NASA Cryospheric Sciences Research to Action: A survey of existing efforts and opportunities

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Synopsis

Cryospheric Sciences are a high-impact but oft-overlooked area of science applications study. The Cryosphere may seem remote, but it has a vital role in the Earth System. To demonstrate the value and potential of NASA Cryosphere information for applications, we analyze fit and maturity across multiple observables and applications sectors for sea and land ice. This analysis addresses three primary questions: How well does NASA Cryospheric Science measure and model various geophysical parameters in a way that is useful to applications; what uptake is there of this information by end-users; and what opportunities are there for future research or capacity development to fill gaps in understanding and applications? We construct matrices for land and sea ice to answer these questions and to serve as a visual guide to inform future Cryospheric Science application activities. Identifying patterns by observable and applications sector, we show where increased foundational, applications, and/or end-user engagement work would benefit development and uptake of NASA Cryosphere information; and we discuss the role of intermediaries between data producers and end-users.

1. Why Assess NASA Cryospheric Applications?

NASA's operational assets and personnel have long positioned the agency to be a leader in cryospheric sciences research and data production. With recent emphasis on the Earth Science to Action strategy and operationalizing research for societal impact [1], there may be a perception that icy, remote places have little bearing on the wellbeing of people and the economy. However, the cryosphere affects numerous sectors, among them fishing, resource extraction, public health, national security, and coastal management.

The link between the cryosphere and these downstream applications may not be immediately apparent, or the cryospheric processes that influence these sectors may not be well-constrained. Therefore, both describing the fundamental understanding of various cryospheric elements as well as contextualizing this work in downstream applications is necessary. Here we seek to address three questions related to application use of NASA cryospheric data, models and processes: **How well does NASA Cryospheric Science measure and model various geophysical parameters in a way that is useful to applications; what uptake is there of this information by end-users; and what opportunities are there for future research or capacity development to fill gaps in understanding and applications?**

2. Assessment Approach

2.1 The Science to Applications Pathway

Here, we define an *application* as having a non-scientific end-user. Scientific intermediaries are necessary for progression to application readiness, especially in the cryosphere, but here we consider the impact of NASA research and information on parties beyond the scientific community. Our evaluation process seeks to identify concrete examples of end-user uptake of NASA's cryospheric information and qualitatively assess potential future development pathways. However, we choose not to assign NASA Application Readiness Levels (ARLs; [2]) or Impact Readiness Levels [3] because it can be difficult to assess the full use of NASA information without direct discussion with end-users. For reference, however, we indicate where ARLs might map to the table (Section 2.2).

We view our assessment as an initial compilation of information that can holistically guide our community as to where end-users of cryospheric data might benefit from technology advancement and basic research; investment in process development; and/or efforts focused on capacity building, development, and adoption.

2.2 The Science to Applications Matrices

In order to assess the utility of NASA cryospheric information across applications, we performed a literature review and survey of available information to assess use of NASA products and processes across multiple different sectors, including water resources; tourism; navigation/shipping; health and safety; and resource use/extraction. These assessments are then further divided by observable or observable combinations for sea ice and land ice (both glaciers and ice sheets).

We summarize these results, with the goal of answering the three questions posed in Section 1, in a series of matrices. In each matrix, geophysical parameters and processes (observables) occupy the columns and downstream applications areas the rows. Partner NASA Earth Science spheres are indicated above the column titles. Each observable(row) /sector(column) pair is split into thirds horizontally and color-coded according to three categories (Figure 1):

- *Applicability* (high/low/none): Does NASA measure/model the geophysical parameter/process in a way that is useful for the downstream application?
- *Need & Uptake* (high/low/none)*:* What is the degree to which measuring/modeling each physical parameter/process is needed by the downstream sector? Is there demonstrated use of NASA Cryosphere information?
- *Future Need & Uptake* (known/unknown): Is there a known or anticipated use of NASA Cryosphere information for this application in the future?

Color coding is supported by extensive referencing and process understanding. We consider several criteria for the questions of information usefulness, evidence of uptake, and future need. Ultimately, a key to uptake is the match between user need and product; "usefulness", with or without uptake, can lie in the spatial and temporal scales of information, in its coincidence with a geographic area of interest to users, and in the accessibility of relevant data. Evidence of the matching between these specifications and end-user needs may be found in derived data products, commercial follow-ons, and in the peer-reviewed and gray literature. Future need for information may also be found in these bodies of literature, whether in calls to action or predictions of future change. Emerging improvements in resolution, or observed changes in the Earth System or sector, also indicate potential future need. In-table citations indicate the degree to which each cell aligns with these informal criteria.

The matrices are designed to provide guidance around possible application support for specific observable/sector combinations. A series of clear take-home messages emerge from this color-coding:

- [*high/high/known*] There is strong scientific basis for this application and high and continued future use by stakeholders. This categorization could correspond to a high ARL ranking. *It is important to maintain this level of effort and success.*
- [*high/low/known*] The scientific basis for a particular use case is strong and there is a need for information but not enough current use by stakeholders. This categorization could correspond to a medium ARL ranking. *Pursuit of user engagement and applications work will fill these gaps.*
- [*low/high/known-unknown*] There is a high demand for a particular piece of information but no scientific basis and/or a lack of measurements/models. This categorization could correspond to a low ARL ranking. *Pursuit of applied research will fill these gaps.*
- [*low/low/known*] There is a high demand for a particular piece of information but no scientific basis and/or lack of measurements/models, therefore no current use among stakeholders. This categorization could correspond to a low ARL ranking. *Pursuit of basic research will fill these gaps.*
- [*low/low/unknown*] It is unclear what the value for stakeholders might be because additional basic research is needed. This categorization would not fall on the ARL ranking scale. *Pursuit of basic research will fill these gaps.*

3. Matrix Interpretation

3.1 Sea ice

Perhaps unsurprisingly, sea ice concentration dominates sea ice discussion in applied contexts. The loss of sea ice coverage is well-described in the media and has popular awareness.[1] While NASA distributes its sea ice concentration products widely, and many users

[1] As of 2023, NASA's Current State of Sea Ice Cover was consistently the most visited page of the Goddard Earth Sciences Division Projects website (earth.gsfc.nasa.gov), totalling over 41,000 page views and exceeding visits to the second-most-visited page by 491%.

run NASA's publicly-available algorithms [4] on their own, the agency faces competition from sites that put data into a user-friendly format for download [5], [6] (see also Section 4.1). For this reason, there is often a disconnect in the table between knowledge of sea ice concentration and its need/use: More user engagement is necessary to understand the appropriate resolution of information as well as its delivery.

Several patterns emerge from the matrix (Table 2), by application area as well as process. Shipping and insurance color-coding often matches up, likely because many of the insurance applications sources concern marine vessels (e.g., [7]). Similarly, subsistence hunting and public health have some overlap due to northern food systems' linkage to an ice-dependent ecosystem [8]. In the cases of public health and insurance, however, future need for information on sea ice thickness, leads, and floe-size distribution (FSD) are unknown. As ice diminishes, hunting opportunities decrease [9]; while ship traffic may increase, it is unknown how insurance schema will change in the presence of less ice.

Indeed, processes like thickness and FSD and lead distribution that are strengths of NASA cryosphere observing and research, and which are anticipated to have significant applications impact, do not always garner mention in applications. These elements of sea ice affect navigability through and across ice by emergency responders and subsistence fishers; they impact ice-breaking capabilities of ships; and they impact regions available for shipping and resource extraction [10], [11], [12], [13]. Their lack of mention in other sectors is a large area of opportunity for applied research. One known applied research challenge is the paucity of data in areas of highest impact. For example, ICESat-2 sea ice freeboard uses a generous (25 km) mask to account for altimetry errors, yet near-coastal sea ice information is critical to many applications, as shown in the thickness column of Table 2a.

In addition to applied research, some geophysical parameters require more basic research. Snow-on-sea-ice differs between the poles and is evolving in response to warming conditions [14], [15]. Given the strong alignment between observing capability and use/need in applications areas such as navigation and public health, snow-on-sea-ice basic research will undoubtedly lead to applications understanding and opportunities in other sectors.

NASA is a leader in some areas that have demonstrated observational capability and strong applications potential, but because those areas are emerging parts of sea ice research they also bear further basic science investigation. FSD is one such area. It is not measured directly from altimetry, but instead derived from measurements of along-track floe length. From these observations modeling studies [16], [17], [18] or highly-localized measurements from imagery [19], [20], [21] are used to create FSD. Different uses of this information on different timescales call for different approaches [18]. Similar to FSD, lead width distribution is a new area of research [22]. Lead studies are localized [23], or use gridded densities [24]. Given the proven potential of FSD information, more basic as well as applied research is necessary in this area.

Just as some applications areas share matrix shading patterns, sometimes one process is inherent in another. Sea ice motion leads to ice rafting onshore and to ridging, the latter of which is considered independently in the table; motion also creates leads and thickness patterns. Because it is an upstream physical process, motion may seem to have less bearing on applications than these other ice attributes. That statement is true in the sense that these behaviors of ice are what directly impacts each sector, but false in the sense that motion underpins all of them. For this study, we consider only those direct mentions of motion in applications sources for the relationship of motion to application areas. Motion is never more evident than when ice shoves ashore, however, which can severely damage coastal infrastructure and create navigational hazards [10].

While the majority of the applications covered by the matrix are Arctic-specific due to the area's population, some of them apply to the Antarctic (e.g., cruise tourism [25]). Many measurement capabilities span both poles, but there are cases where there is a significant

difference between the two. For example, Arctic sea ice information supports any number of sectors. In contrast, Antarctic operational uses are more concentrated in research-station logistics, fisheries, governmental operations, and expedition tourism; commercial resource extraction is prohibited under the Antarctic Treaty system [26]. Environmental differences in observables such as snow lead to measurement challenges [15], [27], and observables such as FSD, leads, and motion depend on ocean circulation [28] and thus have differing spatial context and applications pathways.

3.2 Ice Sheets & Glaciers

Though ice sheets and glaciers are often considered distinct when considering end-users, here we choose to integrate them into a single table (Table 3) both because the observables are the same and because as the Arctic becomes more navigable, the interaction between glaciers, infrastructure, and society is increasing there. Though not all observables/processes are relevant to all sectors at this time, Table 3 highlights several key takeaways about the link between land ice observables and end-users of cryospheric data; we've highlighted these in the following paragraphs.

Ice sheets and glaciers are nearly synonymous with sea level rise. NASA has made substantial progress into understanding "mean sea level change," which is defined as a time-averaged sea level change that is typically representative of a 20-year mean [29], as well as into developing relationships with end-users to increase uptake of this information [30], [31], [32], [33], [34] (Table 3). However, while uptake of sea level rise data is strong; there is a gap in constraining uncertainty in mean sea level change projections over centennial time scales [35]. Further, an impactful area of research will be in advancing understanding in the shorter-term (10-20 year) processes, and how short-term variability will evolve in the future, with a particular focus on glaciers, which can benefit decision making in sectors such as emergency response, public health, national security, coastal management, and insurance [36]. This investment in basic research would support existing frameworks and end-users with higher confidence information about the role of glaciers in sea level rise. Additionally, continued monitoring of land ice is critical for information used in dynamic adaptive policy pathways [37]. The low-confidence processes that can significantly increase sea level rise rates in the coming century are linked to ice sheet collapse. Continued monitoring will provide decision makers with the potential to adapt policy if certain ice sheet thresholds are exceeded.

Table 3 demonstrates that NASA's satellite assets and science support have developed iceberg identification and tracking capabilities (e.g., [38], [39], [40]). All marine sectors are increasing operations in the Arctic [41] and several are increasing operations in the Antarctic, exposing a greater number of vessels to icebergs and sea ice. In the Arctic, there are several entities providing iceberg tracking, primary among them, the International Ice Patrol (IIP), operated by the U.S. Coast Guard and funded by 17 contributing countries [42]. Ships operating in regions of the Arctic are required to use data. Current iceberg tracking relies primarily on multi-polarized synthetic aperture radar (SAR), which is used by the IIP to detect ~90% of tracked icebergs. All surveyed sectors with marine applications utilize iceberg tracking data, suggesting that advances here could have widespread end-user uptake. NASA has the satellite capabilities (LandSat, MODIS, VIIRS), particularly in partnership with other organizations (Sentinel-1). These satellites, in combination with advances in particle tracking and forecasting using NASA's coupled atmosphere-ocean model [43], [44], could provide the opportunity to develop and test a relevant iceberg tracking framework and meaningfully partner with current iceberg tracking efforts, including expanding to regions in Antarctica. Such an effort would also support NASA's outreach and educational goals (e.g., [45]).

NASA observations are unparalleled when it comes to monitoring ice sheet mass change (e.g., [46]) and ice sheet and glacier extent (Table 3). Changes in glacier extent plays a

significant role in peak water, defined as a maximum in annual glacier runoff beyond which runoff steadily decreases [47]. Robust projections of the timing of peak water are critical for the development of hydropower facilities [48], agricultural planning [49], [50], and near-coastal fishing. Currently several sectors are relying on the historical satellite record to provide the expected shift in peak water magnitude and timing (Table 3). Predicting the timing of peak water is relevant across sectors, but relies on the integration of glacier extent (well-constrained by NASA observations), ice thickness (limited), ice velocities (well-constrained by NASA observations), and modeling (e.g. [51]). A step towards this is NASA's Snow4Flow airborne campaign, which will measure glacier thickness and snowfall in selected northern hemisphere regions but more investment is needed to do this from either airborne or satellite platforms around the globe. Additionally, more basic research is needed to investigate seasonal shifts in the timing of glacial runoff, which can aid shorter-term planning. There is clear scientific research supporting the use of glacier extent for planning in these sectors, but current uptake by end-users is limited (e.g.,[52], [53]). Additional investment is needed in collecting observations of glacier thickness measurements; in basic research to connect these observations to projections of peak water; and in forming relationships with end-users in the hydropower, agriculture, and fishing sectors to enhance uptake of this information.

With glacier runoff comes the formation of glacial lakes and their eventual draining, which can be catastrophic (glacial lake outburst floods, GLOFs). NASA capabilities for monitoring glacial lakes are substantial and widely used by multiple sectors (Table 3), including individual countries (e.g., [54]) and intergovernmental organizations [55]. However, there is a mismatch between current NASA capacity and end-user needs, particularly in sectors that would benefit from prediction of GLOF occurrence either in the short (days to weeks) or mid-term (probabilities) (Table 3). This gap can be partly addressed by NISAR [56] and the integration of NASA products, models, and in-situ observations [57]. While many end-user partnerships exist(ed), developing a robust, continuing framework of operations may be as challenging as the necessary scientific research [58].

In each of these examples, and across sectors and observables, the scientific basis for applications use is generally strong and in many instances, there are individual examples of end-user uptake of NASA data or processes. Widespread sector adoption of NASA observations occurs in some instances; however, among the examples presented above, there is a need for near-term prediction (from days for iceberg locations) to years (peak water). This research, in addition to development of sustained frameworks for data production, would serve users of NASA land ice data.

3.3 What is missing?

3.3.1 Partner Observations and Processes- There are cases where what's needed for an application is well observed, but by international entities rather than NASA. For example, European Space Agency (ESA) near-real time (within 1-3 hours) Sentinel-1 SAR imagery is being used to develop operational sea ice drift forecasts as part of their Kickstart program [59], useful to the International Ice Patrol's iceberg detection report.

Though this white paper focuses on NASA observations, in many sectors there may have been substantial effort to produce products for applied use, leading to high recorded need in the matrices. For example, Norway's Nansen Environmental and Remote Sensing Center SIDARUS (Sea Ice Downstream Services for Arctic and Antarctic Users and Stakeholders) project [60], which a decade ago created specialized products for users in the shipping and resource extraction sectors. In the most mature example, portals serve applications-ready information in an accessible user interface (see Section 4.1). Therefore, when exploring the potential applications of cryospheric data, it is critical to engage not just with end-users, but with intermediate-users and interested partners. Such engagement may preclude short-duration

funding cycles.

3.3.2 Ice in Other Forms - These matrices comprehensively examine only two aspects of the frozen Earth System. Permafrost, snow, and river/lake ice are active areas of research with clear applications. Though they do not necessarily fall under the auspices of NASA's Cryosphere Sphere, their research methods and applications overlap substantially with those of the cryosphere. The integration of science from multiple spheres will only strengthen applications utility. For example, permafrost underlies much of the transportation infrastructure serving the same coastal industries relying on sea ice, such as extractive industries, shipping, subsistence hunting, and tourism [61].

4. Key Takeaways

4.1 "End"-users

Often in Tables 2a and 3 there is a mismatch between NASA observations and science capabilities and user needs. Identifying these mismatches can provide guidance around end-user investment and capacity building. One example of a mismatch is subsistence fishing and tourism with sea ice lead information, which is challenging to produce at low latency, raising important questions: Does this preclude the use of current NASA data or is it worth the investment in processing pipelines to reduce data latency? Can intermediate end-users fill this gap? For example, applications such as the British Antarctic Survey's PolarView and DriftNoise's IcySea use data from NASA and other instruments to provide near-real-time sea ice information (concentration, drift, imagery) optimized for low-bandwidth connections to operational users spanning shipping, tourism, commercial fishing, military, resource extraction, and scientific research [5], [6]. In the scenario of NASA tailoring data for operations, it becomes a direct supplier of information to its end-users. Supporting intermediate end-user capacity instead of investing in data processing pipelines may allow more cryospheric data to reach traditional end-users.

In cases where user needs *do* align with science production, there can be a clear science demonstration but a lack of uptake. This mismatch is visible with sea ice meltponds and ridging, where NASA has strength in measurement and there is an articulated understanding of that measurement by downstream users–but the data are not yet *used* in those contexts. All parties are communicating the value of that information, but there is little action. Coordination with boundary organizations is one approach to overcoming this gap.

Many boundary organizations are international, and their capacity to leverage NASA data is key in these situations. Examples of this collaboration are shown across the matrices: the MOSAiC drifting ice expedition [62]; the CRYO2ICE periodic orbital alignment between ESA's CryoSat-2 and NASA's ICESat-2 [63]; ICIMOD, an intergovernmental organization working towards a more inclusive and climate resilient Hindu Kush Himalaya [55]; the International Ice Patrol [64]; and ISMIP community ice sheet projections [65].

Moving forward, engaging intermediate end-users early in product creation may be one way to increase the application use of NASA cryospheric data across multiple sectors while minimizing the gap between science targets and end-user needs.

4.2 Scientists as end-users

So what happens if we *do* consider scientists as "applications" users? Even if scientists are end-users of NASA information, that information is not yet operationalized in all cases, so uses may not qualify as applications per se. In the case of many processes in the matrices, foundational scientific understanding is early-stage enough that the only audience for results is peer scientists. Often a focus is on appropriate measurement to inform a model.

Scientists as end-users are particularly salient when considering Earth System and Climate modeling and the production of forecasts and climate projections. The assimilation of sea ice remote sensing data has been shown to improve forecast skill, and so we include a "prediction" matrix for sea ice (Table 2b), using the same approaches as the other matrices but considering weather, subseasonal-to-seasonal, and decadal timescales. A key end-user of sea ice observational data is the U.S. Navy, who assimilate satellite products of sea ice concentration and thickness to improve the skill of their operational seasonal sea ice forecasts [66], [67], [68]. Though we do not include a prediction matrix for land ice, the need for prediction is addressed in Section 3.2. The representation of glacier runoff at weather to seasonal lead times can be valuable in providing information for agriculture, fisheries, and other sectors that are strongly dependent on meteorological forcings [69]. However, the impact of ice sheet and glacier runoff and calving on atmospheric and ocean circulation at mid and long time scales is still an open research question.

Because subseasonal to seasonal and climate models and outputs are used by a range of end-users, continued improvement of sea ice and land ice parameterizations and outputs are beneficial to end-users of cryospheric data.

4.3 Conclusions

The applications of NASA cryospheric data are wide-ranging and touch a host of sectors (Table 2, 3). This work provides an initial framework to examine the use of NASA data and processes by applications end-users. Though not complete, we consider it a starting point for conversation and decision making. Beyond the sector- and observable/process-specific takeaways highlighted above, this work highlights critical issues for end-users of NASA cryospheric data in the coming years:

- Latency. In any (quasi-)operational context, reducing data latency is key (GLOF monitoring, sea ice lead detection). Communication with end-users about information needs will help to shape how data are structured and delivered, though this approach is challenging to scale. Because iteration of specifics requires more time and effort than many researchers can afford, applications personnel and NASA's EarthRISE project are important links between knowledge producers and end-users.
- Data-modeling integration. Whether data assimilation or other newer approaches such as downscaling techniques, these efforts will bridge the gap between science and applications use by providing robust information at a variety of scales.
- Alignment of community needs and products. Data product measurement requirements are not always developed with applied users in mind, despite having Early Adopters as part of mission pre-launch. Parallel planning workflows prioritizing algorithms to help datasets serve communities would be beneficial to closing the science demonstration-uptake gap. Private-sector data can fill some gaps, and uncorrected data hold a lot of potential.
- Intermediate end-users. Intermediate end-users generally have the reach and capacity to manage the complexity of NASA data while providing data distribution to many local end-users. Building these relationships will reduce duplication efforts and increase data applications use while reducing the burden on instrument science teams and individual scientists.
- Multi-sphere integration. Though this white paper focuses on the cryosphere one of the more interesting areas of potential are identification of potential hazards in Arctic and Antarctic shipping routes. Though there are current operators in this space, NASA observations and modeling from the cryosphere, atmosphere and hydrosphere (ocean) could be valuable contributions with the appropriate communication. There are many other similar examples.

Figures

Figure 1. Matrix color-coding shows interpretation of each triad.

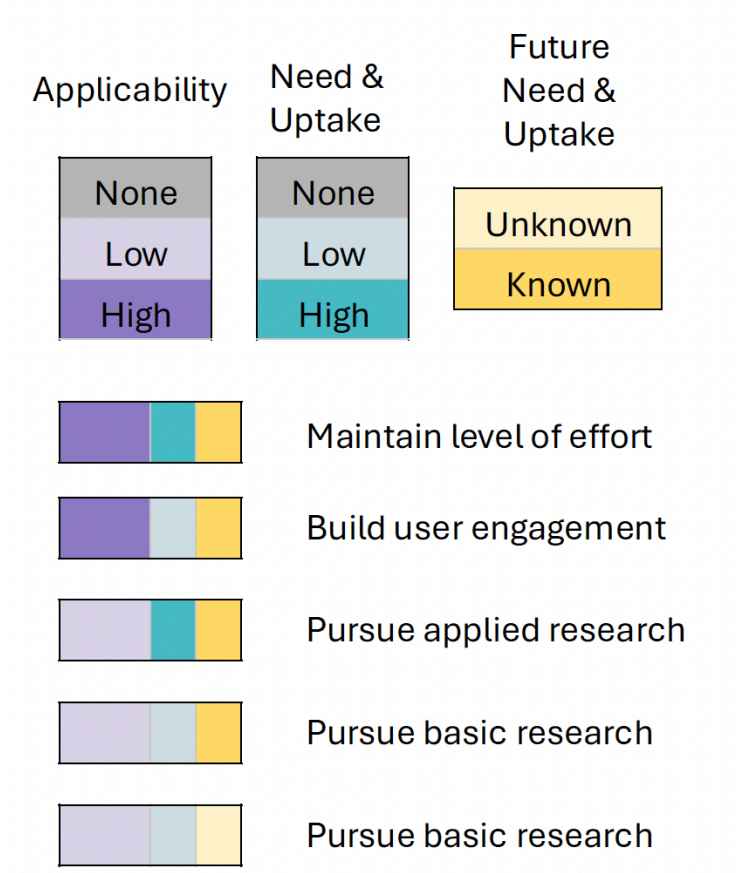

Table 2. **Sea ice matrices**

2a. Sea ice matrix

partner spheres	**atmosphere**									**hydrosphere**												
Sector	surface energy balance			surface: snow			surface: ponds & ridges			ocean surface coverage: concentration			ocean surface coverage: FSD & leads			thickness			motion		
Fisheries																						
commercial	[1], [2]	[2], [3]	[2]	[4]	[5], [6]		[7], [8]		[9]	[10], [11], [12]	[13], [14], [15], [16]	[13], [17]	[18], [19], [20]			[21]	[22]	[21]	[23], [24], [25], [26]	[17], [27]	
subsistence	[28]	[29]	[29]	[30]	[31]	[32], [33]	[34]	[38], [39], [40]	[38], [39], [40]	[35], [36]	[29], [37]	[29], [37]	[18], [20]	[30], [38], [39]	[31], [39], [40]	[41]	[31], [39]	[41]	[24], [42]	[31], [31], [38], [39]	
Tourism	[43]	[30]	[44]		[31]		[45]	3g		[10], [11], [12]	[46]	[17], [45], [47]	[18], [19], [20]		[45], [48]	[49]	[31], [46]	[45], [47]	[17]		[45], [48]
Mining/Resource Extraction		[50]			[27]	[27]		[51]	[52]	[35], [36]	[15]		[18], [20]	[39]		[53], [54]	[39], [52], [55]	[52]		[39], [55]	
Health & Safety																						
public health		[29], [56]		[57]	[32]			[58], [59]		[35], [36]	[29]	[29]	[18], [20]	[60]	[60]	[61], [62]	[39]	[63]	[24], [42]	[31], [38], [39],	

																				[40]	
national security	[64]	[65]		[66]	[67]			[8], [68]			[15], [46], [68], [69]	[69]	[18], [20]	[68]		[70]	[46], [68], [71]	[15]	[23], [24], [25], [26]		
Navigation/Shipping	[72]	[73]		[27]	[74]	[75]		[76]	[27]	[10], [11], [12], [17], [77]	[77], [78], [79]	[17], [78]	[18], [20]	[78]	[78]	[76], [80]	[78]	[78]	[23], [24], [25], [26]	[17]	
Hazards																					
emergency response		[81]		[46]			[82]	[83]				[56]	[18], [20]	[39]	[56]	[40]	[39]	[56]	[42]	[31], [39], [40]	
insurance/re-insurance	[84]	[85]						[8], [86]		[10], [11], [12], [17], [77]	[78]	[78]	[18], [20]	[78]	[78]	[87], [88]	[78]	[78]	[24], [26], [42]		
Coastal Management		[89], [90]			[91]			[92], [93]	[94]		[93], [95], [96]	[37], [94], [95], [96]	[18], [20]	[39]	[94]	[97]	[95]	[95]	[24], [25], [26], [42]	[38], [39]	[93]

2b. Sea ice prediction matrix

partner spheres	**atmosphere**									**hydrosphere**												
Sector	surface energy balance			surface: snow			surface: ponds & ridges			ocean surface coverage: concentration			ocean surface coverage: FSD & leads			thickness			motion		
Forecasting/Prediction																						
weather	[98]	[99]		[100]	[101]		[102] [103]	[104]		[105]	[17]		[18], [19], [20]			[106]			[26], [98]		
S2S	[107]	[108]	[109] [110] [111]		[112]	[113]	[114]			[105]	[17]		[115]	[116]	[116] [117]	[118]	[119]	[120]	[26], [98]		
decadal	[121]	[122]		[123]	[124]		[125]		[8]	[105]	[17]					[126]	[125]		[24], [26]		

Table 3. **Land ice matrix**

Partner spheres	**Hydrosphere**									**Geosphere & Biosphere**								
Sector	Liquid freshwater flux			Iceberg flux & location			Sea level rise			Glacier advance & retreat			Sediment flux & phytoplankton response to glacier runoff			Land motion & GLOFs		
Fisheries																		
Commercial & Subsistence	[1], [2]	[3], [4]	[5], [6]	[7], [8], [9]	[10]	[11]				[12]	[13], [14], [15]		[2], [16]	[17]	[18]			
Water Resources																		
Agriculture	[19], [20], [21]	[22], [23], [24]	[25]				[26]	[27]	[28]	[29], [30], [31]	[32], [33]	[34], [35]				[36], [37], [38], [39]	[23]	[40], [41]
Hydroelectric power	[21], [42]	[23], [32]	[43]							[19], [44]	[32], [33]	[35], [45], [46]	[47]			[36], [37]	[23], [48]	[40], [41]
Tourism				[7], [8], [9]	[10]	[49]	[50], [51]	[52], [53], [54]		[19], [44], [55]	[55], [56]	[57]						
Resource Extraction				[7], [8], [9]	[10], [58]					[44], [59]	[60], [61]	[62], [63]						
Heath & Safety																		
Public Health	[80], [81]		[35], [82]				[50], [51]	[28]	[28], [83]	[19], [44]	[23], [25], [84]	[35], [82]	[47]	[85], [86]		[19], [44], [73], [74]	[23], [75]	[19], [71], [72]
National Security & Homeland Security	[21], [44], [80]	[87]	[87]	[7], [8], [9]	[10]		[50], [51]	[88]	[89]							[19], [44], [73], [74]	[90], [91]	[79]

Navigation & Shipping				[7], [8], [9]	[10]		[50], [51]	[64], [65], [66]	[64]									
Hazards																		
Emergency Response	[67], [68]			[7], [8], [9]	[10]		[50], [51]	[69], [70]	[23]	[19], [71], [72]	[71]					[19], [44], [73], [74]	[23], [75]	[76], [77], [78], [79]
Insurance & Reinsurance				[7], [8], [9]	[10]	[105]	[50], [51]	[106], [107]					[2], [16], [103]	[108]		[19], [44], [73], [74], [81]	[109], [110]	
Coastal Management	[92]		[93]				[50], [51]	[94]	[28], [83], [95]	[44], [96]	[97], [98]	[99], [100]	[101,] [102], [103]	[16]	[104]			

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Note: Land ice and sea ice matrices have separate reference sections, for ease of table lookup and future activities by ice type.

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