Using SAR to Examine Landfast Sea Ice Extent and Variability

Andy Mahoney
PhD Candidate, Snow Ice and Permafrost Geophysics
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Definition of Landfast Sea Ice

Various definitions in the literature

• “Sea ice that remains attached to the coast ...” (WMO, 1970)
• “Ice that is grounded or forms a continuous sheet which is bounded at the seaward edge by an intermittent or nearly continuous zone of grounded ice” (Barry et al., 1979)

We use two criteria for remotely sensed data:
1. the ice is contiguous with the land
2. the ice lacks detectable motion for approximately 20 days
Methodology
### Study area and dataset

#### Table 1: Summary of Radarsat imagery used in this study

<table>
<thead>
<tr>
<th>Ice season</th>
<th># parent scenes acquired</th>
<th># mosaics generated</th>
<th>Mean period spanned by mosaic (days)</th>
<th>Mean period between 3 consecutive mosaics (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-97</td>
<td>134</td>
<td>29</td>
<td>2.7</td>
<td>20.2</td>
</tr>
<tr>
<td>1997-98</td>
<td>126</td>
<td>28</td>
<td>2.5</td>
<td>19.9</td>
</tr>
<tr>
<td>1999-99</td>
<td>111</td>
<td>30</td>
<td>2.5</td>
<td>19.9</td>
</tr>
<tr>
<td>1999-00</td>
<td>113</td>
<td>28</td>
<td>2.6</td>
<td>19.0</td>
</tr>
<tr>
<td>2000-01</td>
<td>91</td>
<td>30</td>
<td>2.4</td>
<td>20.6</td>
</tr>
<tr>
<td>2001-02</td>
<td>152</td>
<td>35</td>
<td>2.5</td>
<td>16.7</td>
</tr>
<tr>
<td>2002-03</td>
<td>123</td>
<td>29</td>
<td>2.6</td>
<td>20.8</td>
</tr>
<tr>
<td>2003-04</td>
<td>109</td>
<td>29</td>
<td>2.1</td>
<td>21.0</td>
</tr>
<tr>
<td>All years</td>
<td>959</td>
<td>238</td>
<td>2.5</td>
<td><strong>19.8</strong></td>
</tr>
</tbody>
</table>
Applying our definition of landfast ice to SAR data

1) The ice is contiguous with the coast
2) The ice lacks detectable motion for approximately 20 days

Requirements:

-a time interval to determine motion / lack thereof
- a single image is not sufficient
- we use 3 consecutive collocated mosaics ⇒ ~20 days

-high quality data
- ScanSAR calibrated geotiffs - 100m resolution
- accurate georeferencing - co-location error < 500m
Towards an automated SLIE detection algorithm

The backscatter signature of landfast ice should remain constant over consecutive images

Smoothing kernel = 700m x 700m

Red = 24 Dec 2001 17:19
Green = 31 Dec 2001 16:58
Blue = 06 Jan 2002 17:23
The gradient of an image is a **vector field** with two components defined by:

\[
\nabla \Phi = \frac{\partial \Phi}{\partial x} i + \frac{\partial \Phi}{\partial y} j
\]

where \(i\) and \(j\) are the unit horizontal and vertical vectors respectively.

In discrete form, it is approximated by:

\[
\left( \frac{\partial \Phi}{\partial x} \right)_{i,j} \approx \frac{\Phi_{i-d,j} - \Phi_{i+d,j}}{d}, \quad \left( \frac{\partial \Phi}{\partial y} \right)_{i,j} \approx \frac{\Phi_{i,j-d} - \Phi_{i,j+d}}{d}
\]

\((d = 3)\)
Gradient field differences

\[ \Delta_{\text{horiz}} (\nabla \Phi) = \sum_{m=1,2} \sum_{n=2,3} \left( \frac{\partial \Phi_m}{\partial x} - \frac{\partial \Phi_n}{\partial x} \right) \]

\[ \Delta_{\text{vert}} (\nabla \Phi) = \sum_{m=1,2} \sum_{n=2,3} \left( \frac{\partial \Phi_m}{\partial y} - \frac{\partial \Phi_n}{\partial y} \right) \]

\[ \Delta(\nabla \Phi) = \sqrt{\left( \Delta_{\text{horiz}} (\nabla \Phi) \right)^2 + \left( \Delta_{\text{vert}} (\nabla \Phi) \right)^2} \]

- Each gradient component of each SAR image is differenced separately to preserve directionality
- Landfast ice exhibits a low gradient difference magnitude

24 Dec 2001 - 6 Jan 2001
Gradient difference mosaic - midwinter

Mosaic all the gradient difference sub-region images together

Threshold at $0.08 \text{ dB m}^{-1}$

22 Dec 2001 - 8 Jan 2002

- Threshold values typically between $\sim 0.05$ and $0.1 \text{ dB m}^{-1}$
- SLIE is clearly visible but discontinuous
Gradient difference mosaic - spring

8 May 2002 - 25 May 2002

- Surface melt and flooding introduce difficulties
- No unique thresholding value for all regions of all images
- Automated delineation technique remains elusive

Threshold at 0.08 dB m\(^{-1}\)
Delineation of the SLIE

SLIEs are manually delineated from

- 3 consecutive mosaics
- the corresponding gradient difference mosaic

May 8-10 2002
May 14-16 2002
May 22-25 2002

May 8-25 2002
Results
Stacked SLIE delineations

222 SLIEs from 1996-2004 stacked on top of each other
probability = fraction of SLIEs occurring at same location
zones of preferred location indicated by orange-green colors
discrete nodes of higher probability within this zone
Interannual variability
Comparison with bathymetry

Water depth

0 20 40 60 80m
Measuring Landfast Ice Width

Landfast ice width is measured along profiles ~normal to the coast

- ~2000 transects performed
- 200 average landfast ice widths calculated
- non-linear co-ordinate axis
Overall development appears asymmetric
- slow advance in winter
- rapid break-up in spring
Peak extent does not coincide everywhere in study area
Temporary extensions can be seen
- landfast ice advances then retreats to previous position
Freezing / thawing degree days

Retreat of landfast ice preceded by onset of thaw
• accumulated thawing degree days at break-up appears constant
Little correlation with freezing degree days
Conclusions

Colocated SAR works!
- automated technique remains elusive
SLIEs have a preferred location zone
- landfast probability correlates with water depth
- discrete nodes suggest SLIE is discontinuously grounded

Timeseries of landfast ice captures episodic events
- high spatial and temporal resolution
- allows detailed comparison with climate data