Cryosphere Breakout
NASA STV
Incubator Study

Starting at:
8:30 am PT
11:30 am ET

Alex Gardner, JPL
Hosts

Alex Gardner, JPL
STV Cryosphere Lead

Batuhan Osmanoglu, NASA Goddard
STV Information Systems Lead
<table>
<thead>
<tr>
<th>Topic</th>
<th>Presenter</th>
<th>PT</th>
<th>ET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intro from HQ</td>
<td>Thorsten Markus</td>
<td>8:30 - 8:40</td>
<td>11:30 - 11:40</td>
</tr>
<tr>
<td>Intro to DS and STV</td>
<td>Andrea Donnellan</td>
<td>8:40 - 8:50</td>
<td>11:40 - 11:50</td>
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<tr>
<td>Overview of SATM</td>
<td>David Harding</td>
<td>8:50 - 9:00</td>
<td>11:50 - 12:00</td>
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<tr>
<td>Land Ice Needs and Targeted Observables</td>
<td>Alex Gardner</td>
<td>9:00 - 9:30</td>
<td>12:00 - 12:30</td>
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<tr>
<td>Sea Ice Needs and Targeted Observables</td>
<td>Ron Kwok</td>
<td>9:30 - 9:50</td>
<td>12:30 - 12:50</td>
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<td>BREAK</td>
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<td>9:50 - 10:00</td>
<td>12:50 - 1:00</td>
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<tr>
<td>How to think about what we need</td>
<td>Alex Gardner</td>
<td>10:00 - 10:10</td>
<td>1:00 - 1:10</td>
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<tr>
<td>Review of Key DS White Papers</td>
<td>Alex Gardner</td>
<td>10:10 - 10:20</td>
<td>1:10 - 1:20</td>
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<tr>
<td>Summary of needs and community input</td>
<td>Alex Gardner</td>
<td>10:20 - 12:00</td>
<td>1:20 - 3:00</td>
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<tr>
<td><strong>land ice</strong></td>
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<td>fast moving outlet glaciers</td>
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<td>10:20 - 10:50</td>
<td>1:20 - 1:50</td>
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<tr>
<td>slow moving interior ice</td>
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<td>10:50 - 11:00</td>
<td>1:50 - 2:00</td>
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<td>floating ice shelves</td>
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<td>11:00 - 11:10</td>
<td>2:00 - 2:10</td>
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<tr>
<td>large mountain glaciers</td>
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<td>11:10 - 11:20</td>
<td>2:10 - 2:20</td>
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<tr>
<td>static topography</td>
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<td>11:20 - 11:30</td>
<td>2:20 - 2:30</td>
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<td><strong>sea ice</strong></td>
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<td>smooth ice</td>
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<td>11:30 - 11:45</td>
<td>2:30 - 2:45</td>
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<td>rough ice</td>
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<td>11:45 - 11:55</td>
<td>2:45 - 2:55</td>
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<tr>
<td><strong>wrap up</strong></td>
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<td>11:55 - 12:00</td>
<td>2:55 - 3:00</td>
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Intro from HQ
What STV Cryo is tasked with doing

*Step 1:* Identify ice sheet, ice shelf, glacier and sea ice topography measurements that are needed to answer key science questions posed by the Decadal Survey

*Step 2:* Review current technologies and assess readiness to address identified needs

*Step 3:* Make recommendations to NASA HQ, via white paper, outlining measurement needs and technology gaps.
Guided by two overarching Decadal Survey questions:

1. How will sea level change, globally and regionally, over the next decade and beyond? [S-3, C-1] [Most Important]
2. What will be the consequences of amplified climate change in the Arctic and Antarctic? [C-8] [Very Important]
Guided by two overreaching Decadal Survey questions:

1. How will sea level change, globally and regionally, over the next decade and beyond? [S-3, C-1] [Most Important]
2. What will be the consequences of amplified climate change in the Arctic and Antarctic? [C-8] [Very Important]
Historic sea level change
ice lost through melt and calving
GREENLAND MASS VARIATION SINCE 2002

Data source: Ice mass measurement by NASA's GRACE satellites.
Gap represents time between missions.
Credit: NASA

RATE OF CHANGE

\[ \rightarrow 279.0^* \]
Gigatonnes per year

* Approximately 35 Gt/yr from peripheral glaciers
>95% of all ice lost through ice flow to ocean
Antarctic Ice Sheet

ANTARCTICA MASS VARIATION SINCE 2002

Data source: Ice mass measurement by NASA’s GRACE satellites.
Gap represents time between missions.
Credit: NASA

RATE OF CHANGE
↓ 147.0*
Gigatonnes per year

* Approximately 8 Gt/yr from peripheral glaciers
Mountain Glaciers (shown in yellow)

Gardner et al., 2013
Global glacier loss: 2002-2019
~250 to 350 Gt yr$^{-1}$

Gardner et al., 2013
Ciracì et al., 2020
Wouters et al., 2019
How will sea level change, globally and regionally, over the next decade and beyond?

Palmer et al (2020)
Uncertainties in projections
Uncertainties in projections

Land ice change is the largest source of uncertainty in GMSL projections

Palmer et al (2020)
What’s needed to make progress?

- Sea level budget closure is necessary but not sufficient.
- Requires advancement in understanding of key time-evolving processes that regulate ice flow, and exchanges of mass and energy at boundaries between ice-and-ocean and ice-and-atmosphere.
It’s about improving understanding of key processes.
Key glacier process that STV can play a role in refining our understanding

- Glacier sliding
- Surface mass balance
- Ice shelf and glacier calving
- Ice shelf melting by ocean
- Pre-existing ice sheet imbalance
- Grounding zone mechanics

- Shear margin mechanics
- Hydrofracture
- Bedrock topography
- Ice flexure
- Ice fracture
- Basal hydrology
The power of repeat satellite measurements of surface height to reveal process driving glacier change.
Change in ice sheet topography

Smith et al. 2020
Vavilov Ice Cap

March 2016

Worldview DEMs from DigitalGlobe Imagery

Willis et al., 2018
Worldview DEMs from DigitalGlobe Imagery

Ice Height Difference from March 20th 2015 to March 19th 2016.

-90
-84
-78
-72
-66
-60
-54
-48
-42
-36
-30
-24
-18
-12
-6
0
6
12
18
24
30
36
42
48
54
60
66
72
78
84
90

Bedrock
Partially Floating
Grounded Ice
Bedrock

Willis et al., 2018
Ice shelf topography

Shean et al., 2019
Ice shelf topography

Thickness

Spatial gradients

Paolo et al., in prep
Climate record

Paolo et al., in prep
Future of repeat surface elevation measurements from space:

- Data Fusion
- Science driven application of machine learning
- Model inversion
Altimetry-Gravimetry Joint Inversion of Mass Change

David Wiese, Alex Gardner, Nicole-Jeanne Schlegel, Johan Nilsson, Fernando Paolo

Trend in Antarctic mass from GRACE, Altimetry, joint-inversion, and Downscaled solution [NO FIRN CORRECTION]
Utilizing timeseries to invert for ice properties

Geophysical Research Letters

Regularized Coulomb Friction Laws for Ice Sheet Sliding: Application to Pine Island Glacier, Antarctica

Ian Joughin 1, Benjamin E. Smith 1, and Christian G. Schoof 2

1Polar Science Center, Applied Physics Lab, University of Washington, Seattle, WA, USA. 2Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, British Columbia, Canada

Abstract

The choice of the best basal friction law to use in ice-sheet models remains a source of uncertainty in projections of sea level. The parameters in commonly used friction laws can produce a broad range of behavior and are poorly constrained. Here we use a time series of velocity and speed data to examine the simulated transient response of Pine Island Glacier, Antarctica, to a loss of basal traction as its grounding line retreats. We evaluate a variety of friction laws, which produces a diversity of...

Figure 1. Modeled response to un grounding from 2002 to 2017 for various friction laws. Results with (a) m = 1 and A = 140, (b) m = 3 and A = 75, (c) m = 6 and A = 43, and (d) regularized Coulombic friction with m = 3, A = 300 m/year, and A = 30 along the profile shown in Figure 2. Observed velocities (V2006, V2007, V2008, and V2015) as well quasi 2002 (Q2002) velocity are also shown. Each panel includes the model and data differences for 2017. Δv = v_m - v_o

Figure 2. Time-dependent along flow and cross flow horizontal velocity components for the Ms (1477-day) tidal period (Figures 8a–8c). (a) Along flow amplitude with contour lines showing horizontal secular speed in 0.2 m/s increments. (b) Along flow phase relative to the median along flow Ms phase over the ice shelf. Contour lines are barytronic below −1200 m from Bedmap2 in 200 m increments. Areas with small amplitude and horizontal secular velocity are crossmatched for clarity. (c)–(d) same as Figures 8a and 8b but for cross flow variability. Phase values in Figure 8c are referenced to the median along flow Ms phase over the ice shelf as in Figure 8b. Grounding line are the same as in Figure 1.

Figure 3. Time-dependent along flow and cross flow horizontal velocity components for the Ms (1477-day) tidal period (Figures 8a–8c). (a) Along flow amplitude with contour lines showing horizontal secular speed in 0.2 m/s increments. (b) Along flow phase relative to the median along flow Ms phase over the ice shelf. Contour lines are barytronic below −1200 m from Bedmap2 in 200 m increments. Areas with small amplitude and horizontal secular velocity are crossmatched for clarity. (c)–(d) same as Figures 8a and 8b but for cross flow variability. Phase values in Figure 8c are referenced to the median along flow Ms phase over the ice shelf as in Figure 8b. Grounding line are the same as in Figure 1.
Ice sheets are predictable but progress in understanding needs to accelerate at a rate faster than the ice sheets themselves !!!
“I contend that a major disaster—a rapid 5-meter rise in sea level caused by deglaciation of West Antarctica—may be imminent or in progress after atmospheric CO2 content has only doubled” Mercer, 1978. Nature

Fig. 3 a, Antarctic ice cover today, and b, after a 5–10 °C warming.
It is our job to articulate the next generation of surface topography measurement needs that will lead to rapid advances in our understanding of land ice processes that are necessary to refine projections of sea level change.
Land Ice measurement needs

Can be broken down into four target surfaces:
1. Fast Moving portions of Ice Sheets and Ice Caps
2. Slow Moving portions of Ice Sheets and Ice Caps
3. Ice Shelves
4. Mountain glaciers
Measurement needs

For each surface we need to define

1. Spatial scales
2. Temporal repeat
3. Measurement accuracy and precision

Also need to think about **applications** needs
- Sea ice mapping and classification
- Ice bergs
- May have unique latency and rapid response requirements
Altimetry and ice-covered Polar oceans

Ron Kwok
Polar Science Center
Applied Physics Laboratory
University of Washington
Seattle, WA
Topics

• Arctic Ocean ice thickness record (1960s – present)
• Sea ice freeboard, thickness, roughness
• Dynamic topography of the ice-covered oceans
Decline in multiyear sea ice coverage: 1999-2017

Decline in multiyear sea ice coverage: 1999-2017

Polyakov et al. 2012, Kwok, 2018
Decline in sea ice thickness (Central Arctic Ocean): (Submarine, AEM, CS-2, Operation IceBridge, and ICESat)

CryoSat-2 altimetry data are from ESA’s data portal (URL: https://earth.esa.int)

Note: Ice thickness is within this polygon
Figure 5. Coupled variability of Arctic Ocean sea ice volume and multiyear sea ice (MYI) coverage. (a) Time-varying sea ice volume (from figure 3) and MYI coverage (from figure 4) in winter (2003–2018). (b) Detrended time series of (a). (c) Scatterplot of detrended ice volume and MYI coverage.
Multi-beam Profiles of Sea Ice From ICESat-2

Transition from thick to marginal zone ice cover

200 km

October 17, 2018 – Ascending Track
Key Science Objectives: Polar Oceans

- **Arctic**
  - Monitoring changes in sea ice thickness/volume
  - Short term forecasts to climate projections/model improvements
  - Dynamic topography

- **Antarctic (Important focus)**
  - Monitoring changes in sea ice thickness/volume
    - Limited retrievals and understanding of approaches
  - Climate projections/model improvements
  - Dynamic topography
Altimetry of the Polar Oceans
Altimetry of the Polar Oceans
Sea Ice Freeboard from Space
Measurement Principle

Total Freeboard

Photo by N. Untersteiner
Sea Ice Thickness from Lidars

\[ h_f = h_{fs} + h_{fi} \]

\[ h_{\text{ice}} = \frac{\rho_w}{\rho_w - \rho_i} h_f - \frac{\rho_w - \rho_s}{\rho_w - \rho_i} h_{fs} \]
Snow Depth: Measurement Principle

\[ h_{fs} = \frac{(h_f^{\text{lidar}} - h_f^{\text{radar}})}{\eta_s} \]

- $h_{fs}$: snow depth
- $\eta_s$: refractive_index(snow)
Reconstruction of thickness from freeboard

Elevation asl (m)

-7
-6
-5
-4
-3
-2
-1
0
1

1 km

SNOW  AIR

SEA LEVEL

SEA ICE

ARCTIC OCEAN

freeboard
draft

graphics from Operation IceBridge:
NASA airborne mission
Sea ice Freeboard Requirements

- Provide surface elevations to enable the determination of sea-ice freeboard
- Key requirements
  - Precision
    - for accurate sea surface reference
  - Spot resolution
    - 80% of leads are <50 m wide
  - Coverage
    - Monthly uniform coverage of ice-covered oceans
Science: Polar Oceans

- Arctic
  - Monitoring changes in sea ice thickness/volume
  - Short term forecasts to climate projections/model improvements
  - Dynamic topography

- Antarctic (Important focus)
  - Monitoring changes in sea ice thickness/volume
    - Limited retrievals and understanding of approaches
  - Climate projections/model improvements
  - Dynamic topography

- Snow depth (both oceans)
  - Requires new technology
Topography of the ice-covered oceans
Break

Start @
10:00 am PT
1:00 pm ET

Alex Gardner, JPL
What do we need to rapidly advance the science?

- **ASPIRATIONAL QUALITY**: What would enable a dramatic advance in cryosphere science objective; that is, what would ideally meet our needs?

- **THRESHOLD QUALITY**: What would enable an important advance, but not dramatic, in cryosphere science objective; that is, what would be a valuable improvement compared to what is now available or is expected to be available in this decade from planned programs or missions?

- How do we objectively make these decisions with sufficient traceability?

- Recommendations need to stand up to inter-discipline / inter-observation competition in a resource limited environment. More is always better, unless it leads to nothing.

- It’s our job to see that these observations are realized for the next generation of cryosphere science that will work to answer some of societies most pressing questions.
So, how many measurements do we need?
Example: Observing System Simulation Experiments (OSSEs) for glacier volume change
Minimum elevation change sampling required to resolve regional volume change

• Select 1000 random samples (with replacement) of decreasing sample size to determine standard error for a range of sample sizes
• Bin measurements of elevation change by elevation and weight by hypsometric area
<table>
<thead>
<tr>
<th># of spot elevations</th>
<th>dh/dt</th>
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<tbody>
<tr>
<td>60986</td>
<td>-0.35 ± 1.96 SE</td>
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# of spot elevations: 20000

$\frac{dh}{dt}$: $-0.35 \pm 0.05$ m yr$^{-1}$
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<th># of spot elevations</th>
<th>$\frac{dh}{dt}$</th>
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</thead>
<tbody>
<tr>
<td>10000</td>
<td>$-0.35 \pm 0.07\ m\ yr^{-1}$</td>
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</table>
# of spot elevations: 5000

\[
\frac{dh}{dt} = -0.35 \pm 0.11 \text{ m yr}^{-1}
\]
# of spot elevations  dh/dt
2500               -0.35 ± 0.15 m yr⁻¹
# of spot elevations: 1000

$\frac{dh}{dt}$: $-0.35 \pm 0.23 \text{ m yr}^{-1}$
# of spot elevations  dh/dt
500  -0.35 ± 0.32 m yr$^{-1}$
<table>
<thead>
<tr>
<th># of spot elevations</th>
<th>dh/dt</th>
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<tr>
<td>250</td>
<td>-0.35 ± 0.45 m yr⁻¹</td>
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</tbody>
</table>
# of spot elevations  dh/dt
100  -0.35 ± 0.72 m yr$^{-1}$
Random Spatial Sampling

planes per 100 km$^2$ divided by $\sigma^*$

- Greenland $\sigma^* = 0.5$
- Antarctic $\sigma^* = 0.4$
- CAA North $\sigma^* = 0.4$
- CAA South $\sigma^* = 0.4$
- Svalbard $\sigma^* = 0.6$
- Russian Arctic $\sigma^* = 0.4$
- High Mountain Asia $\sigma^* = 3.4$

$\sigma^*$ = hypsometry weighted standard deviation in $dh$
Random Spatial Sampling

\[ \sigma^* = \text{hypsometry weighted standard deviation in } dh \]

- Greenland $\sigma^* = 0.5$
- Antarctic $\sigma^* = 0.4$
- CAA North $\sigma^* = 0.4$
- CAA South $\sigma^* = 0.4$
- Svalbard $\sigma^* = 0.6$
- Russian Arctic $\sigma^* = 0.4$
- High Mountain Asia $\sigma^* = 3.4$

planes per 100 km$^2$ divided by $\sigma^*$

standard error in mean $dh/dt$ [m yr$^{-1}$]

$\sigma^*$ = hypsometry weighted standard deviation in $dh$
Conclusion

• sparse elevation change measurements (~2 per 100 km²) provide accurate elevation changes

• Measurements must have representative spatial distribution
Other ways to justify needs

• Peer-reviewed literature
• Community white papers
• National and international reports:
  • Special Report on the Ocean and Cryosphere in a Changing Climate
  • IPCC AR5
• Identify needs for future OSSE experiments or small studies to make objective / traceable recommendations
Summary of key whitepapers submitted to DS

- 6 of 151 RFIs directly pertain to STV Cryo

28. Glacial Acceleration - Reduction of Uncertainty in Sea-Level-Rise Assessment
   Paper motivated by the need to understand glacial acceleration which is a main source of uncertainty in sea-level change assessment. Observables: High-res surface height. Possible Measurement Approach: Swath or multi-beam altimetry in several frequencies. Links of thought: ice-ocean-atmosphere, beyond-ICEsat2, observation suite Themes I, IV, V

49. Lidar-Optical Fusion for High-resolution Measurements of Ice and Vegetation Change
   This proposal outlines measurement requirements for cryosphere and ecosystem science objectives using a combination of lidar and optical measurements from a single space-based observatory.

57. Monitoring ice sheets and sea ice: The need for satellite altimetry data in the coming decades.
   Here we describe a set of science goals for understanding changes in ice sheets and sea ice, and describe a set of measurements that will meet these goals. We propose that laser altimetry measurements provide the best chance to meet these goals and conclude that the heritage of NASA technology will make this mission reliable and affordable.
Summary of key whitepapers submitted to DS: Land Ice

67. Quantifying Mass Change Components of Land Ice and Sea Ice

The cryospheric community advocates for a multi-sensor mission that includes a Lidar capable of precise topographic and bathymetric mapping and a wide-bandwidth dual-frequency radar to reduced uncertainties in future ice mass loss and sea level rise.

78. Linkages of salinity with ocean circulation, water cycle, and climate variability

This white paper addresses the enhancement of capability for space-based measurements of global sea surface salinity (SSS) and sea ice thickness to study the linkages of ocean circulation with the water cycle and climate variability, as well as to facilitate biogeochemistry research.

136. Understanding glaciers and ice sheets response to changes in atmosphere and ocean conditions

Desired geophysical observations for improving understanding of glacier and ice sheet processes relevant to improving projections of sea level change. The three key variables identified are repeat measurements of surface velocity, gravity and elevation.
Summary of key whitepapers submitted to DS: Land Ice

Glacier and ice sheet monitoring: Data needed for cutting edge science in the next decades.

Benjamin Smith, University of Washington Applied Physics Lab
Kelly Brunt, Earth System Science Interdisciplinary Center, University of Maryland
Bea Csatho, University at Buffalo Department of geology
Helen Fricker, Scripps Institution of Oceanography
Alex Gardner, NASA Jet Propulsion Laboratory
Thomas Neumann, NASA Goddard Space Flight Center
<table>
<thead>
<tr>
<th>Ice Sheet Type</th>
<th>Measurement Goals</th>
<th>Unique Challenges</th>
<th>Measurement Priorities</th>
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</thead>
<tbody>
<tr>
<td><strong>Glaciers</strong></td>
<td>- Current trend magnitudes&lt;br&gt;- Process model constraints</td>
<td>Small spatial scales&lt;br&gt;Strong atmospheric signals need downcaled data</td>
<td>- Fine-scale altimetry / photogrammetry&lt;br&gt;- Understanding of SMB processes such as surface reflectance</td>
</tr>
<tr>
<td><strong>Coastal ice sheets and outlet glaciers</strong></td>
<td>- Process-based modeling&lt;br&gt;- Ablation rates</td>
<td>Processes operate on short temporal and spatial scales</td>
<td>- Altimetry / photogrammetry with sub-seasonal temporal resolution&lt;br&gt;- Seasonal velocity measurements</td>
</tr>
<tr>
<td><strong>Interior ice sheets</strong></td>
<td>- Estimating present and recent-past mass balance&lt;br&gt;- Inland propagation of coastal changes</td>
<td>- High precision requirements&lt;br&gt;- Large signals due to accumulation and densification variability</td>
<td>- Long-term laser-altimetry measurements&lt;br&gt;- Accurate firn and SMB modeling&lt;br&gt;- Mission-to-mission radar altimetry calibration</td>
</tr>
<tr>
<td><strong>Ice shelves</strong></td>
<td>- Estimates of ocean and atmospheric forcing&lt;br&gt;- Changes in marginal forcing</td>
<td>- Hydrostatic compensation reduces signal&lt;br&gt;- Large sensitivity to firn-model processes&lt;br&gt;- Advection of small-scale features</td>
<td>- Long-term altimetry time series&lt;br&gt;- Accurate firn and SMB modeling&lt;br&gt;- Velocity mapping</td>
</tr>
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Summary of key white papers submitted to DS: Sea Ice

**Observing the Arctic Ocean Sea Ice Cover: 2017-2027**

R. Kwok¹, J. C. Comiso², T. Markus², A. Schweiger³, M. C. Serreze⁴, J. C. Stroeve⁴

¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
²NASA/Goddard Space Flight Center, Greenbelt, MD
³Polar Science Center, University of Washington, Seattle, WA
⁴National Snow and Ice Data Center, University of Colorado, Boulder, CO
Summary of key whitepapers submitted to DS: Sea Ice

Key Questions:

- How predictable are different aspects of the Arctic sea ice cover, and what is needed to improve predictability at the local and regional scale to facilitate planning, mitigation, and adaptation? Improvements in model physics and specification of initial state. While there are intrinsic limitations on Arctic sea ice predictability, some appear to reside in the initial ice/ocean state and in the longer-term trend; the initial states (e.g. thickness, snow depth, etc.) affect the potential trajectories in the evolution of ice coverage.

- What are the critical linkages between the Arctic system and the larger Arctic and global systems? Although efforts are under way to better understand the role of Arctic sea ice in this broader context, progress has been limited by the lack of coordinated observations of sea ice and associated forcing parameters (atmosphere and ocean) at appropriate time and space scales.

Kwok et al. 2017
Key Sea Ice Parameters

**Ice thickness distribution.** Beyond 2021, there are currently no plans for another altimeter suitable for fully mapping Arctic sea ice thickness. This is an important consideration.

**Coordinated observations: motion and thickness.** Satellite retrievals of sea ice thickness and motion are typically acquired independently with little consideration of the close links between thermodynamic and dynamic processes that control ice conditions, which must be treated realistically to improve predictive models.
Conclusion

• White papers are very high-level and provide little guidance on specifics of measurement needs
• It is the job of the STV to refine the description of these identified needs
<table>
<thead>
<tr>
<th>Area of Interest</th>
<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
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<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
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<tr>
<td>(outlet glaciers)</td>
<td>80%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>50 m</td>
<td>0.1 m</td>
<td>10 days</td>
<td></td>
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<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps</td>
<td>80%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td>(interior ice)</td>
<td>50%</td>
<td>200 m</td>
<td>0.005 m</td>
<td>30 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 m</td>
<td>0.01 m</td>
<td>90 days</td>
<td></td>
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<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
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<tr>
<td></td>
<td>75%</td>
<td>10 m</td>
<td>0.005 m</td>
<td>5 days</td>
<td>30 days</td>
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<tr>
<td></td>
<td></td>
<td>50 m</td>
<td>0.01 m</td>
<td>10 days</td>
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<tr>
<td>All mountain glaciers larger than 50 km^2</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
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<td></td>
<td></td>
<td>25 m</td>
<td>0.1 m</td>
<td>10 days</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static Land Ice DEM</td>
<td>100%</td>
<td>1 m</td>
<td>0.5 m</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td></td>
<td>90%</td>
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<td>1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arctic and Southern Ocean Sea Ice Cover</td>
<td>100%</td>
<td>100 m</td>
<td>0.01 m</td>
<td>5 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>500 m</td>
<td>0.02 m</td>
<td>10 days</td>
<td>30 days</td>
</tr>
</tbody>
</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
## Fast Outlet Glaciers

<table>
<thead>
<tr>
<th>Area of Interest</th>
<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)</td>
<td>100% 80%</td>
<td>1-5 m 10 m 50 m</td>
<td>0.1 m 0.05 m 0.1 m</td>
<td>90 days 5 days 10 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps (interior ice)</td>
<td>80% 50%</td>
<td>1-5 m 200 m 500 m</td>
<td>0.1 m 0.005 m 0.01 m</td>
<td>90 days 30 days 90 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100% 75%</td>
<td>1-5 m 10 m 50 m</td>
<td>0.1 m 0.005 m 0.01 m</td>
<td>90 days 5 days 10 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>All mountain glaciers larger than 50 km^2</td>
<td>100% 50%</td>
<td>1-5 m 10 m 25 m</td>
<td>0.1 m 0.05 m 0.1 m</td>
<td>90 days 5 days 10 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>Static Land Ice DEM</td>
<td>100% 90%</td>
<td>1 m 5 m</td>
<td>0.5 m 1 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Arctic and Southern Ocean Sea Ice Cover</td>
<td>100% 50%</td>
<td>100 m 500 m</td>
<td>0.01 m 0.02 m</td>
<td>5 days 10 days 10 days</td>
<td>10 days 30 days</td>
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</tbody>
</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
# Slow Moving Ice Sheet

<table>
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<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)</td>
<td>100% 80%</td>
<td>1-5 m 10 m 50 m</td>
<td>0.1 m 0.05 m 0.1 m</td>
<td>90 days 5 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps (interior ice)</td>
<td>80% 50%</td>
<td>1-5 m 200 m 500 m</td>
<td>0.1 m 0.005 m 0.01 m</td>
<td>90 days 30 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100% 75%</td>
<td>1-5 m 10 m 50 m</td>
<td>0.1 m 0.005 m 0.01 m</td>
<td>90 days 5 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>All mountain glaciers larger than 50 km^2</td>
<td>100% 50%</td>
<td>1-5 m 10 m 25 m</td>
<td>0.1 m 0.05 m 0.1 m</td>
<td>90 days 5 days</td>
<td>10 days 30 days</td>
</tr>
<tr>
<td>Static Land Ice DEM</td>
<td>100% 90%</td>
<td>1 m 5 m</td>
<td>0.5 m 1 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Arctic and Southern Ocean Sea Ice Cover</td>
<td>100% 50%</td>
<td>100 m 500 m</td>
<td>0.01 m 0.02 m</td>
<td>5 days 10 days</td>
<td>10 days 30 days</td>
</tr>
</tbody>
</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
# Ice Shelves

<table>
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<tr>
<th>Area of Interest</th>
<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>50 m</td>
<td>0.1 m</td>
<td>0.05 m</td>
<td>10 days</td>
</tr>
<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps (interior ice)</td>
<td>80%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>200 m</td>
<td>0.005 m</td>
<td>30 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 m</td>
<td>0.01 m</td>
<td>90 days</td>
<td>30 days</td>
</tr>
<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>10 m</td>
<td>0.005 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 m</td>
<td>0.01 m</td>
<td>10 days</td>
<td>30 days</td>
</tr>
<tr>
<td>All mountain glaciers larger than 50 km²</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 m</td>
<td>0.1 m</td>
<td>10 days</td>
<td>30 days</td>
</tr>
<tr>
<td>Static Land Ice DEM</td>
<td>100%</td>
<td>1 m</td>
<td>0.5 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>90%</td>
<td>5 m</td>
<td>1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arctic and Southern Ocean Sea Ice Cover</td>
<td>100%</td>
<td>100 m</td>
<td>0.01 m</td>
<td>5 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>500 m</td>
<td>0.02 m</td>
<td>10 days</td>
<td>30 days</td>
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</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
## Mountain Glaciers

<table>
<thead>
<tr>
<th>Area of Interest</th>
<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 m</td>
<td>0.1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps</td>
<td>80%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td>(interior ice)</td>
<td>50%</td>
<td>200 m</td>
<td>0.005 m</td>
<td>30 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 m</td>
<td>0.01 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>10 m</td>
<td>0.005 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 m</td>
<td>0.01 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All mountain glaciers larger than 50 km^2</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 m</td>
<td>0.1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static Land Ice DEM</td>
<td>100%</td>
<td>1 m</td>
<td>0.5 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>90%</td>
<td>5 m</td>
<td>1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arctic and Southern Ocean Sea Ice Cover</td>
<td>100%</td>
<td>100 m</td>
<td>0.01 m</td>
<td>5 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>500 m</td>
<td>0.02 m</td>
<td>10 days</td>
<td>30 days</td>
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</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
### Static DEM

<table>
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<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>50m</td>
<td>0.1 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps (interior ice)</td>
<td>80%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>200 m</td>
<td>0.005 m</td>
<td>30 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 m</td>
<td>0.01 m</td>
<td>90 days</td>
<td>30 days</td>
</tr>
<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>10 m</td>
<td>0.005 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 m</td>
<td>0.01 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>All mountain glaciers larger than 50 km^2</td>
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<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 m</td>
<td>0.1 m</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
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<td>0.5 m</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td></td>
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<td>1 m</td>
<td>N/A</td>
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</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
# Sea Ice

<table>
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<tr>
<th>Area of Interest</th>
<th>Coverage (%)</th>
<th>Horizontal Resolution [m]</th>
<th>Repeat Accuracy (vertical) [m]</th>
<th>Repeat Frequency [days]</th>
<th>Latency [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
<td>30 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>50 m</td>
<td>0.1 m</td>
<td>10 days</td>
<td>50m</td>
</tr>
<tr>
<td>Slow Moving portions of Ice Sheets and Ice Caps (interior ice)</td>
<td>80%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>200 m</td>
<td>0.005 m</td>
<td>30 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 m</td>
<td>0.01 m</td>
<td>90 days</td>
<td>30 days</td>
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<tr>
<td>Antarctic and Greenland Ice Shelves</td>
<td>100%</td>
<td>1-5 m</td>
<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>10 m</td>
<td>0.005 m</td>
<td>5 days</td>
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<tr>
<td></td>
<td></td>
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<td>0.01 m</td>
<td>10 days</td>
<td>30 days</td>
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<tr>
<td>All mountain glaciers larger than 50 km$^2$</td>
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<td>0.1 m</td>
<td>90 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>10 m</td>
<td>0.05 m</td>
<td>5 days</td>
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<td></td>
<td>25 m</td>
<td>0.1 m</td>
<td>10 days</td>
<td>30 days</td>
</tr>
<tr>
<td>Static Land Ice DEM</td>
<td>100%</td>
<td>1 m</td>
<td>0.5 m</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>90%</td>
<td>5 m</td>
<td>1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arctic and Southern Ocean Sea Ice Cover</td>
<td>100%</td>
<td>100 m</td>
<td>0.01 m</td>
<td>5 days</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>500 m</td>
<td>0.02 m</td>
<td>10 days</td>
<td>30 days</td>
</tr>
</tbody>
</table>

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold
Wrap-up

• Thank you, thank you, thank you

• Next steps
  • Community survey
  • Further refinement of SATM and mapping to technologies
  • White paper summarizing input

• Feel free to send Cryo related input and recommendations directly to me: alex.s.gardner@jpl.nasa.gov