Interim guidelines for operational implementation of SAR applications for lake ice monitoring and mapping: break-up and freeze-up

Technical Report of the Canada Centre for Remote Sensing.

Contact: tgeldset@nrcan.gc.ca

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1 Introduction

This document provides information for the operational implementation of SAR methods for monitoring and mapping lake ice, as developed at the Canada Centre for Remote Sensing. It specifically deals with SAR applications for lake ice break-up and freeze-up at their stage of development as of 2011-12-31.

Values in red **bold** should be treated as variables in software developed for this application.

2 Lake ice break-up monitoring and mapping

The application development for lake ice break-up is described in Geldsetzer et al. (2010). The relevant operational parameters and methods are described in this document.

This section describes the workflow for processing and classifying SAR images and the subsequent creation of ice-off date maps.

There are six main steps:
1. Compile relevant data
2. Process SAR imagery
3. Classify processed SAR images
4. Calculate ice concentrations for study area for each classification (HH and HV)
5. Select/omit classifications based on meteorological conditions, incidence angle, and calculated ice concentrations
6. Create ice-off map from selected classified images

2.1 Data

RADARSAT-2 data are assumed to be the SAR data source.

2.1.1 Vector data

2.1.1.1 Study area

A vector polygon file outlining the study area(s) is required. The study area polygon(s) should be used to clip the data at some point during the process. This may be the SAR imagery itself, or during classification.

The size of study area(s) depends primarily on the width of the SAR imagery to be used. The objective is to enable the compilation of consistently overlapping images for a season. For RADARSAT-2 FineQuad (FQ) or StandardQuad (SQ) imagery this requires a study area approximately 10 km x 10 km. For regular Standard (S) imagery (recommended) this requires approximately 40 km x 40 km. For Wide or ScanSAR imagery the study areas can be larger.

The north-south dimension can be increased by acquiring two (or more) images in the flight line, but the divergent orientations of ascending and descending images will then limit acquisitions to either ascending or descending (if the north-south dimension becomes too large). If the study area is larger than one image, then the images must first be made into a mosaic; or, alternatively, two study areas, one for each image area can be used. In mid-2011, 50-km wide products became available for FQ and SQ data. Therefore, study areas with consistently overlapping quad-pol images can now be increased to approximately 20 km x 10 km.

When selecting study areas, care should be taken to include entire lakes; i.e. do not cut lakes in half, if possible. In some cases this may not be possible; in which case a lake's freeze-up date is only relevant for the portion within the study area.

The size of lakes of interest within a study area impacts the choice of SAR imagery. Study areas with lakes > 50 ha can be readily monitored using ScanSAR Wide imagery (50 m × 50 m pixels). Study areas with lakes < 50 ha should use Standard imagery (12.5 m × 12.5 m pixels), or even Fine imagery. Refinement of these estimates may be needed for lakes that are narrow in relation to their size.

2.1.1.2 Lake polygons

Lake polygon vector data can be obtained from the 1:50 000 CANVEC database (http://geogratis.cgdi.gc.ca/). Lake polygons need to be buffered by 50 m, inwards from the perimeter of the lake or outwards from islands, in order to reduce potential co-registration problems with imagery. This reduces the operational workload considerably as it eases requirements for co-registration accuracy and, therefore, enables a fully-automated co-registration process.

Some vector editing may be required to add or subtract lakes, or to alter the shoreline of lakes that are obviously incorrect. Changes should only be made if confidence is high.

Depending on the software implementation used, the creator of the buffered lake file may need to ensure that each lake polygon has a unique ID. Note that lakes that are split during buffering may have the same ID (in ArcGIS use the vector editing Explode tool to separate the IDs).

2.1.2 SAR data

Select only SAR imagery that occupies all of a study area. Use of imagery that only has partial coverage will cause errors in ice-off date mapping.

Only the polarizations HH and HV (or VH) have been assessed and their classification thresholds estimated. The incidence angle of all pixels within the study area(s) must be > **35°** for the classifications to be effective. VV polarization can be used, but it has not been fully tested.

Therefore, for lake ice break-up, the following beam modes/polarizations are recommended:

- FQ or SQ 15+ (HH and HV)
- S4 to S7 (HH and HV)
- W3 (HH and HV)
- Portions of ScanSAR images (HH and HV) that have incidence angles > 35°

2.1.3 DEM data

DEM data are needed to orthorectify the SAR imagery (e.g. http://www.geobase.ca/). DEM files will likely need to be processed into a projected mosaic.

The spatial resolution of the DEM should attempt to match that of the imagery (~ 2 × the pixel spacing); however this is not imperative.

2.2 Process SAR imagery

RADARSAT-2 imagery must be calibrated to sigma-naught, and be orthorectified to a desired projection/datum. Speckle should be reduced (recommended: variable-size Enhanced Lee filter). The pixel spacing of the original imagery should be approximately maintained, unless there is a good reason not to. Processing should attempt to result in an ENL ≥ 9.

2.3 Classify SAR imagery

Classification of SAR images is done to discriminate ice from open water based on the radar backscatter in the images. Both HH and HV images are classified at this stage; selection of which polarization to use occurs later.

The following backscatter thresholds can be universally applied (for C-band) to classify lake ice versus open water during break-up. They are valid for imagery with incidence angles > 35°.

HH_threshold = **−21.35** dB (ice above, water below)
HV_threshold = **−24.35** dB (ice above, water below)

There are cases in which historical data are only available in VV, or VV+VH. Although VV imagery has not been fully assessed, initial estimates suggest that the HH threshold can be used as the VV threshold as well. It is assumed that VH = HV. Thus:

VV_threshold = **−21.35** dB (ice above, water below)
VH_threshold = **−24.35** dB (ice above, water below)

A **7 × 7** mode filter is recommended following classification.

2.4 Calculate ice concentration

Ice concentration should be calculated for the bounds of a study area. Study area ice concentrations for both HH and HV polarizations are calculated. Study area ice concentration is used during image/classification selection in the next step.

A sample classification for a 2009-06-03 HH image (Figure 1 left) shows a study area ice concentration > 0.95; the classified lakes pixels are overlain on the SAR image. A sample classification for a 2009-06-10 HV image (Figure 1 right) shows a study area ice concentration of ~ 0.2.

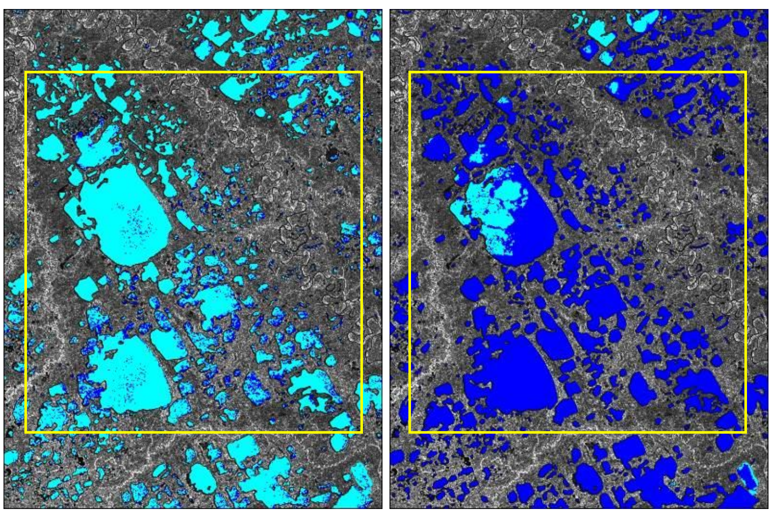

Figure 1. Lake ice versus open water classification: subsets of 2009-06-03 Radarsat-2 HH image (Left) and 2009-06-10 Radarsat-2 HV image (Right) in the Old Crow Flats/Vuntut NP study area. Ice is light blue, open water is dark blue. The yellow rectangle represents a study area.

2.5 Image/classification selection

Select/omit images and classifications based on meteorological conditions, incidence angle, and calculated study area ice concentrations. The flowchart in Figure 2 outlines the logic.

Begin with the latest available image, which has a high likelihood of being completely or mostly open water (i.e. a low ice concentration).

HH (or VV) can be used without accompanying HV (or VH) imagery, if that is all that is available. However, if HV (or VH) imagery is available, it should be employed. This is reflected in the flowchart in Figure 2.

2.5.1 Meteorological criteria

Hourly wind speed data should be obtained at a weather station representative of the study area. Wind speed data to the nearest hour from the SAR image acquisition is needed. Note: SAR imagery is in UTC; conversion to local date/time is needed when assessing meteorological parameters (assuming they are in local time).

Classification of SAR imagery will not provide good results if the wind speed is too strong (wavy water backscatters like ice). This differs depending on the beam mode and the image polarization you are using (HH or HV).

1. If the wind speed at image acquisition time is ≤ 63 km/h, then continue assessment; otherwise skip that image and move on to the next earlier one.
2. If HH polarization is to be used, the wind speed at image acquisition time should be less than the limits in Table 1 (or less than Equation 1a or 1b). If so, continue assessment; otherwise skip that image and move on to the next image.

- The estimation of wind speed may be a judgement call based on how long the wind speed is strong (± hours) and/or local knowledge. If there is no wind data then assume the wind is > 28 km/h, but <63 km/h.

Table 1. Radarsat-2 Standard beam modes and maximum allowable wind speed for lake ice classification using HH imagery. Wind azimuth = 0°.

Beam mode	Centre incidence angle	Wind speed threshold (km/h)	Wind speed threshold (m/s)
S4	36.6	13.2	3.7
S5	39.3	17.0	4.7
S6	43.9	23.6	6.5
S7	46.9	27.8	7.7

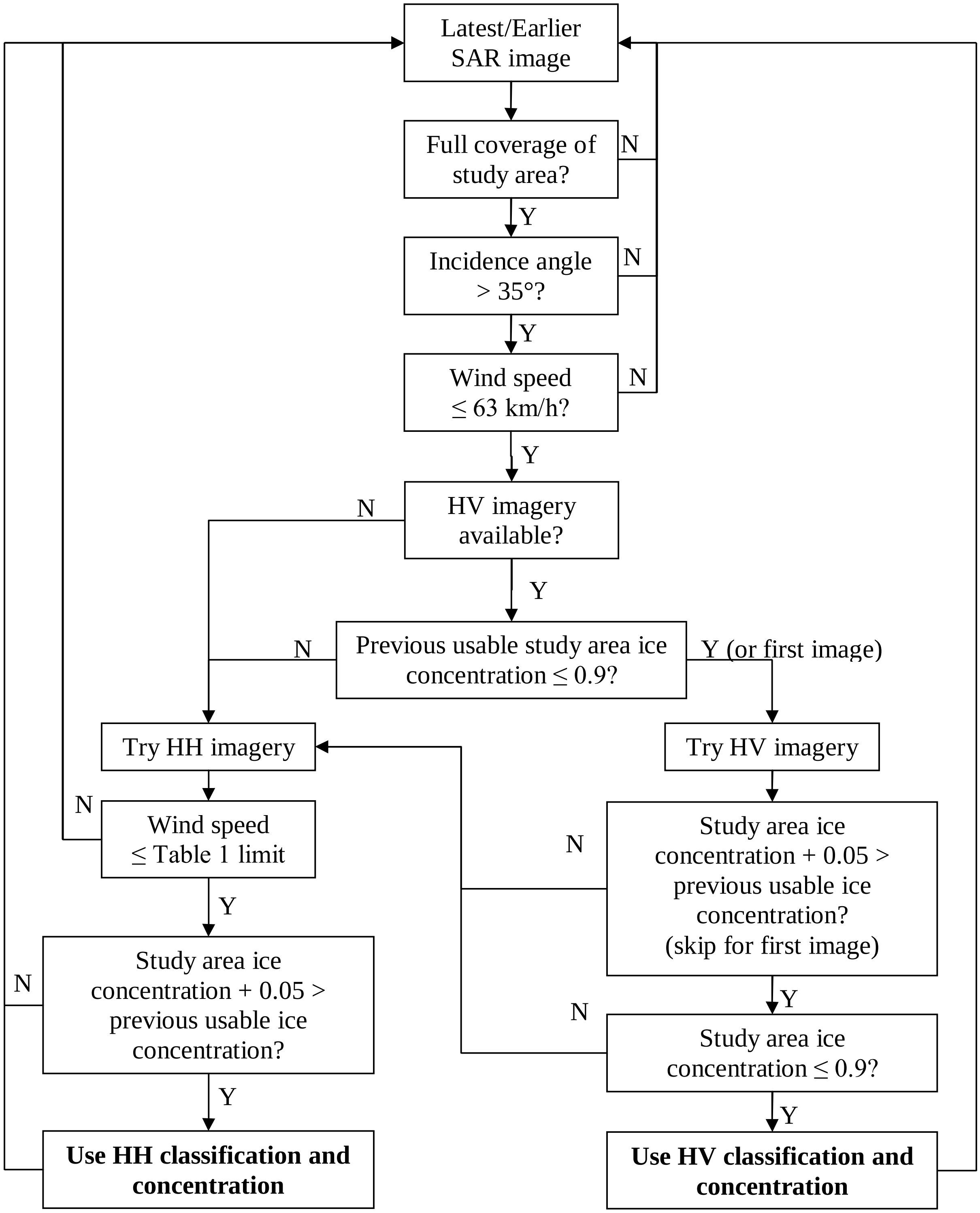

Figure 2. Image/classification selection overview.

More generally, the following relationships can be used to obtain the HH wind speed **threshold** (τ_{HH_wind}) for images at other incidence angles (θ):

$$\tau_{HH\_wind} = -10.734 + 0.3935\theta \quad , \theta > 35° \quad [\text{m/s}] \quad (1a)$$

$$\tau_{HH\_wind} = -38.641 + 1.4168\theta \quad , \theta > 35° \quad [\text{km/h}] \quad (1b)$$

If VV polarization is to be used, the wind speed at image acquisition time should be less than Equation 1c or 1d. If so, continue assessment; otherwise skip that image and move on to the next image. The likelihood that VV imagery will exceed the wind speed threshold is higher than for HH, thus the preference for HH imagery. For example, for S5 imagery, the HH wind speed threshold is 17.0 km/h (Table 1); however, the VV wind speed threshold is only 11.0 km/h.

$$\tau_{VV\_wind} = -6.2463 + 0.2365\theta \quad , \theta > 35° \quad [\text{m/s}] \quad (1c)$$

$$\tau_{VV\_wind} = -22.486 + 0.8512\theta \quad , \theta > 35° \quad [\text{km/h}] \quad (1d)$$

2.5.2 Ice concentration criteria

HH polarized images are used for the earlier part of the spring melt period, and HV polarized images are used for the later part. Working backwards from later to earlier images, the **switch** from HV to HH is done based on the study area ice concentration. The recommended ice concentration for the switch is **0.9**, but this may be adjusted based on local knowledge.

If HH images are used when there is a lot of open water, late in the melt period, wind may cause waves on the water to be classified as ice; HV images are much less prone to this. If HV images are used too early in the spring melt period, the ice has not yet deteriorated enough, and ice may be classified as open water. Lake ice tends to have sufficient deterioration by the time some open water appears within a study area (i.e. ice concentration ≤ 0.9).

2.5.3 Moist snow issue

If early melt season images are unexpectedly classified as mostly open water, then there may be moist/wet snow on the ice. Under such conditions, the ice/water appearance will typically be mottled (Figure 3). If this occurs, the classification is omitted from further analysis or mapping.

To algorithmically identify moist snow images, assess if an earlier image has lower ice concentrations than the next later image (without moist snow). If so, it is likely that the earlier image has moist snow causing more pixels to be classified as open water. It is assumed that no new ice is formed during the spring melt period.

If moist snow is identified in an HV classification, further assessment moves to the corresponding HH classification, which is then used to confirm/refute the moist snow issue.

During assessment, the ice concentration of the earlier classification is increased by **0.05** to allow for zero change, or small differences, between it and the next later classification. This logic is included in the flowchart (Figure 2).

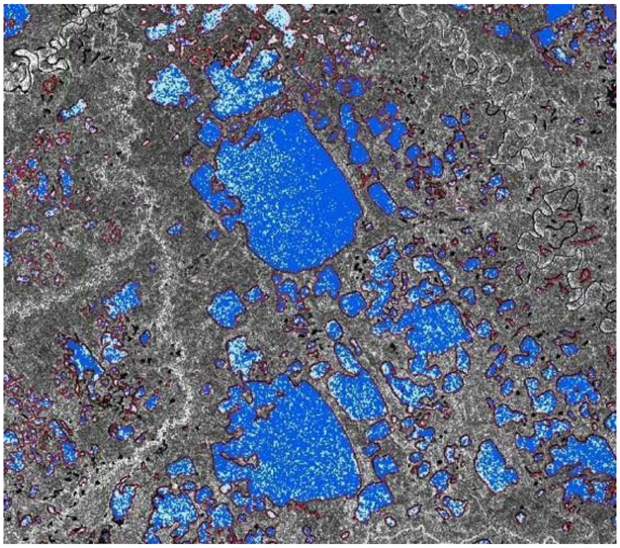

Figure 3. Classified 2011-05-24 HH image with erroneously classified open water due to moist snow effect.

2.6 Limitations

2.6.1 Temporal resolution

If the time interval between images is too great then the procedure for break-up classification/mapping will not function properly. The primary concern is in missing the period of deteriorating ice; this occurs between a moist snow cover and open water. A minimum temporal resolution of every 5 days should capture the necessary deteriorating ice stage.

2.6.2 Spatial errors

In some cases, the lake polygons may not follow the lake outlines in imagery, even when buffered. This error results in land contamination, i.e. land is misclassified as lake ice. These spatial errors may be caused by: 1) poor geolocation of the imagery; 2) changes to the lake outline through drainage; and/or 3) errors in the vector data.

2.6.3 Salt errors

Lake ice with even a small concentration of salt may be misclassified as open water. This is due to the microwave-absorbing properties of salty snow and ice, which can cause the backscatter to fall below the classification thresholds. Such saline lakes should be treated as special cases, and should not be included in classifications or ice-off mapping.

These special cases include: lakes with an inflow from the ocean, lakes exposed to salt blown in from the ocean, lakes with subsurface infiltration of saline groundwater, and lakes with higher than normal salinity due to mineral leeching or saline springs.

2.6.4 Melt stage diversity

Within a study area, lakes may be at different stages of the spring melt period. This occurs if: 1) lakes are at different elevations; 2) lakes are distributed over a large latitudinal range; and/or 3) lakes are located in micro-climates that delay or enhance melting. Any of these may create a classification problem: i.e. within a study area, some lakes may be far into the spring melt period, while some lakes may still have moist snow on them. The lakes with moist snow may have low backscatter, and can be misclassified as open water.

This type of misclassification occurred on 2009-06-29 for Ukkusiksalik NP (Figure 4). The dark areas along the park boundary (in Left image) are indicative of moist snow. This moist snow is also on the lakes, causing them to be misclassified as open water. The lakes at lower elevations are classified correctly as ice-covered (bottom right of Left image). On 2009-07-10 (Right image), the moist snow signature is no longer present and all lakes are correctly classified as ice-covered.

The use of smaller, separate study areas may mitigate this issue.

2.7 Map ice-off dates

Map ice-off dates using the selected classification results throughout a spring melt period.

Lakes are considered ice-free when the **individual lake ice concentration** is $\leq$ **0.1**. This value is used, instead of 0.0, to account for land contamination of lake polygons (i.e. land is classified as ice), caused by inaccurate polygon delineation or poor geolocation. This is a particular concern for small lakes, because even small delineation errors may cause significant land contamination. The ice concentration threshold is an operational variable: it may be changed depending on end-user requirements and lake polygon data quality.

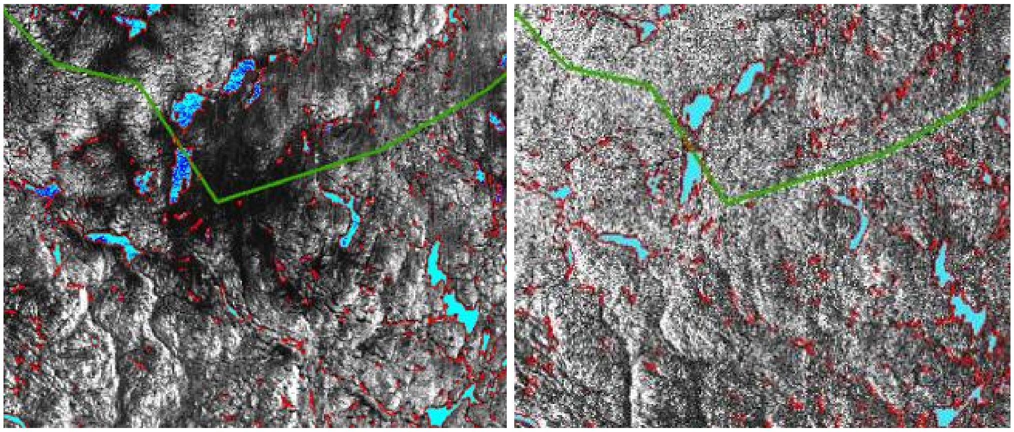

Figure 4. Classified images of a portion of Ukkusiksalik NP showing moist snow at higher elevations on 2009-06-29 HH (left), with misclassified open water. On 2009-07-10 HH (right), all areas are past the moist snow stage. Ice is light blue, open water is dark blue. The green line is the northern park boundary.

2.7.1 Mapping procedure

Beginning with a completely ice-free classified image; i.e. all lakes have ice ≤ 0.1 (although some lake may remain unknown), work backwards in time. This procedure maps the final ice-off date for each lake polygon.

A lake is assigned an ice-off date that is midway between: 1) the date on which its ice concentration is ≤ 0.1 for the first time; and 2) the date of the immediately earlier classification when its ice concentration is > 0.1. The uncertainty of the ice-off date (± days) is half of the date range between the two classifications (Table 2). There are various ways to run the logic.

A lake may be mapped as “Before first date” if its ice concentration is ≤ 0.1 for all classified images. Similarly, a lake may be mapped as “After last date” if it does not reach an ice concentration ≤ 0.1 by the latest classified image. In such cases, it either still has ice, or it has significant land contamination.

Table 2. Example of ice-off date assignments, and uncertainty; values may be rounded.

Image date (DOY)	Lake A	Lake A ice-off date, uncertainty	Lake B	Lake B ice off date, uncertainty	Lake C	Lake C ice off date, uncertainty
						After 181
181	Ice 0%		Ice 1%		Ice 12%	
				171, 11		
160	Ice 2%		Ice 15%		Ice 13%	
		158, 2				
156	Ice 18%		Ice 22%		Ice 13%	

Both *ice-off date* and *uncertainty* (± days) should be values associated with each lake polygon within a study area. The final ice-off date map should be a vector file type with attributes.

A sample ice-off date shape-file is shown in Figure 5. DOY values have been changed to YYYYMMDD.

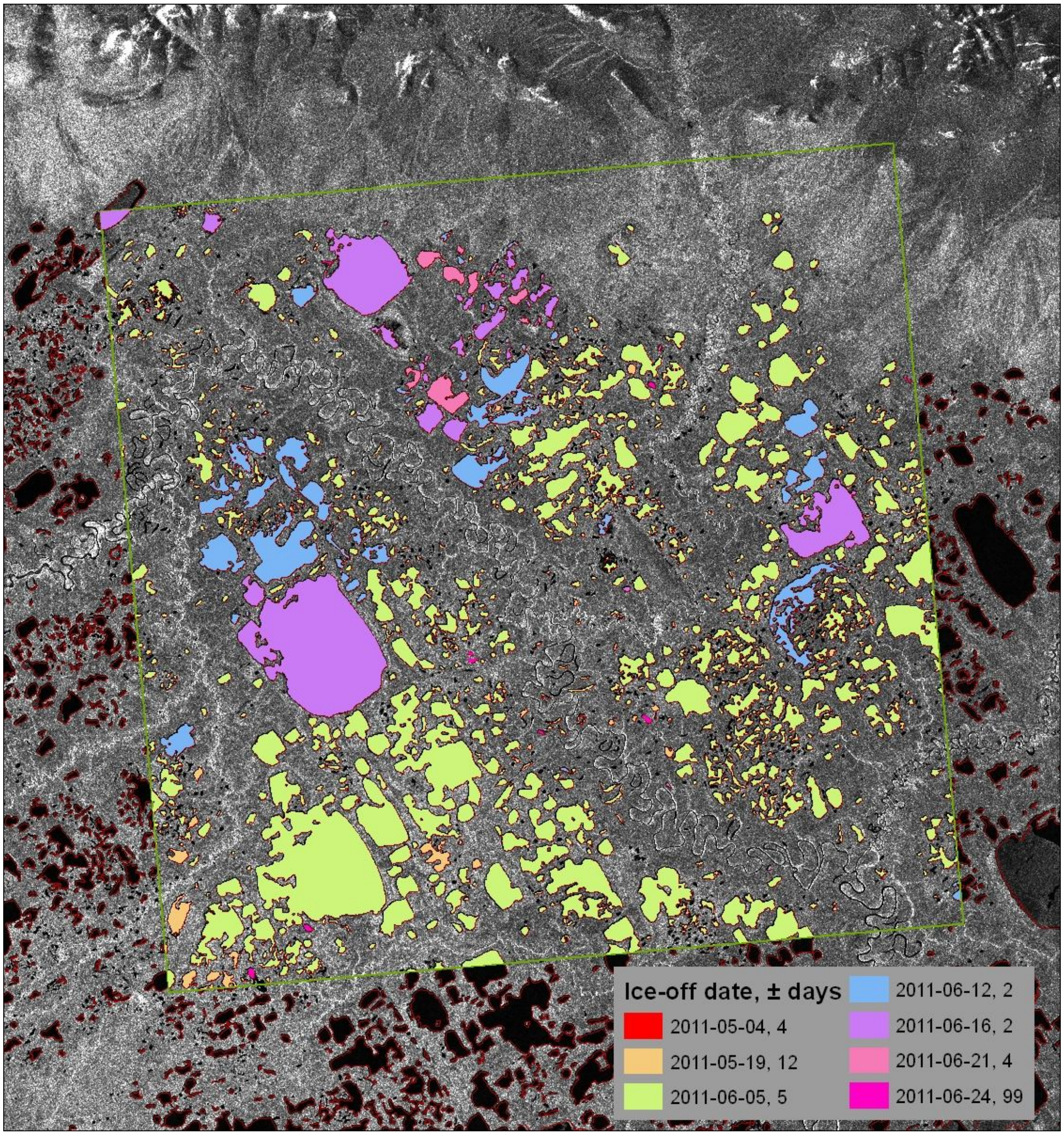

Figure 5. Sample shape-file of ice-off dates and their uncertainty. An uncertainty of 88 indicates that polygons are ice-off before the associated date. An uncertainty of 99 indicates that polygons are ice-off after the associated date (or have land contamination). Background is RADARSAT-2 HH S7 image for 2011-06-10.

3 Lake ice freeze-up monitoring and mapping

Methods for lake ice freeze-up monitoring and mapping differ from the break-up methods. The primary differences are that polarimetric data are needed, and that meteorological data are only used to help identify wind break-up events and/or moist snow events.

Non-polarimetric methods have been developed, but they are less accurate, and their implementation is more complex. They are outside the scope of these guidelines. Contact the authors for more information.

This section describes the workflow for processing and classifying SAR images and the subsequent creation of ice-on date maps.

3.1 Data

RADARSAT-2 data are assumed to be the SAR data source.

3.1.1 Vector data

3.1.1.1 Study area

A vector polygon file outlining the study area(s) is required. The study area polygon(s) should be used to clip the data at some point during the process. This may be the SAR imagery itself, or during classification, or mapping.

The size of study area(s) depends primarily on the width of the quad-pol SAR imagery to be used. The objective is to enable the compilation of consistently overlapping images for a season. For RADARSAT-2 FineQuad (FQ) or StandardQuad (SQ) imagery this requires a study area approximately 10 km x 10 km. In mid-2011, 50-km wide products became available for FQ and SQ data. Therefore, study areas with consistently overlapping quad-pol images can now be increased to approximately 20 km x 10 km.

The north-south dimension can be increased by acquiring two (or more) images in the flight line, but the divergent orientations of ascending and descending images will then limit acquisitions to either ascending or descending (if the north-south dimension becomes too large). If the study area is larger than one image, then the images must first be made into a mosaic; alternatively, two study areas, one for each image area can be used.

When selecting study areas, care should be taken to include entire lakes; i.e. do not cut lakes in half, if possible. In some cases, for large lakes, this may not be possible; in which case a lake's freeze-up date is only relevant for the portion within the study area.

3.1.1.2 Lake polygons

See Break-up section regarding lake polygons.

3.1.2 SAR data

Select only SAR imagery that occupies all of the study area. Use of imagery that only has partial coverage will cause errors in ice-on date mapping.

The incidence angle must be > **31.2°** for the classifications to be effective. Therefore, for lake ice freeze-up, use only the following polarimetric beam modes:

- FQ or SQ 11+

3.1.3 DEM data

See Break-up section regarding DEM data.

3.2 Process SAR imagery

RADARSAT-2 Fine-Quad (FQ) data (or Standard-Quad (SQ)) are used for lake ice freeze-up. Data are calibrated to σ°. Speckle is reduced using variable-sized, edge-aligned enhanced Lee filters; data should be processed to ENL > 10.

3.3 SAR parameters

Lake ice freeze-up methods use the co-polarized ratio (VV/HH) (γ_{co}), and a conformity coefficient (μ) (Zhang et al., 2011). These can be derived from the covariance matrix (C). Additionally, the incidence angle (θ) must be known for each pixel.

$$C = \begin{bmatrix} |S_{HH}|^2 & \sqrt{2}S_{HH}S_{HV}^* & S_{HH}S_{VV}^* \\ \sqrt{2}S_{HV}S_{HH}^* & 2|S_{HV}|^2 & \sqrt{2}S_{HV}S_{VV}^* \\ S_{VV}S_{HH}^* & \sqrt{2}S_{VV}S_{HV}^* & |S_{VV}|^2 \end{bmatrix} \tag{2}$$

$$\gamma_{co} = \frac{|S_{VV}|^2}{|S_{HH}|^2} \qquad (3)$$

$$\mu \cong \frac{2\left(\mathrm{Re}(S_{HH}S_{VV}^*) - |S_{HV}|^2\right)}{\left(|S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2\right)} \qquad (4)$$

3.4 Classify SAR imagery

Classification of SAR images is done to discriminate ice from open water. For freeze-up, a decision tree classifier is used (Figure 6). The conformity coefficient is used ($\mu > 0$) to asses if a pixel can be classified using the co-polarized ratio γ_{co}. The classifier is valid for incidence angles > 31.2°.

γ_{co} is used to classify pixels as ice or open water, using a **co-polarized threshold** (τ_{co}) that is dependant on incidence angle:

$\tau_{co} = -0.1187 + 0.0211\theta$	,for $\theta > 31.2°$	[dB, degrees]	(5a)
$\tau_{co} = 0.9593 + 0.0056\theta$	,for $\theta > 31.2°$	[linear, degrees]	(5b)

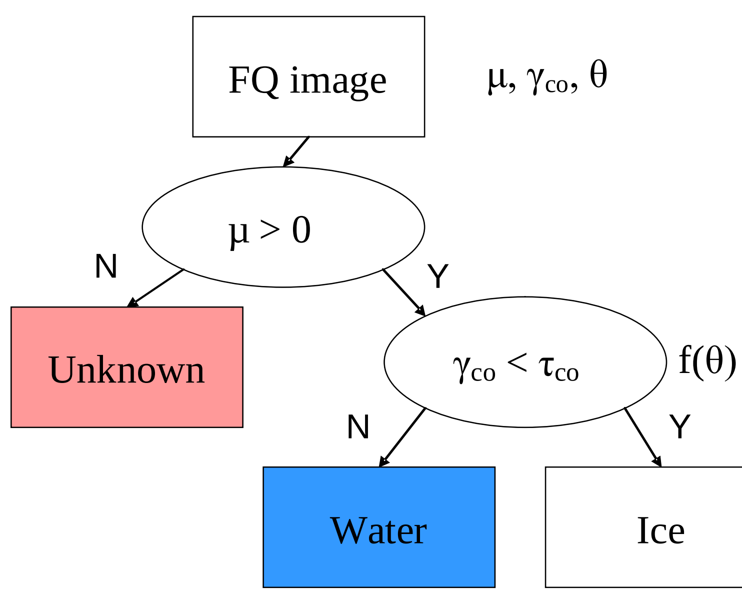

Figure 6. Decision tree classifier for ice versus open water during freeze-up.

A mode filter (**7x7**) should be applied following the decision tree classification. An example of a freeze-up classification is shown in Figure 7.

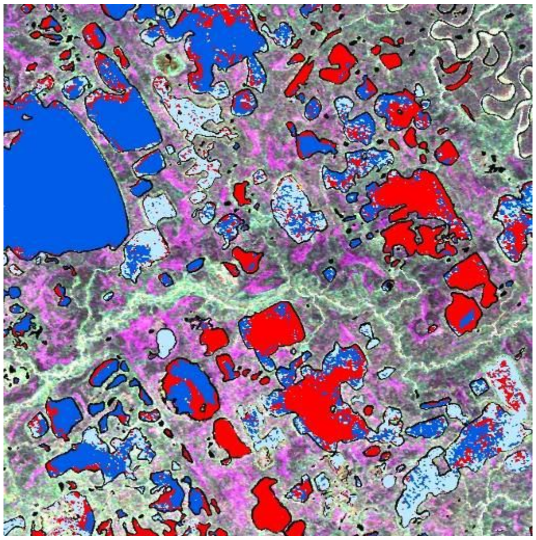

Figure 7. Classified RADARSAT-2 image during freeze-up. Pixels are classified only within the lake polygons: open water (blue), ice (light blue), unknown (red) ($\mu < 0$). Background image is RGB=HH, HV, VV.

3.5 Considerations

3.5.1 Intermittent break-up

During the freeze-up season, ice may form, break-up due to wind and/or warm temperatures, and reform several times before a final robust ice cover forms. Wind speeds > 5 m/s (18 km/h) are associated with break-up of thin ice covers (Ashton, 1986). Wind speed should be evaluated throughout the freeze-up season to identify possible break-up events. This includes both hourly wind speeds, as well as maximum daily gust data. Intermittent break-up images should be kept and used; the latest/final freeze-up date is mapped.

This information helps when assessing possible causes for unexpected freeze-up season open water classification (see next two considerations).

3.5.2 Moist snow issue

If a late freeze-up season image is unexpectedly classified as mostly open water, and no wind-induced break-up is suspected, then there may be moist/wet snow on the ice. Under such conditions, the ice/water appearance will typically be mottled (Figure 3). If this occurs, the classification is omitted from further analysis or mapping.

Although an algorithmic check can be done for moist snow during the break-up season, this is not viable during freeze-up. Therefore, manual assessment for the mottled texture is necessary to omit imagery. Air temperature and precipitation data can usually support the inference of a moist snow surface.

3.5.3 Flooding issue

Another possible complication is the flooding of a lake ice surface by water infiltrating from below through cracks. This occurs when the snow accumulation is sufficiently heavy to depress the ice surface below the water level. Such a situation can readily occur early in the winter while the ice is still thin. As with the moist snow issue, the image may be classified with open water. The texture may also be mottled, but more extensive water areas may be classified near large cracks. Inference of flooding must be accompanied by supporting snow thickness data. Flooded images should be omitted from subsequent mapping, because they will provide incorrectly late freeze-up dates.

A balance equation to estimate the snow thickness (h_s) required for flooding is provided by Ashton (1986):

$$h_s = \frac{\rho_s - \rho_i}{\rho_s} h_i$$

where ρ_s is the snow density, ρ_i is the ice density (~ 900 kg/m^3), and h_i is the ice thickness. For example, assuming an average snow density of 300 kg/m^3, ice flooding can be expected when the snow thickness exceeds half the ice thickness.

3.6 Map ice-on dates

Once images for the freeze-up period are classified (and omitted if necessary), they are then used within a mapping procedure to create an ice-on date map.

3.6.1 Ice concentration

The initial step is to assess lakes on a per-lake basis for ice concentration:

Calculate ice and water concentrations per lake polygon.

- If a lake polygon ice concentration is ≥ 90% ice, then the lake polygon is considered ice-covered;

- Else if a lake polygon water concentration is > 10% water, then it is considered to have open water.
- Else the lake polygon is considered unknown.

Examples:
- If a lake has 90% ice and 10% water, the lake is frozen.
- If a lake has 90% ice and 10% unknown, the lake is frozen.
- If a lake has 11% water and 89% ice, the lake is open water.
- If a lake has 11% water and 89% unknown, the lake is open water.

- Extreme unknown case:
    - If a lake has 89% ice, 10% water, and 1% unknown, the lake is unknown.

By potentially having lakes classified as unknown, there will likely be cases where the ice-on date will be estimated from images several dates apart. This will result in additional ice-on dates, with higher ± days uncertainties. The attribute table should include a class “Always Unknown”.

3.6.2 Mapping procedure

Beginning with a completely ice-covered classified image (some lake may remain unknown), work backwards in time. This procedure maps the final ice-on date for each lake polygon. Ice may form and break-up one or more times before final freeze-up; that is why the procedure works backwards.

Assess each earlier classified image in turn. A lake is assigned an ice-on date that is midway between: 1) the date on which its ice concentration is < 0.9 for the first time; and 2) the date on which it was last ≥ 0.9. Lakes that are “Unknown” within a classification should be skipped. Therefore, the midpoint date may not always be between temporally adjacent classifications. The uncertainty of the ice-on date (± days) is half of the date range between two valid classifications (Table 3). There are various ways to run the logic.

Table 3. Example of ice-on date assignments, and their uncertainty; values may be rounded.

Image date (DOY)	Lake A	Lake A ice-on date, uncertainty	Lake B	Lake B ice on date, uncertainty	Lake C	Lake C ice on date, uncertainty
304	Ice 100%		Ice 100%		Ice 100%	
				295, 10		
285	Ice 95%		Ice 85%		Unknown	291, 14
		281, 4				
277	Ice 50%		Ice 40%		Ice 70%	

Both *ice-on date* and *uncertainty* (± days) should be values associated with each lake polygon within a study area. The final ice-on date map should be a vector file type with attributes.

A lake may be mapped as "Unknown" if all of its pixels consistently have $\mu < 0$. A lake may also be mapped as "Before first date" if its ice concentration is ≥ 0.9 for all classified images. Similarly, a lake may be mapped as "After last date" if it does not reach an ice concentration ≥ 0.9 by the latest classified image.

A sample ice-on date shape-file is shown in Figure 8. DOY values have been changed to YYYYMMDD.

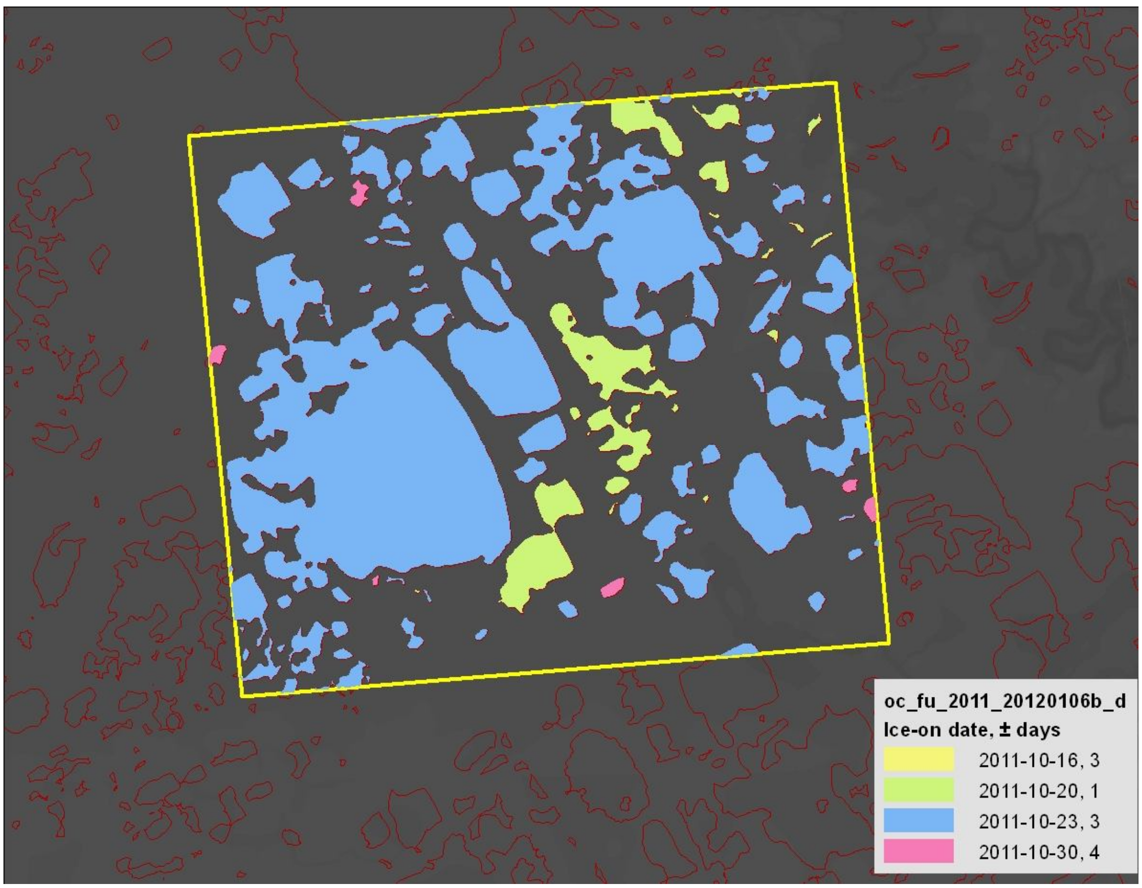

Figure 8. Sample shape-file of ice-on dates and their uncertainty. Background is a DEM.

4 References

Ashton, G.D. (Ed.), 1986. *River and Lake Ice Engineering*. Water Resources Publications, LLC. Colorado, USA. 473 p.

Geldsetzer, T., van der Sanden, J. and Brisco, B., 2010. Monitoring lake ice during spring melt using RADARSAT-2 SAR. *Canadian Journal of Remote Sensing*, 36(2): S391-S400.

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