Global Cryosphere Watch Perspective on Needs for the Space-based Observing System

Jeff Key
NOAA Satellite and Information Service
Madison, Wisconsin USA

Mark Drinkwater
European Space Agency
The Netherlands

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On behalf of:

Global Cryosphere Watch (GCW)

**Mission:** GCW will provide authoritative, understandable, and useable data, information, and analyses on the past, current, and future state of the cryosphere to meet the needs of WMO Members and partners in delivering services to users, the media, public, decision, and policy makers.

Polar Space Task Group (PSTG)

**Objective:** To develop the satellite component of the observing infrastructure in support of polar and high elevation cryosphere observations, by federating space agencies around the world.
The cryosphere collectively describes elements of the earth system containing water in its frozen state and includes: solid precipitation, snow cover, sea ice, lake and river ice, glaciers, ice caps, ice sheets, ice shelves, permafrost and seasonally frozen ground.

The cryosphere is global, ~100 countries.
How the polar regions look from space

Arctic: an ocean surrounded by land

Antarctic: land surrounded by ocean
## Properties of the Cryosphere

### Snow
- snow water equivalent (SWE), depth, extent, density, grain size, albedo

### Solid Precipitation
- snowfall rate, amount

### Lake and River Ice
- freezeup/breakup, thickness, snow on ice

### Sea Ice
- extent, concentration, type (age), thickness, motion, temperature, leads, snow on ice

### Glaciers, Ice Caps, Ice sheets
- mass balance (accumulation/ablation), thickness, area, length (geometry), firn temperature, velocity, snowline/equilibrium line, icebergs, snow on ice

### Frozen Ground/Permafrost
- soil temperature/thermal state, active layer thickness, borehole temperature, extent, snow cover

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There are more than 30 cryosphere properties that, ideally, would be measured. Of those, measurement techniques from space can be considered mature for only 9-12.
Observing the cryosphere requires many satellites

Cryosphere Satellite Missions

Year: 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16

- PALSAR/ALOS L-band
- RA, SAR & Wind Scat/ERS-2
- RADARSAT-1 C-band
- RA2 & ASAR/Envisat C-band
- RADARSAT-2 C-band
- ALOS-2
- GMES S-1A, B
- RCM

- SAR/RISAT C-band
- TerraSAR/Tandem-X X-band
- SAR/COSMO-SKYMED X-band
- ASCAT & AVHRR/MetOp -A
- MetOp-B, -C

- Seawinds/QuikSCAT Ku-band
- ICESAT
- Ku-Scat & MSMR/OCEANSAT-2
- LEO missions
- SCAT / HY-2A, 2B, 2C
- CryoSat-2 / SIRAL
- ICESAT-2
- GMES S-3A, B
- GRACE-FO

- WindSat/Coriolis
- GOCE
- SMOS
- OLS & SSM/I/DMSP... AVHRR & AMSU/NOAA
- MODIS & AMSR-E/EOS-Aqua
-ASTER/MODIS/EOS-Terra
- COCTS/HY-1A
- HY-1B
- HY-1C
- HY-2B
- HY-2A

- VIIRS/SNPP
- JPSS 1
- MODI & MERSI/FY-3A
- FY-3B
- FY-3C
- Landsat-8
- Landsat-5, -7
- SPOT-4/-5/-6/-7
- HEO missions

- Arctica-M 1 & 2
- PCW 1 & 2

Sea ice extent and concentration, ice sheet elevation, glacier velocity, snow accumulation
Ice sheet elevation, sea ice thickness
Ice sheet mass change
Sea ice extent and concentration, glacier area, surface albedo and temperature, radiation budget

In Orbit | Approved | Planned/Pending approval | Solid = R & D; Hatched = operational mission

Courtesy: M. Drinkwater
Product Examples

Annual Cycle of Snow and Ice

Multisensor Automated Snow/Ice
Aug 17, 2013

(Animation courtesy of P. Romanov)
Product Examples

Ice Surface Temperature

Surface Albedo
Product Examples

CryoSat-2 Sea Ice Thickness (ESA)

Sea Ice Thickness from S-NPP VIIRS

2-day composite
Product Examples

Ice Sheet Elevation
Large area velocity mapping produced with Landsat 8.

(T. Scambos, NSIDC)
Applications, Users

Application areas:
- Weather forecasting
- Navigation, shipping
- Agriculture
- Fisheries
- Hazards
- Recreation
- Process studies
- Climate

Some users:
- *Ice services* for commercial and recreational uses: North American Ice Service (NAIS), U.S. National Ice Center (NIC), Alaska Ice Desk
- *Numerical weather prediction* centers: ECMWF, Met Office, CMC, JMA, NCEP, BoM, RosHydroMet
- *Security*: Navy, Coast Guard (various)
- *Research*: University and government scientists
Supporting Operational Ice Services

Satellite data used routinely in operational Ice services
Coastal Research

The Arctic coastal zone is undergoing rapid changes related to loss of sea ice

- Increased coastal erosion
- Later formation and earlier breakup of landfast ice
- Increased commercial activity

... but a consistent sea ice concentration data product is not available

- Passive microwave estimates suffer from “land contamination”

(Courtesy of A. Mahoney)
Prediction

WWRP Polar Prediction Project

Arctic opening comes with opportunities ...

... and risks!

Better Arctic forecasts ➞ better mid-latitude predictions

Photo by Chilean Navy/Reuters

Coming up:

Jung et al. 2014
Error reduction of subseasonal forecasts with improved Arctic predictions

YOPP
YEAR OF POLAR PREDICTION
(mid-2017 – mid-2019)

Data gaps and model deficits cause poor forecasts in polar regions

Uncertainty of near-surface temperature initial conditions (K)

Hamill, pers. comm.
Ice Surface Temperature in Navy Model

ACNFS NAVO Modeled Ice Thickness with NPP IST
8/16 1340 UTC overlay
Assimilating Ice Thickness

While little work has been done on assimilating ice thickness in models, indications are that doing so would improve ice forecasts.

The difference in mean ice thickness for September between the corrected and the control runs of the PIOMAS model, where corrected runs use IceBridge and SIZONet ice thicknesses to correct the initial thickness field. The thin red lines are the ice extent (0.15 ice concentration) lines for each of the corrected ensemble members and the thick red line is the mean for the ensemble. The thick green line is the mean of the ensemble of control runs and the black line is the observed September mean ice extent.

From Lindsay et al. (2012)
Climate Trends, Interactions, and Feedbacks

Cloud and Surface Temperature Trends

Sea Ice Extent

Greenland Mass Loss
Cryosphere Requirements: IGOS

The first comprehensive set of cryosphere observational requirements and gaps was compiled for the IGOS Cryosphere Theme (2007). These and others are available on the GCW website.

### Observed Requirements

GCW observational requirements are being formulated. They will draw from various sets of existing user requirements and will be vetted by the scientific community. They will become part of the WMO Rolling Review of Requirements (RRR) and will be accessible through the Observing Systems Capability Analysis and Review Tool (OSCAR), which has a cryosphere theme. OSCAR is the official source for WMO requirements. The IGOS Cryosphere Theme Report (see Documents) contains the most comprehensive set of observational capabilities and requirements for the cryosphere. It is the starting point for GCW. The IGOS and OSCAR cryosphere requirements are given below. Click the Filter Options button to filter the results. Each entry in the table gives the current measurement capability in green, the threshold requirement (minimum necessary) in blue, and the objective requirement (target) in orange, if available.

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<thead>
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<td>Climate</td>
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<td>1 year</td>
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<td>Sea ice</td>
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<td>Operational</td>
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<td>10 m</td>
<td>10 m</td>
<td>1 year</td>
<td>1 day</td>
<td>IGOS 20C</td>
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<td>Sea ice</td>
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<td>100 cm</td>
<td>100 cm</td>
<td>1 day</td>
<td>John Eyn (OSCAR)</td>
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<td>Sea ice</td>
<td>High Res MIP</td>
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<td>100 cm</td>
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<td>1 day</td>
<td>John Eyn (OSCAR)</td>
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<td>Sea ice</td>
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<td>100 km</td>
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<td>Sea ice</td>
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<td>Climate</td>
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Overall Need of CryoLand Snow, Glacier and Lake Ice Products for User Group

Which of these products are of relevance for you

**Snow products**
- High relevance: 53%
- Essential: 33%
- No relevance: 15%

**Glacier products**
- Low relevance: 37%
- Medium relevance: 17%
- Essential: 14%
- No relevance: 20%

**Lake and river ice products**
- No relevance: 24%
- Low relevance: 35%
- Medium relevance: 11%
- Essential: 19%
- No information: 8%
PSTG User Needs: Floating Ice

The Polar Space Task Group (PSTG) is compiling user requirements for space-based observations of the polar regions.

For **floating ice** the variables deemed most important are **sea ice thickness**, **snow on sea ice**, and **sea ice deformation**:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Frequency Band</th>
<th>Target Locations</th>
<th>Repeat</th>
<th>Resolution</th>
<th>Polarization</th>
<th>Incidence Angle</th>
<th>Seasonality</th>
<th>Complementary Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Ice Thickness</td>
<td>C+L or X+L; Investigate S</td>
<td>Global polar and sub-polar sea ice areas; Arctic ocean ice export gateways; Antarctic around bases and experimental sites</td>
<td>Daily; every 6 hours</td>
<td>&lt;10m to 10's of km</td>
<td>Multi-polarization; research with full polarimetry</td>
<td>10 – 50°</td>
<td>Year-round</td>
<td>Altimeter, Low Freq PMR, VIS/IR</td>
</tr>
<tr>
<td>Snow Cover on Sea Ice</td>
<td>Combination of all bands (Potential for interferometry)</td>
<td>Global polar and sub-polar sea ice areas; priority Antarctic</td>
<td>Daily; every 6 hours</td>
<td>&lt;10m</td>
<td>Multi-polarization; research with full polarimetry</td>
<td>10 – 50°</td>
<td>Winter, spring</td>
<td>Altimeter, Low Freq PMR, VIS/IR</td>
</tr>
<tr>
<td>Sea Ice Deformation</td>
<td>L; Combination of all bands (Potential for interferometry)</td>
<td>Beaufort, Chukchi, Baltic, Kara, Caspian Seas; Sea of Okhotsk, Other Arctic areas of economic activity; Antarctic</td>
<td>Hourly to Daily</td>
<td>&lt;1-10m</td>
<td>Multi-polarization; research with full polarimetry</td>
<td>10 – 50°</td>
<td>Year-round</td>
<td>Altimeter</td>
</tr>
<tr>
<td>Sea Ice Concentration</td>
<td>C</td>
<td>Arctic and Antarctic seas; targeted coastal areas; Canadian Arctic Archipelago</td>
<td>Daily; every 6 hours</td>
<td>&lt;25m</td>
<td>HH+HV; HH+VV</td>
<td>20 – 50°</td>
<td>Year-round</td>
<td>VIS/IR, PMR, AMS</td>
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<td>Sea Ice Classification</td>
<td>C+L or X+L; Future Ku</td>
<td>Global polar and sub-polar sea ice areas</td>
<td>Daily; every 6 hours</td>
<td>&lt;10m</td>
<td>HH+HV; HH+VV; research with quad-pol, full polarimetry, support pol</td>
<td>10 – 60°</td>
<td>Year-round</td>
<td>VIS/IR, PMR, AMS</td>
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Snow priorities include (but are not limited to):

- Assure continuity in routine continental scale monitoring of snow areal extent and SWE data in support of GCW Snow Watch and snow applications and service development.
- Develop new methods for retrieval of snow depth on sea ice.
- Plan SAR data as complement to passive microwave and 300 m optical data for continental scale snow extent/SWE; also in alpine regions.
- Develop a snow product intercomparison exercise in connection with GCW CryoNet for quality assurance.
PSTG User Needs: Ice Sheets

Ice sheet priorities include (but are not limited to):

• Coordinated acquisition plan of SAR/InSAR imagery over Antarctica and Greenland.

• SAR and gravimetric ice sheet mass balance.

• To provide complementary data on ice sheet surface accumulation and albedo.

• To extend optical imaging and stereo image data for generation of digital elevation models, glacier and ice cap outlines and hypsometry.

• To investigate capabilities of SAR altimetry over mountain glaciers and ice caps.
Permafrost priorities include (but are not limited to):

• Routine high-resolution circumpolar SAR coverage.

• Multi-sensor monitoring around key research locations where GTN-P and in-situ measurements are made ("cold spots").

• Bi-weekly InSAR for subsidence.

• Obtain <1 m summer (July-Aug) optical images around each Arctic Cold Spot for up-scaling/downscaling of local periglacial processes.

• Quantify rates of pan Arctic coastal erosion. Annual circumpolar Arctic coastline mapping at < 10m optical resolution; InSAR estimates of erosion/degradation).

• Other: Land surface temperature, albedo, SWE, DEM, land cover
User Needs: Snowfall

Snowfall (solid precipitation) priorities include (but are not limited to):

- **CloudSat** gives us the first active snowfall observations at high latitudes. However, single-frequency, non-Doppler radar quantitative snowfall estimates have large uncertainties (> 50%).

- Passive microwave radiometer-based retrievals offer some hope, but snowfall event detection - much less quantitative precip estimation - is still developing.

- Passive microwave radiometer snowfall retrievals over snow and ice surfaces are very difficult.

- **Dual-frequency radar** may be the best tool for high-latitude space borne snowfall estimates. However, this is a long way off.

- We need trustworthy ground-based validation sites at high latitudes.
The Climate and Cryosphere (CliC) project identified the following priorities for Earth Observation (January 2015) (not a complete list):

**Sea ice:**
- Sea ice thickness
- Snow on sea ice
- Sea ice mass balance
- Polynyas, thin ice, and marginal ice processes
- Sea ice drift and deformation

**Snow:**
- Snow mass and water equiv.
- Albedo
- Density, grain size
- Vegetation-snow interactions

**Glaciers:**
- Elevation
- Volume change

**Ice Sheets:**
- Accumulation rates
- Mass balance
- Elevation

**Permafrost:**
- Gas emissions (CO2, CH4)
- “Hot spots” of change

**Hydrology:**
- Arctic lakes and rivers
Side note: To meet user requirements, not only do we need to plan for new instruments and products, we also need to fully understand the products that we have.
The Arctic from space: pseudo-geo

Large-scale circulation from geostationary and polar-orbiting satellites
Conclusions

• User needs for short-term applications have the following priorities for future (near and far) remote sensing of the cryosphere:
  
  – Sea ice thickness, deformation, and motion (altimetry, PM, vis/IR)
  – Solid-precipitation/snowfall (dual frequency radar)
  – Snow on sea ice (possibly with laser + radar altimetry)
  – Snow mass, SWE (PM, SAR)
  – Ice sheet mass, mass variability, mass balance (SAR, altimeters, gravimetry)
  – Permafrost: subsidence (hi-res SAR), surface characteristics (various)
  – Sub-surface phenomena - such as in ice sheet thermal sounding (similar to atmospheric sounding) and permafrost
  – Bidirectional reflectance of snow and ice (multi-angle optical)

• Some of these are also priorities for climate. Though many climate requirements have been defined (e.g., GCOS), space agency requirements have traditionally been driven by NWP.
globalcryospherewatch.org