flow during which players are exposed to projected future sea-ice conditions for 2035, as well as plausible socio-political shifts for that time horizon.

Our second objective probed how users experience and gain confidence in a forecast's reliability estimate. For example, does a threshold exist that is low enough to render predictions irrelevant? Similarly, at what level is reliability high enough to decrease navigational uncertainties for mariners? Our third objective arose in our search for a research method that would allow us to achieve the first two objectives. We aimed to develop a method that would be cost effective and yet provide sufficiently reliable results to be useful to service providers and end users.

Direct questioning about perceived risks and uncertainties during operations does not always lend itself well to conducting research into a complex nexus of factors, especially those arising from three different domains. As an alternative, experiential research approaches such as participatory and computerized simulation are able to provide a rich and reliable environment that also facilitates three basic goals of research: experimentation, replication and learning. Simulation-games have already been employed in some (mostly hydro-meteorological) forecast service experiments (e.g. Tall et al., 2014; Arnal et al., 2016; Crochemore et al., 2016; Terrado et al., 2019) and in communicating about the risk of flooding (e.g. Skinner, 2020). Our research proposes a novel framework that integrates into the simulation key social-economic-technological scenarios that represent current and future socio-material dimensions and also biophysical parameters, such as projections of sea ice conditions. Our aim was to design a foresight-based framework for the coproduction of climate/weather/metocean forecast services to take the long (or seasonal) view of the diverse and dynamic drivers that shape the meaning of salient services in different user contexts.

We combine anticipatory methods such as scenario development, with participatory simulation and a custom-developed computerized game. Finally, we consider the implications of our approach for brokering effective partnerships in the development of decision-driven and science-informed climate services.

1.3 Conceptual Framework

Co-production refers to the voluntary exchange of ideas, collaboration across organizations and disciplines, through which input from individuals and groups is transformed into goods and services (see for example Brudney and England, 1983; Ostrom, 1996; Meadow et al., 2015; Alexander and Dessai, 2019). Co-production does not refer to a single approach to collaboration (e.g. Brandsen and Honingh, 2016; Miller and Wyborn, 2018) and different frameworks have been explored in the context of diverse disciplines and rationales (Turnhout et al., 2020). Co-production in climate services should be inclusive, collaborative and flexible (Vincent et al., 2018), so as to improve mutual understanding among actors (Bremer et al., 2019) and result in improved products that are useful, useable and used (Vaughan et al., 2018). Though the rationale for co-production varies from citizen empowerment to the depoliticization of the science-policy interface, typically all co-production projects aim to align the production of information with their demand (e.g. Sarewitz and Pielke Jr, 2007).

Numerous monikers have been coined for the study of alternative futures and each distinct name has its own history in literature (Sardar, 2010). In this paper we use the term ‘foresight’ for anticipatory activities. Foresight aims to increase our understanding of systems (social, ecological, industrial/sectoral) and complex interactions and feedbacks (Saritas, 2013) to explore emergent properties and probable future system states. Scenario building is a widely used foresight tool, often used to explore with stakeholders important dynamics between present actions and future outcomes in the context of climate change (Sheppard et al., 2011; Lovecraft et al., 2017).

Simulation-games are a category of games that have a purpose beyond entertainment and which is usually educational or instructional (e.g. Fleming et al., 2020). Game mechanics can make learning and instruction more engaging or immersive (e.g. Whitton, 2011; Whitton and Moseley, 2014), while providing a place for experimentation, feedback and a sense of accomplishment (Kapp, 2012). The value of simulation-gaming methods for learning, training and instruction have been well-established in the literature (e.g. Voinov and Bousquet, 2010; Le Page et al., 2013; Litinski, 2013; Voinov et al., 2018; Sheldon, 2020) and games have been deployed, for example, to improve disaster preparedness (e.g. Lovreglio et al., 2018). A longer horizon use of participatory simulation is to help organizations to solve complex problems or guide multi-stakeholder decision making (Becu et al., 2017; Becu, 2020; Bommel, 2020). Participatory simulations can help stakeholders to collectively explore and clarify new ideas and strategies (Crookall and Becu, 2020; Student et al., 2020).

Debriefing is the key to the generation of learning that can result from an immersive, experiential activity such as simulation and gaming and participatory simulation (Crookall, 2010; van den Hoogen et al., 2016; Doddema, 2019). The simulation-gaming facilitates player engagement, which results in emerging emotions, understandings, decisions and perceptions, while debriefing provides a platform for the fruitful discussion of those experiences (Crookall, 2014). The debriefing session is also often where the most valuable data is collected, which was the case in our research. Debriefing must be planned in advance and provide a structured environment.

2. Methods

2.1 Demonstration Service

Early stages of planning for a new demonstration service used scoping workshops (Lamers et al., 2018b), one-on-one interviews and surveys (Jeuring and Knol-Kauffman, 2019) to collect information from key stakeholders about the spatial and temporal parameters of the problem space. For example, participants were asked to map the geographic areas that needed enhanced climate services, and the time scale at which the service would be most optimal. Questions around dissemination probed questions about desired lead-time and an optimal interval of dissemination.

Based on stakeholder input, a website showing seasonal forecasts of sea-ice concentration has been developed by MET Norway (Figure 1). The forecasts are produced by the European Centre for Medium-Range Weather Forecasts seasonal prediction system called SEAS5(Johnson et al., 2019) and provide probabilistic information based on 51 different simulations. The sea-ice map shows probabilities for concentrations greater than 15% for the following 6 months, with the outlook initialized starting from the date of visit to the website. The reliability of the forecast is provided for users (Figure 2), and depends on its range (how far out it is viewed) and the season. The reliability estimates communicate the likelihood that the forecast is more reliable as prediction based on climatology. The reliability estimates communicate the likelihood that the forecast is more reliable than a climatological information, and are based on an analysis from Palerme et al. (2019).

In order to help stakeholder participate in the simulation-gaming exercise, a dedicated gaming version of the sea ice forecast was developed separately. Its functions were designed 1) to provide players with the possibility of initializing a forecast on any day of the month, and 2) to enable a 2035 'forecast' or projection of sea-ice probabilities for the 2035 period of the game. The 2035 projection was based on the MPI-ESM-LR model for the period 2030-2039. Using the 2019 forecast's reliability estimates (Figure 2) as a baseline, we approximated probabilities for the 2035 projections to simulate expected future improvements in skillfulness. These future reliability estimates, used only for gaming purposes, simulated a one to eighteen week increase in outlook (depending on the month and reliability level) compared to 2019 estimates.

The demonstration service was initially showcased to and tested, in two separate sessions, by two key stakeholders who had experience in navigating ice-infested waters and in vessel scheduling. One session was held remotely (March 2019 via Skype), the other was held in person (June 2019 in Tromsø, Norway). The sessions were semi-structured to elicit spontaneous and calculated feedback.

2.2 Participatory Simulation

We developed a simulation-gaming environment called ICEWISE, and calibrated it for the cruise tourism sector, as this is one of the influential sectors in the region in need of salient forecasts. ICEWISE allowed us to facilitate a participatory simulation in which potential users of the new S2S sea-ice forecast make voyage plans. ICEWISE simulated certain aspects of the end-users decision environment, and helped service providers understand how the product would be used on the job.

2.2.1 Foresight

The 2035 scenarios were developed in a workshop in collaboration with twenty three experts in the fields of Arctic maritime sectors, navigational safety, Arctic communities, economies, policies, regulations, climate services and climate change. The workshop's focal question was: "What information is needed for optimal decisions toward safe and sustainable maritime activities now and through 2035?" This emphasized long-term safety and sustainability, as a shared goal among marine actors, independent of industrial-sectoral affiliation. Participants produced environmental, social, economic and technical factors that drive decisions around marine operations. These key factors and future projections produced by participants were used in a robustness analysis (Gausemeier et al., 1998) to produce three scenario outcomes with a unique emphasis on either consistency or plausibility, or a combination of both (robustness) (Blair and Muller-Stoffels, 2019). The robust scenario bundle was then illustrated by an artist (Figure 3) and used in the development of event cards and narratives for the simulation (Supplementary Table 1).

2.2.2 Developing and Testing the Gaming Environment

The game was developed using Unity Engine and its 2D GUI utilities. We chose Unity due to its streamlined development interface and multiple documented (Juliani et al., 2018) advantages: ease-of-use, cross-platform compatibility, and a graphical user interface designed to efficiently streamline the iteration of complex environments or novel tasks. This allowed for easy iteration of the game's systems and user interface, allowing time to make necessary changes and tests throughout development.

The game was designed to simulate multiple scenarios in which end-users would use the forecasting system. The simulation was designed with both near-horizon activities (one- to two-week outlook, e.g. navigational planning) and longer-term activities (up to sixteen-week outlook, e.g. certain fleet and itinerary planning) and decision makers in mind. Users are asked to assume the role of an itinerary planner for a fictional Arctic cruise company. The simulation begins by emphasizing to participants that they are to assume a planner's role, which may be different from their normal routines (e.g. in the case of mariners who participate). Facilitators discuss with participants the contrasting situations regarding (a) what is real: in which several metocean factors are important to safe operations in real life, and b) what is simulated and experimental (ICEWISE): in which we isolated sea ice forecasts. Each participant works individually. A total of twelve rounds of play are divided into two periods – six rounds in 2019 and six in 2035. Before the 2019 period a short slideshow summarizes important events and developments impacting Arctic cruising at the time.

Similarly, before the 2035 period begins the simulation shows a brief narrative based on key factors developed at our scenario workshop.

Participants are told that the reward system underlying the game calculates money accumulated and reputation points that simulate public perception of the participant's cruise company. The participant is then asked to view an itinerary; in some rounds in Greenland and in other rounds in Svalbard (Supplementary Table 2). Next the participant rolls a virtual dice, and in return receives an event card describing a specific incident or development that either increases or decreases their bank and reputation points. The event cards serve to simulate potential social, political, economic and environmental developments that can impact the player's business environment and in turn their strategies and voyage planning activities. Figure 4 depicts screenshots of the event card and itinerary displays.

In half of the rounds the participant is instructed to select a start date for the cruise season as early in the spring as safely possible, while in other rounds they have to select the season's final voyage date late in the autumn. After date selection, the participant invests money in the voyage from an available bank of money, and then indicates their own sense of certainty in the success of the voyage between 0 (complete uncertainty) to 100 (complete certainty). Success is defined as a voyage without major disruptions or adverse events. Unsuccessful rounds translate to loss of financial investment and loss of reputation points due to customer dissatisfaction or diminished safety record. Next, the participant examines a sea ice forecast, in each round with a different lead time (alternating between <4, 4<8, and 8<12 weeks) and with varying degrees of certainty, which are announced. At this point the participant is able to update their chosen date, investment amount and self-assessed certainty score. Participants are made aware that the more risky their selected date (the earlier in the spring, or the later in the autumn), the higher the potential return on their investment due to an extended cruise season, but also the greater the risk of failure (loss of money and/or reputation points).

The player finishes each round by clicking on the ship's 'throttle' to launch the voyage and receive feedback[1] on its success and change in bank and reputation points. The return on investment is adjusted in an inverse relationship with the risks faced. A final screen prompts the participant to rate the quality of the forecast as well as their own performance, one of 5 levels of agreement allowed between 1 (very bad) to 5 (very good), after each round. Figure 5 is an overview of the simulation's steps.

We tested the Beta version of the game (October 2019) with five mariners of an expedition cruise company who had ample experience navigating ice-infested waters. Feedback from testers was used to fine-tune the simulation environment ahead of the participatory simulation workshop. This was held on 28 January, 2020 in Tromsø (Norway).

2.2.3 Debriefing

A structured debriefing session was conducted after the gaming session. We made plans for individual feedback (in between rounds and at the end) as well as for group feedback during breakout group discussions. Individual feedback was recorded during the simulation at the end of rounds 3, 6, 9, 12. The feedback at this stage was designed to be a quick snapshot of the player's journey through

[1] Winning or losing each round was based on a probabilistic algorithm using the forecast's reliability estimates.

the simulation. Questionnaires contained eight evaluative statements (3.2.2), each with a 4-point scale using emoji icons from happy to sad as here: ☺ !__!__!__!__! ☹. The emoticons can be considered as approximate indicators of participants' progress through the simulation.

For the debriefing after the simulation, the prepared questions included:

- What were your feelings/emotions during the simulation?
- What differences and similarities did you see between the simulation and reality?
- What thoughts or ideas of yours about voyage planning have changed, or new ones been generated, as a result of participation? What elements of the simulation contributed to the change?
- What elements in the simulation influenced your sense of confidence in the reliability of forecasts? Why and how did these elements influence your confidence?
- What advice would you give to MET Norway for modification of the design of their product?

3. Results

3.1 Demonstration Service Testing

The testing sessions yielded a set of concrete recommendations for product improvement such as altering the model to show 10% instead of 15% sea ice concentrations to align the forecast with Polar Code[2] requirements, and offering the option to zoom for customized resolution. Other recommendations were made about the timing when, and context in which the product would be useful, for example:

The time spread of useful seasonal forecasts is likely to broaden over time:

Climate change is expected to continue to drive changes in sailing patterns. As a result of this trend, new waters and new timings of voyages will increase the demand for a broader range of S2S predictions and will increase the usefulness of products such as our S2S sea ice forecast.

The usefulness of a S2S forecast depends on the user's operational context, even within the same sector:

Testers noted that for a cruise company a 3- 6 month outlook can be useful for planning purposes, for example for routes in the Northwest Passage where monitoring of the sea ice starts in January. An S2S sea ice forecast can help the shipping sector decide when to postpone services or alter routes. On the other hand, for the ice piloting sector, a roughly one-week outlook is normally sufficient for scheduling and planning purposes.

Users who prefer ice charts over a forecast based on probabilities, would make use of a forecast under certain circumstances:

A probabilistic outlook can still be useful as an extra layer of information for planning and client relations in certain situations. For example, in ice pilotage, if climatology and the probabilistic forecast say fundamentally different things, with potentially adverse impacts for a client's itinerary, probabilistic forecasts can be helpful for discussions and making final planning

[2] The International Code for Ships Operating in Polar Waters (the Polar Code) was adopted by the International Maritime Organization in 2017. It is a binding, mandatory framework for ships operating in polar waters covering construction, equipment, operational, training, search and rescue and environmental protection matters.

decisions. Explicitly stated uncertainties (reliability estimates) further help in the evaluation of alternate courses of action.

3.2 The simulation workshop

Six mariners (five captains and one navigation officer) from the cruise and ice pilotage sectors and three researchers from MET Norway participated in the simulation exercise. Mixing users and providers enlivened the debriefing session, by allowing the researchers to put themselves in the day-to-day experience of users, enabling them to ask targeted questions. Five workshop facilitators were present to assist with game play, to take notes and to moderate the debriefing session.

3.2.1 Simulation results

The participants were assigned their own workstations with dedicated computers running the game (Figure 6). Facilitators were seated at workstations between players (one facilitator per two players) to answer any questions that may arise, and to show on a separate monitor the relevant forecasts for the players as they progressed in the game. Participants moved through the 12 rounds in less than 1½ hours. The data input by participants was saved to a database.

Some of the data were used during debriefing in an exploratory capacity to stimulate discussion and to reflect on choices made at key moments in the simulation. A key reflection point related to shifts in self-reported confidence levels and in investment amounts during each round. This was calculated based on the difference in players' confidence and investment (in their selected voyage date) before and after viewing the sea ice forecast (Figure 7). The chart does not indicate a link between participants' decision patterns and forecast probabilities. Greater forecast skill did not necessarily result in greater player confidence and higher investments; an uptick in confidence at the 60% reliability level was detected, but a downturn at 70% based on confidence scores and investment amounts. We used the charts to prompt mariners to reflect about the complexities of their decision-making at different reliability levels.

After the workshop, we checked each participant's average self-reported confidence levels in rounds that took place in 2019 and 2035. Two participants reported virtually no change in how confident they felt about their chosen voyage dates in the current or in the future period (<2% confidence increase in the 2035 average); two participants showed an increase in their confidence in 2035 simulation rounds (13-17% increase), while two participants showed decreased 2035 averages (11% decrease in confidence levels for both). Interestingly however, money investments did not follow the same pattern. Five players invested on average more money in 2035 than they did in 2019 (group average= €128,000 investment increase in 2035), and only one participant invested less (€33,000 decrease). Though statistical significance could not be confirmed via our small cohort, these preliminary findings suggest two potential questions to be explored further:

1. the extent to which willingness to invest and self-reported uncertainty may paint entirely different pictures about participants' feelings about their decision environment; and
2. the extent to which better forecast reliability versus more favorable sea-ice conditions may increase participants' confidence in operational planning in the 2035 period.

In 2035 participants generally chose the first and last voyage dates earlier in the spring and later in the fall than they did in 2019 (Table 1). For the earliest voyage to circumnavigate Svalbard in 2019 most players selected a date in July, and in 2035 a date in June. Similarly, in 2019 most scheduled the last date of the season for September, and in 2035 for October. The Northwest Svalbard itineraries were similarly stretched into earlier and later adjacent months in 2035 in comparison with 2019. The Disko Bay, W. Greenland itinerary was the only exception, where the preferred shoulder season dates were similar in 2035 and in 2019.

3.2.2 Debriefing results

In-simulation feedback is shown in Table 2 from the first debriefing checkpoint (round 3) to the last (round 12). Round 3 feedback indicated a sense of satisfaction (higher number of happy emoticons) among the group for some statements such as complexity, issues, confidence in forecasts, random events, outcomes, but voyage planning and self-confidence were rated as low. At the same time the group exhibited neutral feelings regarding forecast reliability. By the end of round 12, the scores for all propositions had risen. The group responded with higher satisfaction levels to all propositions except the proposition about wildcard events.

After the simulation, a 2.5-hour group debriefing session was led by an experienced facilitator. It is noteworthy that the debriefing took one hour or roughly 70% longer than the simulation. Participant feedback about the forecast product, factors that impact its use and its potential impacts on navigation included the following themes:

Forecast-guided decisions:

Participants explained that, in choosing their dates, even when a forecast had high reliability, the ratio to which the forecast vs. their own experience factored into their final decision was roughly 40/60 (the forecast had a roughly 40% influence over the final decision). When given an itinerary that included unfamiliar areas, this ratio changed to 60% reliance on the forecast and 40% on their own experience and intuitions. Participants agreed that when they use services with which they are familiar and which they trust explicitly, they rely 90% on the forecast, and only 10% on own experience. A participant noted “When I am in doubt, my own knowledge and experience wins every time in terms of decisions I make”.

Probabilistic forecasts of sea ice:

The concept of predicting sea ice is not yet trusted. In real life, sea ice is not homogenous in any one area, and depending on the forecast’s resolution, this can have an impact on forecast reliability. Offering users the option to display probabilities for various sea ice concentrations (10%, 20%) would be a useful feature. Some participants felt it was somewhat difficult to fully operationalize the two layers of probabilities embedded in the product: the probabilities of the sea-ice concentration in combination with the forecast’s reliability estimate.

Usability:

Participants agreed that the full potential of S2S sea-ice predictions materializes in route and capacity planning, but useful applications for tactical and navigational decisions exist in certain sectors (e.g. schedule-dependent cargo shipping). For mariners who work on much shorter (3-7 days) tactical timescales, usefulness is generally more limited (e.g. product would be used in consultation / combination with other services), but this depends on the location: For example in the Northwest Passage where the possibility of reaching Cambridge Bay varies year-to-year, a longer (3-4 week) sea ice forecast outlook would be useful between Nuuk and Cambridge Bay.

Trust:

Trust in a service is crucial to its usefulness, and develops over time, though the length of time may be mitigated by familiarity with the service provider (trusted providers' products are trusted faster). Mariners discover through experience which climate and weather services are the most reliable. Generally, they put their trust in global weather services, thanks to positive experience during use in open waters. When sailing close to coastlines, local weather services are preferred, as they tend to have more resources to develop relevant services.

Designing the future of safe, sustainable Arctic navigation

It forms a risk for operators when policy makers base decision on data without checking the practices and routines of stakeholders. Policy makers may be motivated to refer to a S2S sea ice forecast to regulate where companies can go and when as Arctic routes see an increase in traffic. A participant wondered about such regulatory impacts in the future, and noted that a recent publication of 15-20 year historical sea ice data and risk assessment index showed supposed un-navigable areas at certain times when their company definitely operated there without issues. He emphasized that the cruise sector is quite flexible with adaptable itineraries unlike cargo ships that must adhere to set schedules. The mismatch between policy and operational needs at times is tangible in the provision of services, for example MET Norway does not provide ice charts on the weekend.

Participants have observed shifting socio-economic trends for the Arctic cruise sector, and the industry around Greenland and Svalbard is expected to continue to grow. An increasing number of cruise companies are interested in Greenland's tourism potential. It is expected that once waters become too busy around other tourism hot spots such as Iceland, more and more cruise companies will relocate activities further north. In the near future, the expansion of the Arctic cruise will likely result in companies increasing the number of ships with which they operate, as opposed to expanding the season. These trends will grow the demand for, and investments in, salient metocean services for planning purposes. As companies invest more into Arctic operations, they also increase the financial risk potential of major disruptions or adverse events, driving the demand for accurate, decision-relevant information.

Changes in the physical environment are also swift. Participants shared that the 2035 sea ice models in the simulation are realistic and they are already observing these trends. Participants have encountered more drift ice (bigger concentrations of broken multi-year ice) during operations in the past ten years. When they consider operating in such conditions, the weather must be good and the ship must be able to navigate openings in the ice. All the factors involved in that scenario have high variability, and mariners need effective and sustainable decision support tools. Changing, dynamic environments diminish the navigator's ability to rely on past trends and experience. If a changing climate results in the generation of new sailing patterns, this will also increase the role of forecasts in mariners' decision making. Participants proposed that a future sea-ice forecast, optimized for navigators, should include layers of different sea-ice concentrations and combine drift and wind information on the map. For navigators, such a service would be most relevant at the medium-range time scale, making available data of the ten previous days, and showing predictions ten days out.

Although the primary objective of the workshop was to gather feedback about MET Norway's sea ice service, participant feedback inevitably also provided insights for improvements to the simulation:

Learning:

Participants mentioned learning as a positive impact of the simulation. Some reported more awareness about how the reliability of the sea ice forecast is calculated, and greater ease of use in reading the sea-ice probabilities on the forecast. For mariners, the game highlighted the different motivations and working contexts of vessel-based crew and onshore personnel or 'office guys' as they put it; concluding that "safety and money need to work together". Safety may be first, but the robustness of the business goes hand-in-hand with safety and sustainability. For this, collaboration between crew and onshore personnel is needed, even if they have different ways of making decisions.

Realism:

The simulation was of course limited in complexity compared to real life, as many more factors besides ice must be considered when navigating Arctic waters. Choices about vessel ice class could be added for an extra layer of decision making. In terms of long-term planning however, the simulation was deemed to be fairly isomorphic with real life. The sea ice forecast is not as relevant for the West Greenland itinerary as it is for those in Svalbard and East Greenland because in West Greenland glacier ice is the most relevant parameter for sailing. Stretching the shoulder season into the spring makes sense, but for cruise tourism late fall means little or no wildlife sightings and no interest from customers. For now, economic incentives also draw operators away from the Arctic in the fall/winter season as many head south to profitable Antarctic itineraries.

Enjoyment:

Most participants considered the simulation to be enjoyable and felt positive about experimenting. They agreed that the gambling element (increased rate of return for increased push into shoulder season) and the roll-the-dice event cards were difficult for them to handle as for mariners safety is first, and they do not routinely interact with social, economic, and political context of marine operations. They agreed, however, that for long-term planners this element of the game would be more familiar as itinerary development can have an element of gambling in it. Lastly they agreed that the success/failure feedback indication, about what went wrong or right at the end of rounds, was too vague.

4. Discussion

4.1 S2S Prediction of Sea-Ice Probabilities: Potential Applicability

The extended-range lead time of S2S predictions is where decisions are made in a range of sectors but this new frontier is still in development for both its operational and application-focused capabilities (White et al., 2017). Our project confirmed a number of present and future socio-economic applications of sea-ice probabilities at this time scale among representatives of Arctic marine sectors, and also highlighted several constraints that impact usability and uptake [Objective 1]. Participants agreed that the concept of predicting sea ice beyond the tactical (1-2 days) window will take time to trust, even if forecast skillfulness is transparently communicated to them. They also agreed that expected changes in the physical environment and simultaneous developments in Arctic routes will increase the applicability of, and reliance on, extended range outlooks. Presently, only schedule-dependent sectors would find use for an S2S sea-ice service for navigational decisions, while in the cruise sector the usefulness is limited to specific locations or to route and capacity planners who make use of lower spatial and temporal resolution forecasts (though navigators too may find a practical use for it in combination with other services).

Concern arose about future policy implications, mainly that regulators would use probabilistic predictions to control traffic, without sufficient understanding of operators' practices and the diverse margins of safety across sectors. User feedback such as those obtained during the simulation-game, can help determine location- and sector-specific constraints that govern buy-in and the social benefit that may be derived as a result. Teasing out the diversity of needs and potential benefits, is where social science research and innovative, participatory methods can contribute to a seamless prediction system by identifying channels for generating and communicating decision-relevant information, assessing the use and value of this information, and transferring knowledge and experiences to other regions (Brunet et al., 2010).

Rapid Arctic changes bring about new opportunities by expanding the scope of marine operations and linked markets, but they also pose risks and reveal vulnerabilities. In response, the portfolio and quality of services are expected to grow in the coming years, as providers strategize about how to optimize development in an efficient and responsible manner. However the skill and reliability of S2S sea ice predictions in reducing uncertainties and risks for Arctic mariners has to be demonstrated, and the service trialed, before users have confidence in and trust emerging services and technologies. S2S forecast skill and reliability is gradually improving but the middle ground between what is required and what is possible needs to be explored further (White et al., 2017). More work is also needed to develop transparent, easy-to-understand communication of forecast skill. Some users are more risk-averse than others as a function of the specific requirements of their operational environment, while others are less so. For example, some sectors depend heavily on interactions with the Arctic Marginal Ice Zone (expedition cruise tourism, research and some fishing vessels), others prefer to operate on the outskirts (shipping) or avoid ice completely (resource extraction, infrastructure development activities), and yet other, highly specialized user groups may operate in continuous ice cover (Palma et al., 2019; Wagner et al., 2020). While accurate predictions are vital to all users, the margin of safety is different across user groups, driving diverse information and forecast skill assessment needs. Co-production can highlight context and user-specific appropriate mechanisms for generating and communicating decision-relevant measures of forecast skill.

Results from our simulation-gaming workshop could not confirm a low threshold for reliability estimates that renders predictions irrelevant, nor did a universal high threshold emerge that reduced uncertainties for users [Objective 2]. Users' own experience, familiarity with a location and with the historical range of local conditions, as well as trust in a forecast (or its provider) greatly mitigate the extent to which any single forecast reduces uncertainties in planning and tactical decisions. For example, a captain who is experienced in navigating sea-ice can find their practical knowledge lacking on new routes where glacial ice is the most prominent challenge. Although our participants explained that when ambiguities arise about a forecast's skill, it is their experience that will be most prominent in driving decisions; they also admitted that some service providers they trust enough that even their new products would be quickly trusted implicitly. Yet end-users tend to consult multiple types and sources of data depending on the temporal and spatial availability of, and their access to, services and then use them in combination to enable best decisions. Users from large scale operations typically have detailed and advanced information services at their disposal, tailored to their needs, which often require a fee and are sometimes even more advanced than what public meteorological services deliver (Knol et al., 2018). Smaller operations typically have access to some publicly available services and some historical data, but they tend also to rely heavily on field experience.

For some users, predictions about the probability of high-impact events are more relevant than most probable future mean states (Brunet et al., 2010). In one such example, a participant noted that the area between Cape Farewell and Iceland tends to have extremely bad weather from September to May. For traffic in those areas, weather warnings are most important. Awareness of such operational priorities are an important consideration for service providers and for policy makers as well.

4.2 The Role of Simulation and Foresight-based Tools in Climate Services Co-production

The socio-economic benefits (e.g. protection of life and property, sustainability of the environment) of predictive systems that pursue a seamless process, are enhanced when they incorporates social science with users' knowledge and experience (Brunet et al., 2010). Participatory, experiential research approaches engage diverse user groups for mutual learning. Our simulation- and foresight-based framework has been particularly successful in helping participants to learn about the goals, needs and perspectives of other (user and provider) groups, and to think about present and future strategies in support [Objective 3]. We found that participants had a stimulating effect on each other following simulation-gaming; when ideas and perspectives resonated among participants it often propelled spontaneous, insightful discussions. For example, in one discussion during the debriefing, reflection about the simulation turned into a sharing of enriching anecdotes between two captains. The simulation and debriefing provided an opportunity for in-depth reflection on routines and on a wealth of ideas (Crookall, 2010). Participants also reported increased awareness in general about the science behind sea-ice reliability measures, and greater ease of use of the product. Our mariner participants also grew their understanding of the different working contexts of vessel-based crew and onshore personnel, which, according to them, is vital for the harmonization of the operational safety and the long-term economic viability of the business.

The simulation and debriefing also revealed that, even when predictions make explicit underlying uncertainties, and even when reliability estimates are high, experienced mariners can be cautious to adopt a new service into their routine. This is important for service providers and policy makers, because it entails a lag in the uptake of the services that are in development now, or those that are planned for the near future. This lag translates to a delay in the implementation of solutions that are designed to mediate risks inherent in the safety and sustainability of Arctic social and ecological systems. Participatory simulation-gaming and foresight methods allow participants to think in advance about future needs, and about how to adapt when changes and new demands arise, what services can best support adaptation and how to build up trust. Future-facing climate service co-production models have an important role to play in the resilience of communities and industries in all rapidly changing regions.

The expectation is that co-production results in services that are at once decision-driven and science-informed, and experts have the capacities to confidently lead the production of such marketable, salient products. However, it has been argued that the co-production of services entails several paradoxical relations (Blair et al., 2020) that create conflictual conditions and significant tensions for providers of sea ice predictions: Scientists have to balance simultaneously expertise- and user-driven innovation without losing grasp of production-oriented, high-impact research; they have to assess and make transparent to users their own limitations; and they also must communicate the uncertainties and skill underlying their products, all the while confidently meeting ever-evolving user needs. In addition, one can argue that the automation paradox (Bibby et al., 1975; Bainbridge, 1983) will become increasingly pervasive in sea-ice prediction, as services evolve from mainly manual processes to increasing automation. Ironically the automation of forecasting services will likely require ever-increasing levels of human input in order to become usable information (Jeuring et al., 2020).

In navigating these multiple, simultaneous and conflicting requirements, it is more important than ever that the forecasting innovation model is product-relevant (how will risks and benefits be distributed), process-relevant (who, when and how should be involved) and purpose-relevant (who will benefit and what are the alternatives) (Stilgoe et al., 2013; Blair et al., 2020). Co-production can lead to more enlightened decisions by facilitating learning and aligning the mindset of policy makers and scientists regarding investments into the future of forecasting with the practical needs of end-users. Because co-productionist models and resulting services are always selective in whose needs they serve and they might come with unintended consequences, social science also plays an important role to create awareness of these potential double effects (Chilvers and Kearnes, 2020).

While co-production is a resource-intensive process for service users and providers alike; it is not always a necessary or appropriate mode of engagement and timing is key. A practical step in further developing S2S predictions is determining the sociomaterial environments of user groups and the type of information gaps that exist. Where demand and potential for use for S2S forecasting is high, and where knowledge uncertainty is also high (the problems that need solutions are complex, high-stakes and push the boundaries of existing technological and scientific capacities), user-driven product development is necessary to pool the material, social and cognitive capacities necessary for innovation and to ensure the eventual uptake of the product. Where knowledge uncertainties and demand are both low, more traditional, science-driven design models and ad hoc stakeholder engagement as needed, may be sufficient.

5. Conclusions

Considerable advancements have been made in the development of S2S predictions but much work remains to explore the applicability of services and potential social benefits. Products and services should aim to align the supply of information with user demand, should be tailored to specific user interest and routines; and should be ready to integrate in the decision-making practices of users. Many challenges remain in the optimization of S2S sea-ice prediction to provide the most reliable information on relevant scales for all users. Immersive, experiential co-production methods are an underutilized resource that can help to manage expectations, and to prioritize the most useful features and thresholds in order to generate benefits from innovation. Practice or user-driven co-production frameworks are most fitting and feasible in cases of high problem complexity, of high knowledge uncertainties, of high stakes and in which diverse stakeholders are involved or impacted. This study demonstrated a user-centric, climate-service approach to designing a S2S forecast of sea-ice probabilities, generating decision-relevant feedback on the current and future applicability of S2S predictions and user-tailored uncertainty and confidence measures. Risk management and decision-making across sectors will continue to require effective dialogue between service providers and users, and thus to require tools that balance mutual influence between actors. Foresight-based participatory simulation that includes a range of user-relevant parameters, such as biophysical, social, economic and political drivers of change that impact stakeholders' decisions and interactions, can play an important role in mitigating long-term risks, supporting sustainable adaptation and enhancing sectoral and societal resilience in fast-changing environments.

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Figure legends

Figure 1. Screenshot of demonstration sea ice service depicting (sub)seasonal sea-ice probabilities

Figure 2. Probability in weeks during which the forecasts outperform climatology (assessed from the forecasts starting between 1999 and 2014). The climatology is defined as the mean observed sea-ice conditions during the 10 years preceding the forecasts. The three probability columns represent the duration in weeks during which the probability that the forecasts are better than the climatology is 75 %, 50 %, and 25 %.

Figure 3. Twelve illustrated future projections from the 2035 most robust 2035 scenario bundle (Blair and Muller-Stoffels, 2019). Panel captions follow the format ‘Key Factor | Future Projection’: A) Accessibility of Arctic Sea Routes | Easy Access; B) User-centric Information Infrastructures and Data | Few Specialized Actors; C) Predictability of Sea-Ice Variability | Gradual Improvements in Predictive Models; D) Regulations and Policies Affecting Arctic Operations | Economic and Commercial Uses Dominate; E) Demand for Arctic Resources | Seafood First; F) Global Economic Trends | Arctic Rush; G) Geopolitical Stability | Status Quo (occasional bullying); H) Major Incidents and Critical Events | Status Quo; I) Sustainable and Resilient Arctic Communities | Expat Haven; J) Trajectory of Development in Marine Technologies | Techno-utopia for Some, Stormy Seas for Others; K) Fluctuating Energy Prices | Northern Push; L) China’s Strategic Plan | Chinese Finger Cuffs. Illustrations by Bas Köhler.

Figure 4. Panel A: The game console showing an event card in play based on a roll-the-dice game mechanism. The narrative reads “Batten down the hatches, a digital storm! Pay 30,000 euros. Following a particularly destructive cyber-attack new EU legislation has mandated a complete overhaul of cyber security measures. Fees for subscription-based forecast services and for satellite-based communication have risen sharply.” The console shows the current year, available bank and reputation points (pink bar). Panel B: The itinerary view. Itineraries are based on project partner Hurtigruten’s cruise portfolio. Players were informed about the voyage duration, planned activities, main ports of call and vessel specifications.

Figure 5. The simulation flow.

Figure 6. The workshop setting during participatory simulation.

Figure 7 Mariner group mean results showing forecast reliability estimates in percent values (x-axis) and change (y-axis) compared to initial input after viewing the forecast and its reliability, in (1) self-reported confidence (Panel A), and (2) money invested (Panel B). The data represents all rounds and 2019 and 2035 playing periods combined.

Tables

Table 1 Date choices for each itinerary. Months show the number of players who chose a date in each month. Red denotes highest frequency.

Itinerary	Year	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
First voyage of the season:													
10 days: Circumnavigate Svalbard	2019					1	1	3	1				
	2035				1		3	2					
6 days: NW Svalbard	2019					3	1	2					
	2035				2	2	2						
16 days: Disko Bay, W. Greenland	2019					3	3						
	2035					3	3						
Final voyage of the season:													
10 days: Circumnavigate Svalbard	2019							1		3	2		
	2035									1	4	1	
6 days: NW Svalbard	2019								1	4	1		
	2035									1	4	1	
16 days: Disko Bay, W. Greenland	2019									2	2	2	
	2035									1	4		1

Table 2 Results from eight evaluative statements during individual debriefing between rounds. Table shows number of respondents who placed marks on the smiley-face side of the scale at the beginning (round 3) and at the end (rounds 12) of the simulation.

	☺ **round 3: Nº of selections**	☺ **round 12: Nº of selections**
I understand the complexities	6	6
Forecast reliability seems to be	3	5
I find it easy to plan the voyage	2	6
My grasp of the issues is	4	5
My confidence in myself is	1	6
My confidence in the forecasts is	4	5
I appreciate the wildcard events	4	3
I am optimistic about the outcomes	4	6

Figure 1.JPEG

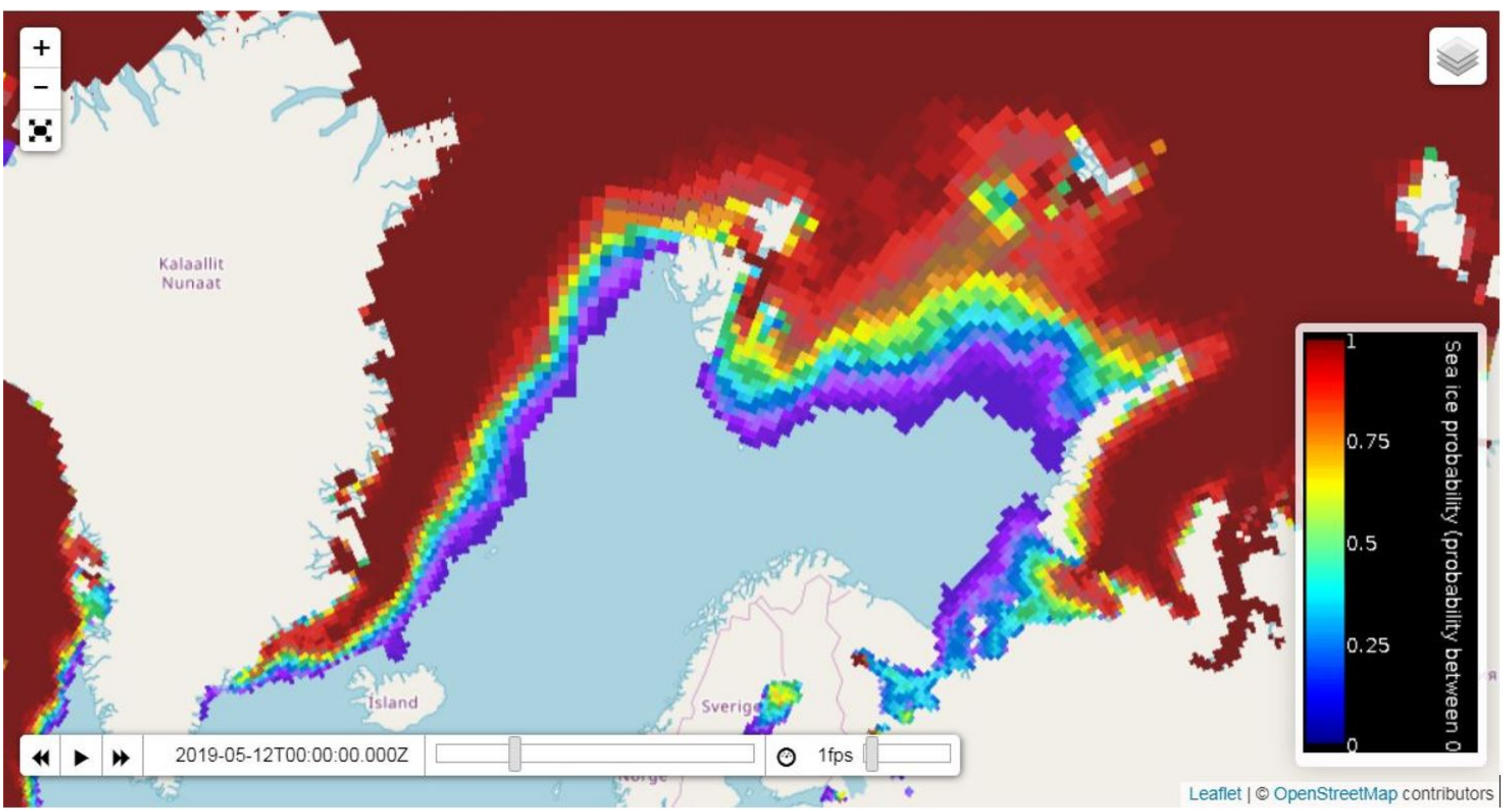

Figure 2.JPEG

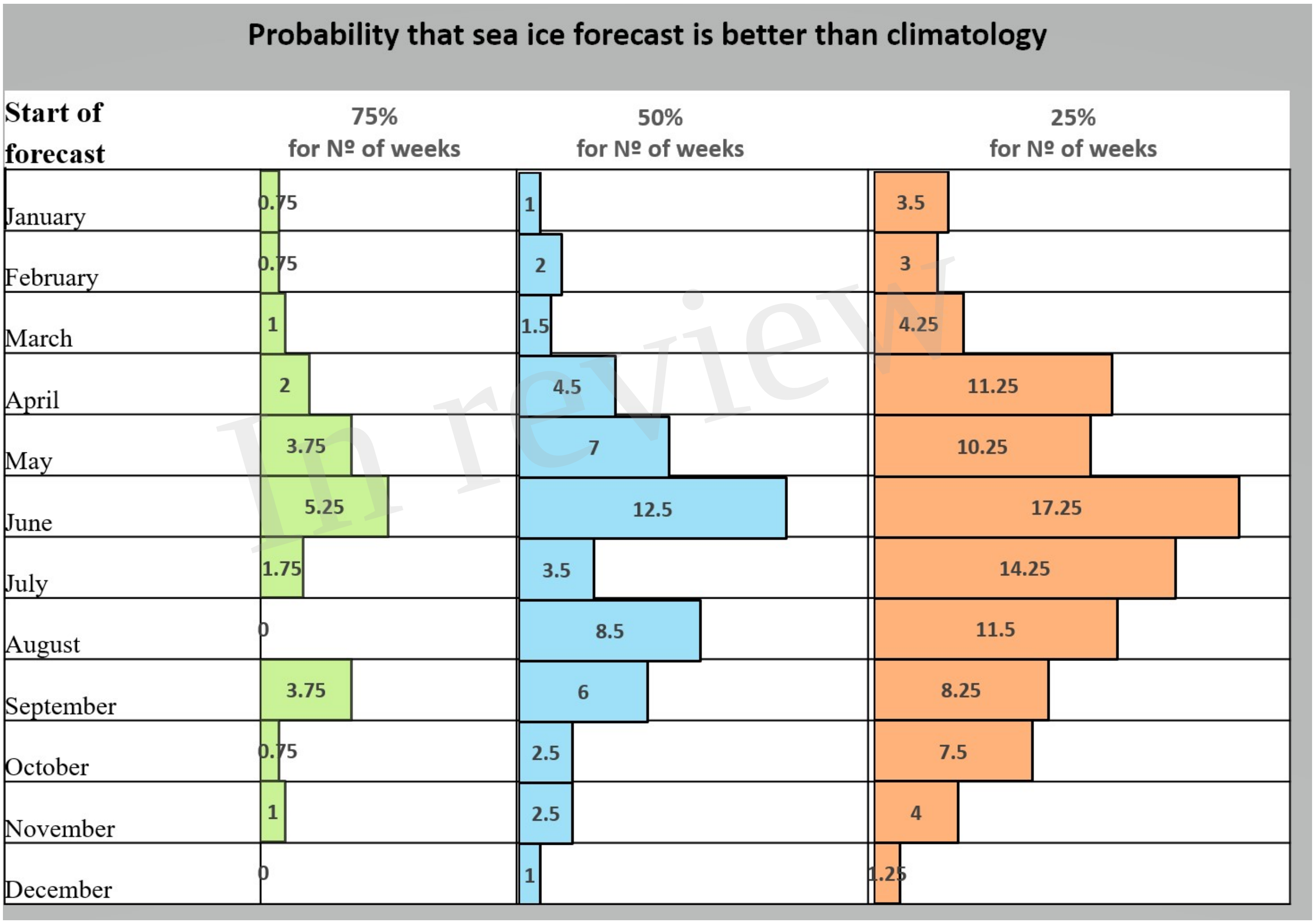

Figure 3.JPEG

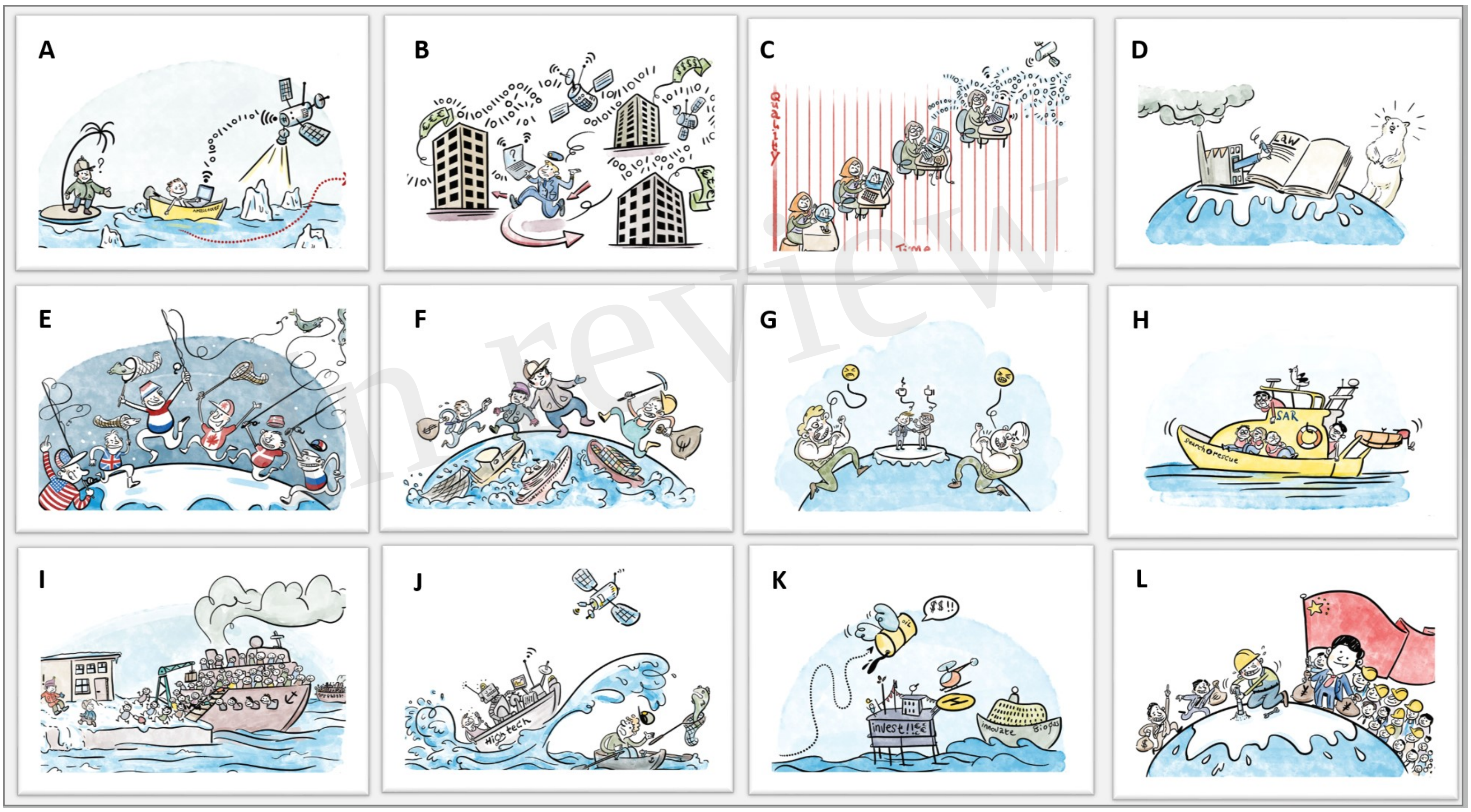

Figure 4.JPEG

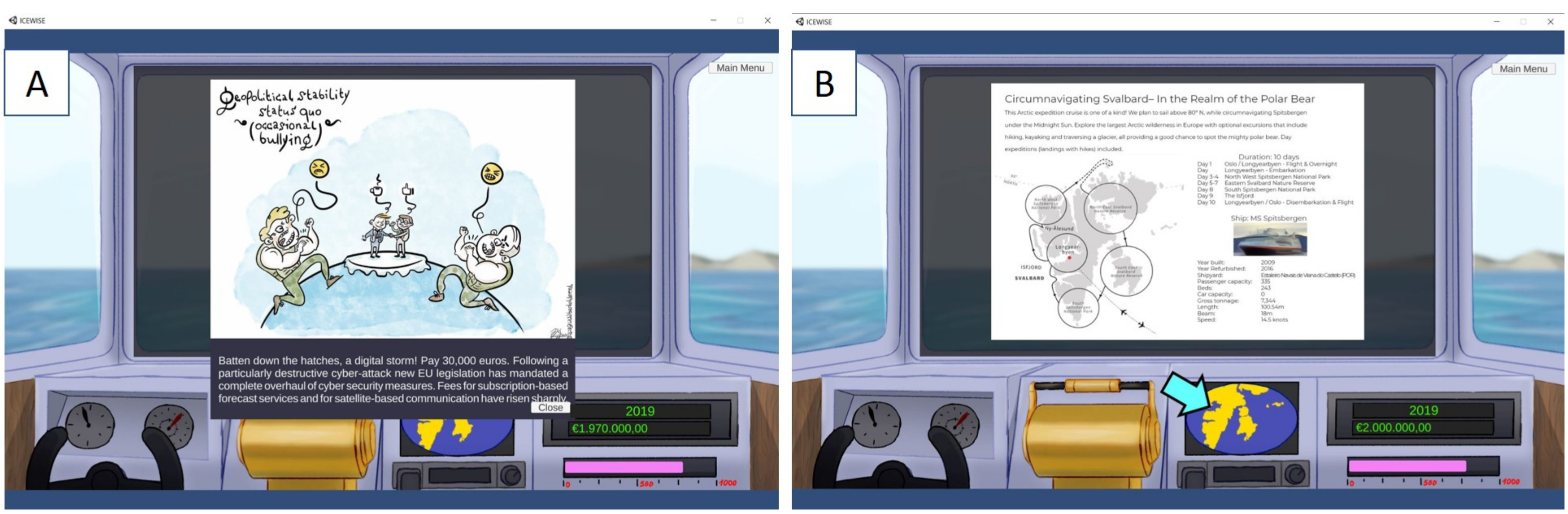

Figure 5.JPEG

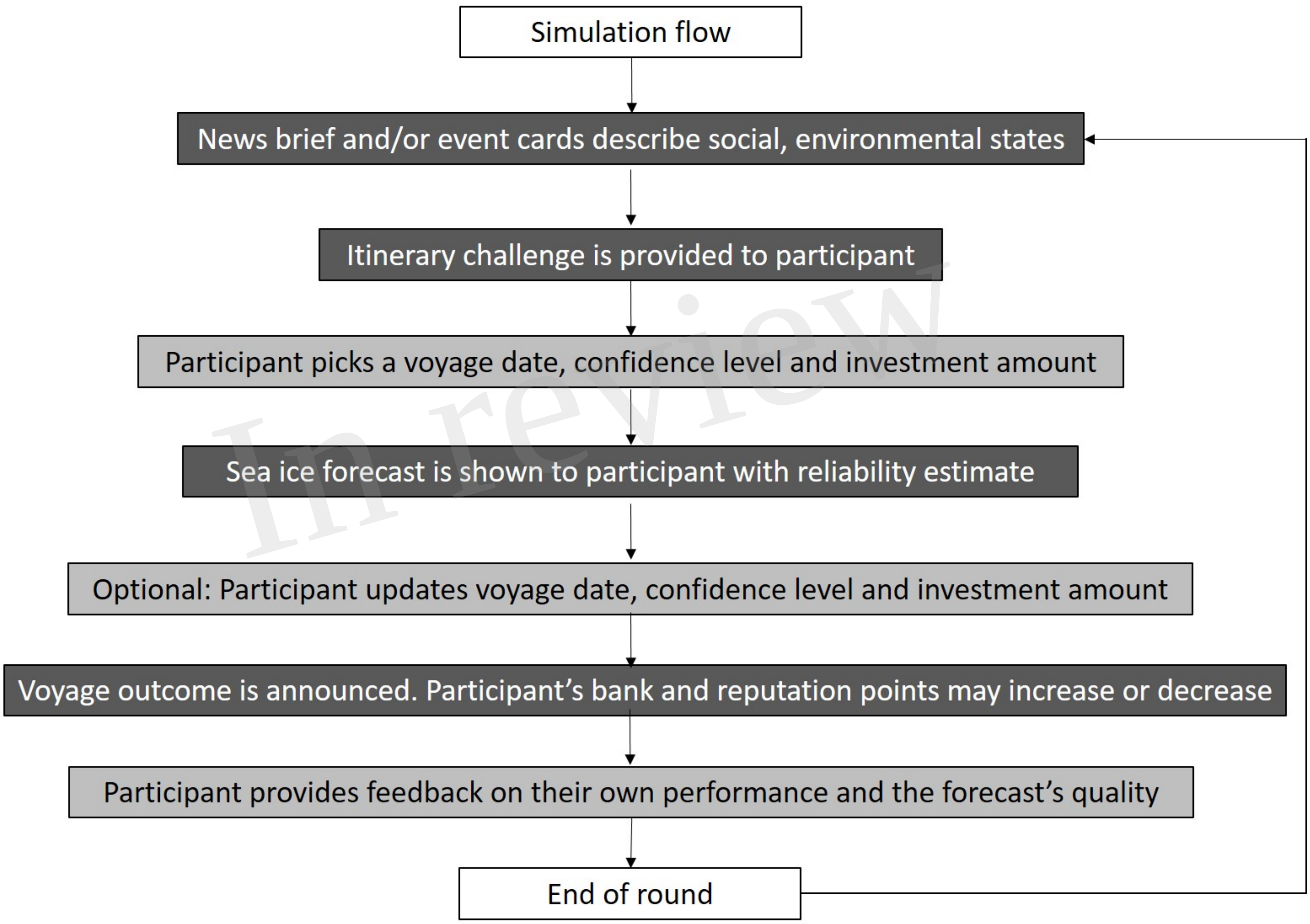

Figure 6.JPEG

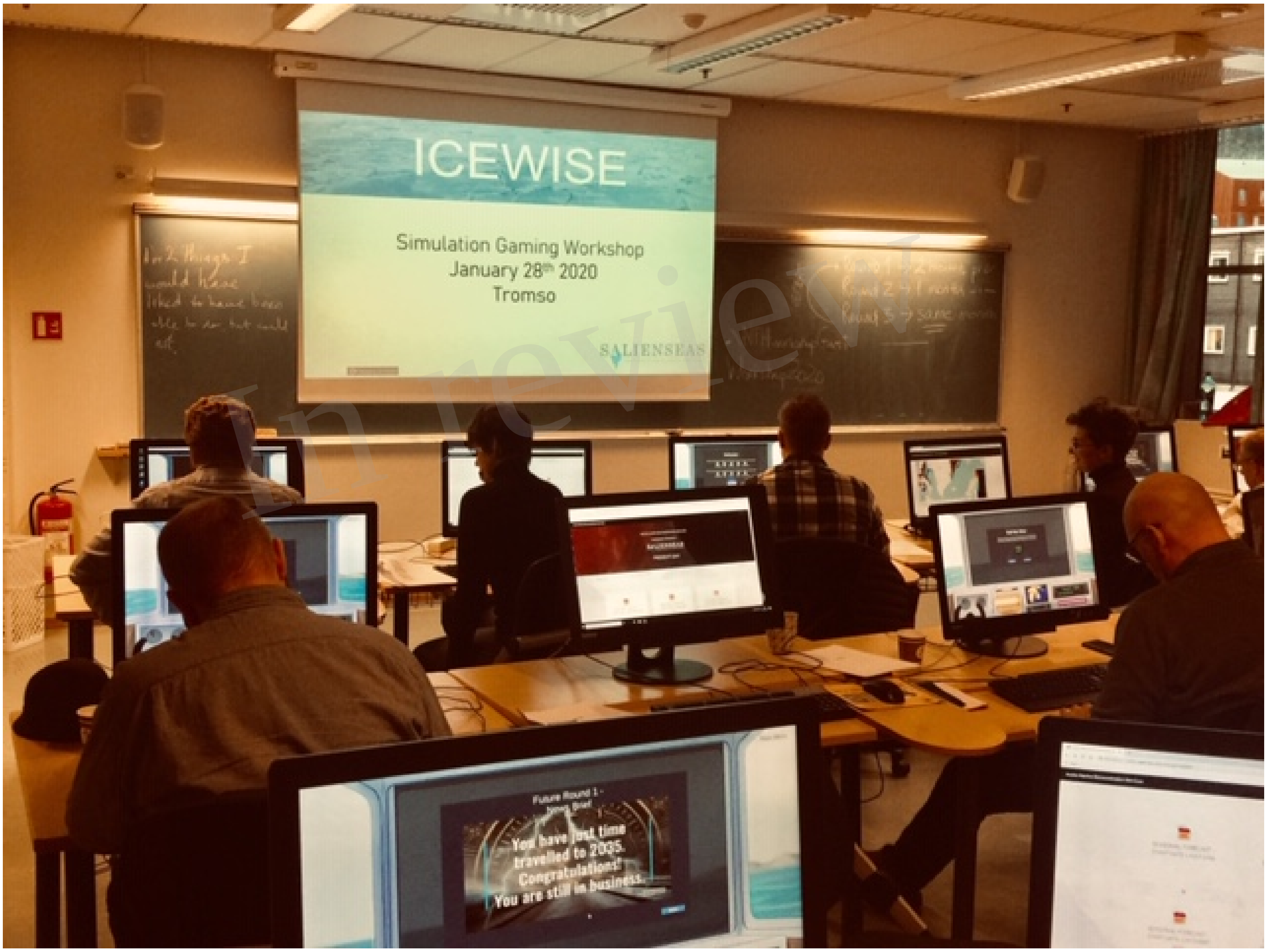

Figure 7.JPEG

Trends in user input during the simulation