Assimilation of high resolution satellite data for improved ice cover

K. A. Scott, L. Wang, and D. Clausi
Department of Systems Design Engineering, University of Waterloo, Canada
Contributions from Mark Buehner, Lynn Pogson and Tom Carrieres from CMC and CIS
Outline

• Introduction to data assimilation
• Benefits and challenges with using data from SAR (synthetic aperture radar)
• Retrieval of observations
  • Ice concentration from SAR
  • Ice/water from SAR
• Assimilation of observations – method and results
• Related work using VIS/IR
• Future work
The data assimilation cycle

Source: T. Carrieres
Updating the state estimate

- There are many methods used to carry out data assimilation
- Most result in an analysis increment that can be written as:

\[
\delta x = B H^T (H B H^T + R)^{-1} (y - H(x_b))
\]

- \(\delta x\) – analysis increment \((x_a - x_b)\)
- \(x_a\) – analysis (optimal state)
- \(x_b\) – background state
- \(y\) – observations
- \(H\) – observation operator
- \(B, R\) error covariance matrices
Sea ice concentration from passive microwave data: Retrieval under cold conditions

Source: Alec Casey, York U
How can we use data from SAR to improve sea ice concentration estimates?

<table>
<thead>
<tr>
<th>Observation</th>
<th>PRO</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice/water</td>
<td>Mature methods exist to retrieve ice/water</td>
<td>Binary data – difficult to map to ice concentration</td>
</tr>
<tr>
<td>Ice concentration</td>
<td>Easy to assimilate – ice concentration is a model variable</td>
<td>Methods to retrieve ice concentration under development</td>
</tr>
</tbody>
</table>
Study region for SAR – Gulf of St Lawrence (GSL)

- January 17\textsuperscript{th} - 31\textsuperscript{st} 2014
- Freeze up, mostly new ice on the 17\textsuperscript{th}, thicker ice (30cm) by the 31\textsuperscript{st}
- Observations:
  - SAR data
Background state: Ice-Ocean-Atmosphere Model

- Output from the analysis system at CMC
  - Ice model – CICE
  - Ocean model – NEMO
  - Atmosphere - GEM

- Grid resolution approx 4km
- Currently not coupled to the model
  (calculating analyses)
Retrieval of ice concentration from SAR imagery
Previous work has used *engineered features* in a neural network to estimate ice concentration (Karvonen, 2012, 2014).

These features are dependent on region and season.

Retrieval of ice concentration using SAR data

Adapted from Karvonen 2014
How does a Convolutional Neural Network (CNN) learn ice concentration?

- CNN *learns features* directly from the images (LeCun, 2014)
- May be easier to apply to different regions and seasons
Features learned – 100 % Ice
Features learned – 100% Water

Input patches
100% water

CNN
Features learned – 20% ice

Input patches
Ice (20%)

CNN
CNN results: New Ice (January 17, 2014)
CNN results: Wind roughening

Ice Concentration (CNN)

Ice
Water

Ice/water
CNN results: Impact of patch size

- 25x25 - 10km x 10km
- 35x35 - 14km x 14km
- 45x45 - 18km x 18km
- 55x55 - 22km x 22km
Retrieval of ice/water from SAR imagery
Retrieval of ice/water from SAR

- Use image analyses as training data
- Calculate a probability of ice and water using Bayes theorem
- Threshold probabilities to obtain ice/water observations
Data Assimilation
Data assimilation approach

\[
J[x] = \frac{1}{2} (x - x_b)^T B^{-1} (x - x_b) + \frac{1}{2} (y - H(x))^T R^{-1} (y - H(x))
\]

- $x$ – analysis (optimal state)
- $x_b$ – background state
- $y$ - observations
- $H$ – observation operator
- $B, R$ error covariance matrices
Assimilation of ice/water from SAR

Scott et al., Tellus 2015
Ice concentration analyses – January 17th

Background state
SAR IC observations
SAR IC analysis
SAR ice/water observations
SAR ice/water analysis
Ice concentration analyses – January 31\textsuperscript{th}

SAR IC observations

SAR IC analysis

SAR ice/water

SAR ice/water analysis

SAR image
Comparison between image analysis charts and DA output

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \text{Abs}(\text{IC}<em>{\text{chart}} - \text{IC}</em>{\text{ana}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.245 +/- .0023</td>
</tr>
<tr>
<td>SAR SIC</td>
<td>0.197 +/- .0017</td>
</tr>
<tr>
<td>SAR Ice/water</td>
<td>0.212 +/- .0018</td>
</tr>
</tbody>
</table>
Related work assimilating data from AVHRR
Related work assimilating data from AVHRR

Scott et al. RSE 2012
Future Work

• Should we consider spatially correlated observation errors in the assimilation of SAR image data?

\[ x_a = x_b + K(y - H(x_b)) \]
Concluding remarks

• Both ice/water and ice concentration observations from SAR imagery can be retrieved and assimilated
• Impact of SAR observations on the sea ice state is positive
• More research is required on the retrieval of ice concentration from SAR
• These methods can also be applied to the assimilation of information over lakes

All RADARSAT images shown are
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Extra Slides
Ice thickness can also be retrieved from IR data

Ice thickness can be retrieved from ice surface temperature (IST) using a heat balance equation

\[ F_{l}^{dn} - F_{l}^{up} + F_{sens} + F_{lat} + F_{cond} = 0 \]

\[ F_{cond} = \frac{k_{i}(T_{freez} - T_{surf})}{h_{i}} \]
Reasons for limited range of ice thickness values?

\[
F_{\text{cond}} = \frac{k_i (T_{\text{freez}} - T_{\text{surf}})}{h_i}
\]
Can we average ice/water obs to get ice concentration?

- Choose state so concentration of ones in an interval (20 points) increases linearly

- Sample observations from the true state
  - If $IC_{true} = 0$, obs = 10 + error
  - If $IC_{true} = 1$, obs = 20 + error
Can we average ice/water obs to get ice concentration?
How does a CNN learn ice concentration?

A CNN applies multiple layers where each layer has 3 operations:
- Convolution filter – produces a set of features
- Nonlinear activation – selects features that continue to the next layer
- Subsampling – reduces dimension of data set

http://deeplearning.net/tutorial/lenet.html
Motivation to use image analysis charts

- CNN and ice/water from SAR trained using image analysis charts
- ASI SIC uses passive microwave data, trained using Arctic conditions
- ASI significantly underestimates ice concentration in the region
Retrieval of ice concentration from passive microwave data - Method

- Based on 10.65 GHz (low frequency to reduce atmospheric contamination)
- Use image analysis charts as training data make two histograms
  - One that represents pr10 values for points where SIC(ImA) > 0.9
  - One that represents pr10 values for points where SIC(ImA) == 0

Markus et al. 2009
Retrieval of ice concentration from passive microwave data – comparison with image analyses.

$L_1(SIC(ASI)-SIC(ImA)) = 0.305$

ASI Ice concentration

$L_1(SIC(pr10)-SIC(ImA)) = 0.100$

PR10 ice concentration

Ice concentration from image analysis chart
Retrieval of ice concentration from passive microwave data – comparison with image analyses

\[ L_1(\text{SIC(pr10)-SIC(ImA)}) = 0.100 \]
\[ L_1(\text{SIC(ASI)-SIC(ImA)}) = 0.305 \]