Observing Snow: Conventional Measurements, Satellite and Airborne Remote Sensing

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Outline

Three Snow Lectures:

1. Why you should care about snow...
2. How we measure snow...
   • Conventional snow observations
   • Step through 3 measurement requirements:
     - coarse (25 km) resolution SWE (satellite)
     - snow depth on sea ice (airborne)
     - high (1 km) resolution SWE
3. Snow and climate modeling...
How Do We Learn About Arctic Snow?

1. Conventional weather station observations:
   - single points that may or may not be representative
   - primarily limited to snow depth
   - issues with international reporting standards and consistency

2. Satellite remote sensing:
   - cloud cover and cloud/snow distinction for optical snow extent
   - algorithm uncertainties for microwave approaches to snow mass

3. Land surface models driven by reanalysis (lecture 3):
   - coarse spatial resolution/excellent temporal information
   - full suite of variables, but uncertainties in model physics/forcing
Conventional Observing Networks

Meteorological Service of Canada
Surface Network
(single point snow depth)

Meteorological Service of Canada
Snow Course Network
(transects of snow depth/density/SWE)
MSC Network Characteristics

Distance from nearest station (km) reporting snow depth

Mean distance to nearest station (km) versus latitude

Environment and Climate Change Canada
Environnement et Changement climatique Canada
MSC Network Characteristics

Interpolated surface elevation (m) obtained on a 100 km grid with 250 km search radius and Gaussian weighting
Measurement Uncertainties: Snow Depth

- How well do points compare to linear transects?
- What bias is introduced by most stations being located at airports?

Maximum 10 cm
Minimum 2 cm
Reported 3 or 4 cm

On the scale 0 cm
Reported 3 cm

Neumann et al., 2008
Measurement Uncertainties: Snow Courses
Measuring falling snow is a challenge in any environment, but uncertainty is particularly high in the Arctic because precipitation gauges can:

- become plugged with snow
- drift in
- capture re-suspended snow during ground blizzards
- fail to record trace amounts of snow

*Precipitation data in the MSC archive are uncorrected!*

Goodison et al., 2001
Take Home Point: Conventional snow measurements can be highly uncertain, and are poorly suited for most applications.
Remote Sensing of Terrestrial Snow Cover Extent

- Mapping snow extent from optical satellite imagery is a mature field
- Limited primarily by cloud cover, polar darkness, and dense vegetation
Microwave Remote Sensing of Snow: Requirements

1. Coarse resolution (25 km) SWE for climate applications

2. Snow on sea ice for altimetry and climate

3. High resolution (1 km) SWE for NWP/hydrological modeling
• Classic equations compare two frequencies (high and low frequency)
• Confounding factors
  • Size, shape and clustering of snow grains (microstructure)
  • Structure (layering, ice lenses)
  • Snow wetness

Requirement: Coarse Resolution SWE
Passive Microwave Remote Sensing
Standalone Passive Microwave Remote Sensing of Snow

- 1978 through 2000
- 1264 unique snow survey locations, over 170,000 total cases
- Surveys are 500 m to 2000 m in length

RMSE = 92 mm
Brightness Temperatures (19V and 37V GHz; SMMR, SSM/I, or AMSR-E)

Snow depth observations from synoptic weather stations (ECMWF)

*Observed* field produced by kriging synoptic weather station observations. Estimate of kriging interpolation variance also obtained.

Weather station measurements of snow depth used as input to forward model TB simulations. Model fit to satellite measurements by fluctuating the effective grain size.

Spatially continuous background field of effective grain size (including a variance field) produced by kriging.

*Radiometer* field produced through forward Tb simulations using the kriged effective grain size. Model fit to satellite measurements by fluctuating the SWE.

Assimilation procedure adaptively weighs the *observed* and *radiometer* fields to estimate final SWE and a measure of statistical uncertainty.
Algorithm Evaluation: Eurasia

**SWE < 150 mm**
- RMSE = 33 mm
- Bias = 3 mm

**All SWE**
- RMSE = 47 mm
- Bias = -6 mm

88.5%
Algorithm Evaluation: Eurasia

RMSE = 47 mm

RMSE = 92 mm
Difference between final assimilated SWE and background SWE from interpolated synoptic weather station data.
Summary of the ESA GlobSnow SWE product

- Daily maps of hemispheric SWE
- 25km spatial resolution
- Glaciers and regions with high topographical variability are masked out:
  - Alpine regions
  - Glaciers
  - Greenland
- Assimilation approach produces uncertainty for each grid cell
- Temporal coverage 1979 – present
GlobSnow vs. Other SWE Datasets

Climatological NH snow water mass, 1981–2010

Multidataset SWE climatology, February–March, 1981–2010

Mudryk et al., 2015
Comparisons with in situ Data

- ERA-land: +42mm bias, 74.7 mm RMSE
- GlobSnow: -4mm bias, 44.9 mm RMSE
- MERRA: +15mm bias, 57.9 mm RMSE
- CROCUS: +5mm bias, 48.0 mm RMSE
- GLDAS: -11mm bias 49.5 mm RMSE
Validation of GlobSnow Retrievals

Comparisons of maximum seasonal SWE from various gridded datasets over eastern Canada.

- GlobSnow retrievals are characterized by spatially ‘smooth’ SWE patterns.
- This is likely the result of the kriging procedure not considering the impact of land surface characteristics (i.e. forest versus open), which can strongly influence mesoscale variability in snow cover properties.
Transects of snow surveys conducted across the boreal to tundra transition in northern Manitoba and the Northwest Territories between 2004 and 2007 were utilized to determine the extent to which snow properties can vary over relatively short distances (i.e. between adjacent grid cells).

<table>
<thead>
<tr>
<th></th>
<th>Boreal to Boreal</th>
<th>Tundra to Tundra</th>
<th>Boreal to Tundra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean distance between sites (km)</td>
<td>20.3</td>
<td>17.5</td>
<td>24.6</td>
</tr>
<tr>
<td>n</td>
<td>63</td>
<td>22</td>
<td>9</td>
</tr>
<tr>
<td>Δ Density (%)</td>
<td>2.6</td>
<td>1.4</td>
<td>46</td>
</tr>
<tr>
<td>Δ Depth (%)</td>
<td>-2.6</td>
<td>-18.2</td>
<td>-57</td>
</tr>
<tr>
<td>Δ SWE (%)</td>
<td>0.1</td>
<td>14.1</td>
<td>-34.7</td>
</tr>
<tr>
<td>GlobSnow prototype Δ SWE (%)</td>
<td>-3.6</td>
<td>-3</td>
<td>-6.6</td>
</tr>
</tbody>
</table>
Use of Field Measurements to Evaluate GlobSnow

Boxplots of % change in snow properties between adjacent EASE-Grid cells across the boreal to tundra transition.
Use of Field Measurements to Evaluate GlobSnow

Derksen et al., 2009
Requirement: Snow Depth on Sea Ice

- Very difficult variable to measure remotely

M. Sturm, University of Alaska, GI
• Snow plays a key role in the growth and decay of Arctic sea ice via albedo feedbacks and insulation
• Accurate estimates of snow depth on sea ice are necessary for sea ice thickness retrievals using altimetry

Webster, et al., JGR, 2014

Requirement: Snow Depth on Sea Ice

- University of Kansas Center for Remote Sensing of Ice Sheets (CReSIS) Snow Radar
  - 2-6.5 GHz frequency modulated continuous wave radar
  - ~14.5 m along track and 11 m across track resolution
  - Retrieval relies on identification of returns from the air-snow and snow-ice interfaces to determine thickness of the snowpack
- Known uncertainties involving both physical (snow and ice surface topography) and system properties (flight path characteristics, radar side lobe)
  - ~5.7 cm uncertainty (Kurtz et al., 2013)
  - 3.5 – 5 cm uncertainty (Kwok et al., 2011)
  - **Limited datasets to validate retrieval**
2014 Environment Canada Eureka Campaign

- Intensive 10 Day field campaign (March 24-April 1 2014)
  - Situated near Eureka, Nunavut
  - Heterogeneous ice conditions

- Multi-scale approach to snow sampling:
  - 1 x 50 km transect experiment
  - 3 x Gridded (500 x 250 m) experiments

King et al., 2015
Transect Measurements and Retrievals

(a) Variograms for the FYI and MYI sites. Snow depths and QL retrievals along the (b) FYI and (c) MYI transects. Red lines show the 40m in situ mean and standard deviation is shaded in grey. Probability distributions using 2 cm bins for the FYI site and 5 cm for the MYI site.

King et al., 2015
Grid Measurements and Retrievals

(top) Comparison of measured and retrieved snow depths discretized by undeformed (U-FYI), deformed (D-FYI), and multiyear (MYI) ice types. Root-mean-square error (RMSE) is shown in the legend.

(bottom) The probability distributions are shown with 2 cm bins for the FYI sites and 5 cm for the MYI site.

King et al., 2015
Correlation between the QL retrievals and in situ measurements as a function of (left) aggregation and (right) as a function of maximum $H_{\text{topo}}$ between 25 and 55 cm. Dotted lines show the 95% confidence intervals.

King et al., 2015
2016 Field Campaign Update
Example MYI Grid Site

Snow Depths:
n=7052
avg = 30.9 cm
STDV = 25.1 cm
Terrestrial LiDAR MYI Scan

Large-Scale Topography
70 x 70 m
2 cm resolution

April 17th 2016

Jack Landy (University of Manitoba) & Thomas Newman (NOAA)
Requirement: High Resolution SWE

- Environment Canada has identified high resolution (~1 km) snow water equivalent (SWE) with frequent revisit as a priority observational gap which limits the development of enhanced operational environmental monitoring, services, and prediction.

How much snow is there? Where, in what ways, and why are snowpacks changing?

Specific scientific objectives for high resolution (~1 km) terrestrial snow products:
1. Quantify the spatially and temporally dynamic amount of freshwater stored in seasonal snow (monitoring and process studies)
2. Provide observational support for high resolution prediction (via data assimilation and verification) of the land surface for NWP, seasonal forecasting, and hydrological modeling (predictions)
3. Diagnose systematic snow mass biases in the land modules of current Earth System Models (projections)
Secondary Science Drivers

QuikSCAT multiyear ice coverage (Polyakov et al., 2012)

QuikSCAT mean melt date, 2000-2009 (Wang et al., 2011)

RADARSAT sea ice area flux, M’Clure Strait, (Howell et al., 2014)

ASCAT derived ocean surface winds (50 km; NOAA-STAR)
Example Mission Concept Trade Offs

Sidetooling ScanSAR:
- Single look high res (~50m)
- 100km swath
- Cryosphere coverage in 15 days

Rotating SAR:
- Single look res (~250m-500m)
- 700km swath for high res
- Cryosphere coverage in 2 days

Pulsed imaging radar:
- Convoy with MetOp SG
  Sat-B = flexible multi-frequency active/passive
- Cryosphere coverage in 2 days
  - Single look res 1-5 km
Summary

• Users must be clear on the uncertainties and limitations of conventional snow measurements (snowfall, snow depth, snow courses)
• Satellite remote sensing provides essential observing capabilities for snow, but field campaigns are required for algorithm and product validation, and to address specific observing gaps (i.e. snow on sea ice)
• New spaceborne capabilities are required to address some observational gaps
• Land surface models also provide complementary snow information to satellite data, particularly for climate modeling applications (full talk on this tomorrow)