Validation of NOAA Interactive Snow Maps in the North American region with National Climatic Data Center Ground-based Data

Christine Chen
CUNY City College
ABSTRACT

Both the areal coverage of snow and the volume of water in its subsequent melt are of concern for the creation and maintenance of both hydroelectric power and local water supply. The interactive multisensor snow and ice mapping system (IMS) is a geographic interactive system that allows for both the viewing of various sensor data and the mapping daily both snow and sea ice extent by an analyst on one platform.

This thesis investigates the agreement between the National Oceanic and Atmospheric Administration’s (NOAA) interactive multisensor snow and ice mapping system (IMS) and snow depth values obtained from the National Climatic Data Center’s (NCDC) observing stations in the North American region between 30 – 60° North latitude and 60 – 140° West longitude throughout January 2006 – February 2010.

A comparative analysis is made on the basis of land cover, snow type, and snow depth. The first comparison is the most basic comparison. It is a general comparison station-by station between the two datasets. The second, third, and fourth comparisons are all attempts to further the analysis between the interactive multisensor snow and ice mapping system and National Climatic Data Center observing stations. The motivation behind these comparisons is to shed light on the strengths and weaknesses of the NOAA interactive multisensor snow and ice mapping system at different conditions. This knowledge may then be used for future IMS product development. The second and third comparisons involve supplemental datasets. These supplemental datasets are used to examine the role and effects of land classes and snow classes. A 0.5 km AVHRR land classification dataset is used in the second comparison. A 1 km snow classification dataset...
is used in the third comparison. The fourth comparison is an investigation into the effects of snow depth. In this case, the agreement between the NOAA interactive multisensor snow and ice mapping system (IMS) and snow depth values obtained from the National Climatic Data Center’s (NCDC) observing stations is determined upon the placement of the stations into prescribed snow depth intervals.

The results from the first comparison show a good agreement between the National Oceanic and Atmospheric Administration’s (NOAA) interactive multisensor snow and ice mapping system (IMS) and snow depth values obtained from the National Climatic Data Center’s (NCDC) observing stations. The agreement ranges from 79% - 100% throughout the study period. The results from the second comparison suggest that the correlation (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the National Climatic Data Center snow depth values are higher for woodland and wooded grassland than the grassland and cropland. More insight as to the relation in the correlation (%) ranges for the select land classes may be determined through further investigation. This may include investigations based on location or snow depth. The results from the third comparison suggest that the agreement between the two datasets is stronger for the ephemeral snow class and weaker for the maritime, warm taiga, and prairie snow classes. The higher values of correlation (%) for the ephemeral snow class is likely due to a larger number of match situations in which the NCDC observing station records 0 cm (no snow) and the IMS result is land (no snow). The results from the fourth comparison suggest that the agreement between the IMS and NCDC observing stations increases with increasing snow depth.
ACKNOWLEDGEMENTS

I would like to thank Tarendra Lakhankar for all of his guidance throughout this project. Thank you for our weekly meetings. I really appreciated your help and understanding when I got started with computer programming in MATLAB. I am always grateful for your comments and reviews.

I would also like to thank NOAA CREST researcher Peter Romanov for his valuable insight and advice. I am lucky to have someone with your expertise on my side.

I would like to express my gratitude to Reza Khanbilvardi for his time and input into this project. Thank you for your input and your advice during the meetings with research group. I feel your comments always push me and my research to a new level.

I am grateful for our visit to the National Ice Center and the fruitful discussions with Sean Helfrich and Pablo Clemente Colon. It is through this visit that we received insight into the IMS product firsthand.

Thanks to my family for all their support throughout my graduate studies at The City College of New York. I would not have gotten this far without you.

Thanks to all the NOAA Cooperative Remote Sensing Science and Technology (CREST) staff, faculty, and students. NOAA CREST played a large role during my time at The City College of New York and I want to thank the center for the opportunity to participate in the student technical seminar series, early career scientist summer exchange, and various conferences.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>SECTION TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 NOAA IMS PRODUCT</td>
<td>3</td>
</tr>
<tr>
<td>1.2 NCDC SNOW DEPTH RECORDS</td>
<td>7</td>
</tr>
<tr>
<td>1.3 OBJECTIVE</td>
<td>8</td>
</tr>
<tr>
<td>2 STUDY AREA AND DATA SETS</td>
<td>9</td>
</tr>
<tr>
<td>3 METHODOLOGY AND ANALYSIS</td>
<td>10</td>
</tr>
<tr>
<td>3.1 GENERAL COMPARISON</td>
<td>11</td>
</tr>
<tr>
<td>3.1.1 METHODOLOGY</td>
<td>12</td>
</tr>
<tr>
<td>3.1.2 ANALYSIS</td>
<td>17</td>
</tr>
<tr>
<td>3.2 COMPARISON INVOLVING LAND TYPE</td>
<td>19</td>
</tr>
<tr>
<td>3.2.1 METHODOLOGY</td>
<td>21</td>
</tr>
<tr>
<td>3.2.2 ANALYSIS</td>
<td>25</td>
</tr>
<tr>
<td>3.3 COMPARISON INVOLVING SNOW TYPE</td>
<td>30</td>
</tr>
<tr>
<td>3.3.1 METHODOLOGY</td>
<td>32</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Polar stereographic interactive multisensor snow and ice mapping system image of the Northern Hemisphere taken from January 1, 2007. The sea is blue, the land is green, the red is snow, and the orange is sea ice.</td>
<td>4</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Polar stereographic weekly image of the Northern Hemisphere taken from April 21 – 27, 1998. The weekly image is the predecessor of the daily interactive multisensor snow and ice mapping system product (Source: Ramsay 1998).</td>
<td>5</td>
</tr>
<tr>
<td>Figure 3</td>
<td>The cooperative, first order, and second order National Climatic Data Center observing stations selected for the study are in red. Selected stations meet the criteria of having at least one snow depth observation within the study period and are present in the 30 – 60°N latitude and 60 – 140°W longitude study area.</td>
<td>9</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Station-wide comparisons are performed in an attempt to validate the interactive multisensor snow and ice mapping system product. The comparisons may include ancillary data such as snow classification or land classification data.</td>
<td>10</td>
</tr>
<tr>
<td>Figure 5</td>
<td>A processed interactive multisensor snow and ice mapping system image from January 1, 2007. The processing involves cropping the original image down to the study area of interest.</td>
<td>13</td>
</tr>
</tbody>
</table>
Figure 6  The correlation between the interactive multisensor snow and ice mapping system product snow extent and National Climatic Data Center snow depth records. The overall agreement is good and ranges from 79% - 100%. ................................................................. 18

Figure 7  The global Advanced Very High Resolution Radiometer (AVHRR) land cover classification dataset. It has a spatial resolution of 1 kilometer (GLCF-UMaryland 2010). ....... 19

Figure 8  A processed global AVHRR land cover classification dataset image. The processing involves cropping the original image down to the study area of interest. ................................................. 21

Figure 9  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as woodland................................................................. 27

Figure 10  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as wooded grassland................................................................. 27

Figure 11  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as grassland................................................................. 28

Figure 12  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as cropland................................................................. 28
Figure 13 The global snow classification data at a spatial resolution of 270 arc second. The dataset contains 8 classes. (Liston 2010)

Figure 14 A processed global snow cover classification dataset image. The processing involves cropping the original image down to the study area of interest.

Figure 15 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as maritime.

Figure 16 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as ephemeral.

Figure 17 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as prairie.

Figure 18 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as warm taiga.

Figure 19 The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between trace – 3 cm.
Figure 20  The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between 3 cm – 6 cm. ................................................................. 47

Figure 21  The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between 6 cm – 9 cm. ................................................................. 47

Figure 22  The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between 9 cm – 12 cm. ................................................................. 48

Figure 23  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as evergreen needle leaf forest. ................................................................. 55

Figure 24  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as deciduous broadleaf forest. ................................................................. 56

Figure 25  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as mixed forest. ............................................................................. 56
Figure 26 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as closed shrub land. .......................................................... 57

Figure 27 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as open shrub land. .......................................................... 57

Figure 28 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as bare ground. .......................................................... 58

Figure 29 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as urban and built. .......................................................... 58

Figure 30 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as tundra. .......................................................... 59

Figure 31 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as cold taiga. .......................................................... 60
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1  A table showing the distribution of the National Climatic Data Center stations over each land class. There are no stations identified as evergreen broadleaf forest or deciduous needle leaf forest.</td>
<td>24</td>
</tr>
<tr>
<td>Table 2  A table showing the distribution of the National Climatic Data Center stations for the selected land classes. Selection was based on the number of stations in a particular land class. More stations are preferred for the analysis.</td>
<td>26</td>
</tr>
<tr>
<td>Table 3  A table showing the distribution of the National Climatic Data Center stations over each snow class. There are no stations identified as ice.</td>
<td>35</td>
</tr>
<tr>
<td>Table 4  A table showing the distribution of the National Climatic Data Center stations for the selected snow classes. Selection was based on the number of stations in a particular snow class. More stations are preferred for the analysis.</td>
<td>37</td>
</tr>
</tbody>
</table>


THE USE OF VISIBLE AND NEAR INFRARED REGION OF ELECTROMAGNETIC SPECTRUM FOR SNOW COVER USE IS KNOWN. SNOW EXTENT WAS ONE OF THE FIRST GEOPHYSICAL MEASUREMENTS MADE BY SATELLITES AND WAS
created through use of VIS/near IR. These measurements were then incorporated into snowmelt-runoff models. The earliest satellites for snow mapped the snow extent, like the Landsat Multispectral Scanning Subsystem (MSS), the Landsat Thematic Mapper (TM), and the NOA, Advanced Very High Resolution Radiometer (AVHRR). Hyperspectral instruments are also used to measure snow (Dozier and Painter 2004).

Visible imagery for snow extent has a few limitations. These include when the sun is not that bright, it is cloudy, the canopies are so thick and bunched together that the snow on the floor cannot be measured or cannot be measured accurately, and discriminating between snow and clouds in a mountainous area. The brightness of the sun is not an issue for passive microwave imagery for snow extent and generally this is true for cloudy sky conditions as well. However, it has trouble in certain land conditions (ie. highly vegetated areas) or snow conditions (ie. patchy, shallow and/or wet) (Robinson and Frei 2000). The advantages of microwave data include the ability to see through cloudy conditions and at night time (Lo 1986; Ferraro, Weng et al. 1996; Ramsay 1998).

Remotely sensed snow cover products are typically compared against a separate snow product or against in situ ground based observations during validation. Comparisons may explore the accuracy of a snow map as a function of land cover or snow depth (Hall, Riggs et al. 2006; Xie, Song et al. 2010).

Xie et al (2010) explores the validation of both snow cover and snow water equivalent (SWE) data for Advanced Microwave Scanning Radiometer – EOS (AMSR-E) and Moderate-Resolution Imaging Spectroradiometer (MODIS) over the Heilongjiang basin for winters between 2002 and 2007. Both MODIS snow cover maps and AMSR-E snow water equivalent
(SWE) data were compared to ground based observing stations. The stations provided snow depth data among other things. An underestimation of AMSR-E was found to occur during the accumulation and ablation periods of October – November and March – April (Xie, Song et al. 2010).

Brubaker et al (2005) validates both the Interactive Multisensor Snow and Ice Mapping System (IMS) and Moderate-Resolution Imaging Spectroradiometer (MODIS) snow cover product by comparing them to the data obtained from cooperative and SNOTEL observing stations in the continental US for the year 2000. IMS product with 24 kilometer spatial resolution was used during investigation (Brubaker, Pinker et al. 2005). It was found that during the snow accumulation period, both MODIS and IMS snow products were increasing in accuracy in detecting snow but decreasing in accuracy in detecting snow-free areas.

1.1 NOAA IMS PRODUCT

The interactive multisensor snow and ice mapping system (IMS) is a geographic interactive system that allows for both the viewing of various sensor data and the mapping of both snow and sea ice extent by an analyst on one platform. The completed snow and sea ice image (Figure 1) may be saved on the same system (Ramsay 1998).
Figure 1  Polar stereographic interactive multisensor snow and ice mapping system image of the Northern Hemisphere taken from January 1, 2007. The sea is blue, the land is green, the red is snow, and the orange is sea ice.

The daily interactive multisensor snow and ice mapping system products are used by the National Weather Service (NWS) for numerical weather forecasting (Foster and Chang 1993; Ramsay 1998). The accuracy of snow extent affects the models. Higher accuracy leads to improvements in forecasting (Helfrich, McNamara et al. 2007). Snow and ice maps are also important to studies of climate (Robinson, Dewey et al. 1993; Ramsay 2000). The daily IMS maps replace weekly maps of snow and sea ice extent drawn by hand which are an important climate data record (Ramsay 1998). The IMS products, daily charted snow and sea ice maps, are used by the National Weather Service (NWS) for numerical weather forecasting (Foster and Chang 1993; Ramsay 1998).
The weekly maps, the predecessor to the interactive multisensor snow and ice mapping system, have been drawn by the analysts of the NOAA since 1966. The maps depict the snow and sea ice extent within the Northern Hemisphere using visible satellite imagery and in situ data (Ramsay 1998). A weekly map from the week of April 21 – 27 1997 is shown below.

Figure 2  Polar stereographic weekly image of the Northern Hemisphere taken from April 21 – 27, 1998. The weekly image is the predecessor of the daily interactive multisensor snow and ice mapping system product (Source: Ramsay 1998).

The production process of the weekly polar stereographic maps would take up to 10 hours. The completed maps would be digitized with a superimposed grid (Ramsay 1998).
The daily interactive multisensor snow and ice mapping system products serve as a replacement for the weekly snow maps (Matson and Wiesnet 1981; Matson, Ropelewski et al. 1986; Ramsay 1998). The weekly charts were created from 1966 to 1999. The IMS has been operational since 1997, allowing for a two year overlap between the two maps. Advantages of the interactive multisensor snow and ice mapping system product over the weekly product include an increase in the number of satellite source imagery, improved completion times, and an increased spatial resolution (Ramsay 2000).

An analyst will typically use multiple sources within the interactive multisensor snow and ice mapping system to determine the snow and sea ice extent. The analyst begins charting using the map from the previous day, then uses the satellite inputs accordingly. It takes anywhere from 1 – 5 hours for the analyst to chart an IMS snow and sea ice extent map (Helfrich, McNamara et al. 2007).

The interactive multisensor snow and ice mapping system was originally available in a spatial resolution of 23 kilometers. Improvements in computer processing have led to the availability of the IMS product at a spatial resolution of 4 kilometers (Helfrich, McNamara et al. 2007). Source imagery for the IMS includes special sensor microwave/imager (SSM/I) automated snow maps, station data, snow maps from the previous day, and satellite imagery from the visible range (Ramsay 1998). Continuous improvements are made to the IMS. These include the addition of other satellite imagery, such as channel 3A of the advanced very high resolution radiometer (AVHRR), channel 1 of Moderate-Resolution Imaging Spectroradiometer (MODIS), and the addition of an automated first guess extent map (Ramsay 2000; Helfrich, McNamara et al. 2007).
1.2 NCDC SNOW DEPTH RECORDS

The National Climatic Data Center (NCDC) snow depth records include recordings made by cooperative, first order, and second order stations (NCDC 2005; NCDC 2009). A majority of the cooperative station observers are volunteers. The first and second order stations on the other hand are manned by certified observers. The quality of the data is maintained by computer and by hand. This includes comparing the station values with surrounding stations (NCDC 2009).

Schools, state cooperatives, and the National Weather Service (NWS) provide data from cooperative stations. The start date of this data varies by state. Some of the earliest records are from 1948 while others are from 1946. Some data collected by state universities and organizations is available before 1946. Most of the measurements are made either at 7 AM or 7 PM local time. Records of snow depth at observation time are made to the closest inch. A trace value is recorded in cases where there is less than half an inch. A missing value is recorded in cases where no measurement is made (NCDC 2009).

First order station data is obtained from the National Weather Service (NWS), the US Air Force, the US Navy, and the Federal Aviation Administration. Most of the data is from the 1940s, although a few are from the 1890s. A majority of the recordings are made at 12 Greenwich Mean Time, although records from stations in Alaska and part time stations are made at a different time. The snow depth at observation time is recorded to the closest inch. A trace value is recorded in cases where there is less than half an inch. A missing value is recorded in cases where no measurement is made (NCDC 2005).
1.3 OBJECTIVE

This study will explore North American snow coverage through the validation of NOAA/NESDIS’ interactive snow maps with NOAA/NCDC ground-truth data. The daily snow coverage record of the North American region of NOAA’s interactive multisensor snow and ice mapping system (IMS) product is compared to the daily National Climatic Data Center (NCDC) snow depth archives. Upon the confirmation of geographical correspondence between the two maps on a given day, the maps will be analyzed for statistics of correspondence in areas such as land classification (e.g. grassland, mixed forest, bare ground), snow classification (e.g. ephemeral, prairie, warm taiga) and snow depth intervals (e.g. trace - 3 cm, 6 - 9 cm, 9 - 12 cm).
2 STUDY AREA AND DATA SETS

Daily maps over the course of the January 2006 - February 2010 period are obtained for the IMS snow product. Snow depth data from observing stations is obtained from the ‘at observation time / snow, ice pellets, hail, ice on ground (inches) section of the ‘surface summary of the day, continental U.S.’ dataset of the National Climatic Data Center. The NCDC stations used in this study are shown in Figure 3 below.

Figure 3 The cooperative, first order, and second order National Climatic Data Center observing stations selected for the study are in red. Selected stations meet the criteria of having at least one snow depth observation within the study period and are present in the 30 – 60°N latitude and 60 – 140°W longitude study area.

The January 2006 - February 2010 period allows for coverage over more than three complete snow seasons. The study area consists of the American and Canadian regions between 30 to 60 degrees North latitude and between 60 to 140 degrees West longitude.
3 METHODOLOGY AND ANALYSIS

The snow extent of NOAA/NESDIS’ Interactive Multisensor Snow and Ice Mapping System (IMS) product is validated through a station by station comparison with in situ observations from the National Climatic Data Center. Prior to the station by station comparison, the data from both the IMS product and the NCDC observing stations undergo processing and filtering.

Figure 4 Station-wide comparisons are performed in an attempt to validate the interactive multisensor snow and ice mapping system product. The comparisons may include ancillary data such as snow classification or land classification data.

Four comparisons are made between the IMS product and the in situ data. They include a general comparison, a comparison with an emphasis on land type, a comparison with an emphasis on snow type, and a comparison with an emphasis on snow depth through the use of defined snow depth intervals. The results of this study may be used to determine the strengths and weaknesses of the Interactive Snow and Ice Mapping System and may be used to improve upon the current Interactive Multisensor Snow and Ice Mapping system.
In the following pages, each of the comparisons are discussed one by one in the following order: general comparison, comparison involving land type, comparison involving snow type, comparison involving snow depths. Each section includes a discussion of the primary objective of the particular comparison, the methodology used in making the comparison, as well as an analysis of the results. MATLAB is used to process and analyze all the data. ENVI and Geomatica were used for a small portion of the processing for the comparison involving land type.

### 3.1 GENERAL COMPARISON

A general comparison is made to examine the correlation between the snow extent of the Interactive Multisensor Snow and Ice Mapping System and the snow depth values of the National Climatic Data Center observing station data. The correlation percentage is plotted on a daily basis from January 2006 – February 2010. The daily correlation percentage is determined as follows:

\[
\text{Correlation (\%)} = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = Σ stations in either of:

- Situation I: station snow depth > 0 and IMS = snow
- Situation II: station snow depth = 0 and IMS = land (no snow)

and Mismatch = Σ stations in either of:

- Situation I: station snow depth > 0 and IMS = land (no snow)
- Situation II: station snow depth = 0 and IMS = snow
Observing stations having a missing snow depth value (i.e. no record was made that day) are not taken into the calculation of the correlation (%). In such an event, it is impossible to classify the event as a match or mismatch situation.

3.1.1 METHODOLOGY

Daily 4 kilometer Interactive Multisensor Snow and Ice Mapping System images from January 1, 2006 – February 28, 2010 were downloaded via FTP. While an image was available for a substantial portion of the study period, there were certain days in which no image was available. For year 2006, these include days 185, 186, 187, and 188. For year 2007, these include days 72, 73, 300, and 332. For year 2008, this includes day 71. For year 2009, these include days 69, 70 and 85 (NSIDC 2004). Latitude and longitude grids corresponding to the 4 kilometer IMS images were downloaded via FTP as well. These latitude and longitude grids are in degree decimal format.

The daily snow depth records at observing stations were obtained by downloading the Summary of the day, continental U.S. data from the National Climatic Data Center via FTP. This data was available for download upon request of both state and time period. For example, one may request the Summary of the day, continental U.S. data for the state of California during January 1, 2006 – February 28, 2010. This would include all the data for the cooperative and first order stations within California during that time period. Of particular interest for this research project are the snow depth records within the Summary of the day, continental U.S. data record. These snow depth records include ice pellets, hail and ice. The station data include the specifics of latitude and longitude in degree minutes format.
The processing for the Interactive Multisensor Snow and Ice Mapping System images include cropping the daily polar stereographic Northern Hemispherical images down to the study area of interest to improve processing speed. A sample image is found below in Figure 5. The sea is dark blue, the land is light blue, the snow is red, and the sea ice is yellow.

![Processed interactive multisensor snow and ice mapping system image from January 1, 2007. The processing involves cropping the original image down to the study area of interest.](image)

A pixel within an Interactive Multisensor Snow and Ice Mapping system image may either alternate between a sea and sea ice combination or a snow and land combination. Therefore, in our investigation of snow extent, we are only looking at the snow and land combination pixels. The result is always binary. The pixels may either be snow or land, also known as no snow.
More processing is involved for the National Climatic Data Center observing station data. In total, 9929 observing stations were found to be within the study area of 30 – 60 degrees North latitude and 60 – 140 degrees West longitude. However, not all the stations were suitable for the study. Stations were selected for the study as long as they had at least one snow depth value recorded within the January 2006 – February 2010 study period and did not correspond to a sea and sea ice pixel combination for the IMS images. Of the 9929 observing stations, 8659 stations (or 87.2%) were selected for further processing.

Further processing of the National Climatic Data Center snow depth recordings include the removal of records coinciding with the missing IMS data days mentioned earlier. No comparison can be made when there is missing data. The latitude and longitude values of the observing stations are converted from degree minute to degree decimal format to match the formatting of the Interactive Multisensor Snow and Ice Mapping System latitude and longitude grids.

This is important because for a given observing station and a given day, it is necessary to locate the proper pixel within the IMS product for the specified station. The proper pixel within an IMS product image for a specified station is determined as follows:

1. The absolute difference between the station latitude coordinate and the latitude grid of the Interactive Multisensor Snow and Ice Mapping system images are calculated for each grid cell. In mathematical terms:

   \[ A = |\text{station latitude coordinate} - \text{latitude value for particular grid cell}| \]

   to be performed over all grid cells, resulting in matrix A.
2. The absolute difference between the station longitude coordinate and the longitude grid of the Interactive Multisensor Snow and Ice Mapping system images are calculated for each grid cell. In mathematical terms:

\[ B = |\text{station longitude coordinate} - \text{longitude value for particular grid cell}| \]

to be performed over all grid cells, resulting in matrix B.

3. The average of the two calculated values from steps 1 and 2 are calculated for each grid cell of the IMS image. In mathematical terms:

\[ C = \frac{A + B}{2} \]

to be performed over all grid cells, resulting in matrix C.

4. The grid cell corresponding to the minimum value of the entire grid obtained from Step 3 is determined to be the IMS pixel corresponding to the latitude and longitude coordinates of a particular observing station. In mathematical terms:

\[ D = \text{minimum value of matrix } C \]

in which D is a single value.

This procedure is repeated for each of the 8659 observing stations.

Those National Climatic Data Center observing stations in which the described procedure results in IMS image pixel values of only sea or sea ice, rather than the preferred snow and land combination, are removed from the study. This situation may occur if the observing station is at a coastal location.
A comparison between a daily Interactive Multisensor Snow and Ice Mapping System image and the daily National Climatic Data Center snow depth values at the 8659 observing stations may be made following the processing of the data. The procedure described earlier is used to determine the proper IMS grid cell corresponding to a particular station latitude and longitude coordinate. Each of the daily IMS images is opened one by one, followed by the determination of the pixel location for a particular station latitude longitude coordinate. The pixel value of that daily IMS image of the specified grid cell is then compared to the NCDC observing station snow depth value for that particular day. This procedure is performed over all 8659 stations before another IMS image is opened and the procedure is repeated.

In each of the comparisons between the pixel value of the daily IMS image of the specified grid cell to a NCDC observing station snow depth value for a particular day, the situation was classified as either ‘match,’ ‘mismatch,’ or ‘missing.’ Details for each of the situations follow. A ‘match’ event occurs under the following situations:

- Situation I: station snow depth > 0 and IMS = snow
- Situation II: station snow depth = 0 and IMS = land (no snow)

A ‘mismatch’ event occurs under the following situations:

- Situation I: station snow depth > 0 and IMS = land (no snow)
- Situation II: station snow depth = 0 and IMS = snow

A ‘missing’ event occurs if the station snow depth is ‘missing’. Comparisons to the IMS are not performed for those ‘missing’.
For a given Interactive Multisensor Snow and Ice Mapping system daily image, a correlation between the image and all the NCDC observing station snow depth values are calculated through the summation of the ‘match’ events and ‘mismatch’ events. The formula for the correlation was described earlier as:

\[
\text{Correlation (\%) = } \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = Σ stations in either of:

**Situation I:** station snow depth > 0 and IMS = snow

**Situation II:** station snow depth = 0 and IMS = land (no snow)

and Mismatch = Σ stations in either of:

**Situation I:** station snow depth > 0 and IMS = land (no snow)

**Situation II:** station snow depth = 0 and IMS = snow

### 3.1.2 ANALYSIS

The correlation (percent) between the IMS image and the snow depth values of the National Climatic Data Center are calculated for each day for the period of January 2006 – February 2010. A plot of the correlation (percent) as a time series is made in Figure 6 below.
Figure 6  The correlation between the interactive multisensor snow and ice mapping system product snow extent and National Climatic Data Center snow depth records. The overall agreement is good and ranges from 79% - 100%.

A cyclical pattern is evident in which the correlation (percent) is the highest during the summer months and lowest during the winter months. The correlation (percent) increases during the snow ablation season (i.e. snow melt) and decreases during the snow accumulation season.

The correlation (percent) between the Interactive Multisensor Snow and Ice Mapping System snow extent and National Climatic Data Center snow depth records range from 79% - 100%. Therefore, the correlation between the two overall is in good agreement all year long during the said study period.

The highest correlations of 100% occur during the summer months. This is likely due to the situation in which the IMS snow extent pixel value is ‘snow’ and the NCDC snow depth reading is 0 inches. This result is not as significant as the other lower correlations. In the other months in which the correlation is less than 100%, this is likely due to the situations in which there is a
mismatch in the values provided by the Interactive Multisensor Snow and Ice Mapping System and the National Climatic Data Center snow depth readings. Therefore it is in these months in which the correlation between the two products is more interesting or significant.

### 3.2 COMPARISON INVOLVING LAND TYPE

An investigation into the effects of land type on the comparison between the snow extent depicted in the Interactive Multisensor Snow and Ice Mapping system and the snow depth values of the National Climatic Data Center observing stations is made in this section. This is made possible through the use of ancillary data. In this case, a global AVHRR 1 km land classification dataset is used to classify the stations into various land types. The land classification dataset may be seen in Figure 7 below.

![Global land cover classification dataset](image)

**Figure 7** The global Advanced Very High Resolution Radiometer (AVHRR) land cover classification dataset. It has a spatial resolution of 1 kilometer (GLCF-UMaryland 2010).

This data, acquired from the University of Maryland Global Land Cover Facility (www.landcover.org), is GeoTIFF-formatted and was created in 1998 through the collection of measurements...
AVHRR images between 1981 and 1994. In total, it contains 14 land classes. They are: water, evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, woodland, wooded grassland, closed shrubland, open shrubland, grassland, cropland, bare ground, and urban and built.

After the stations are classified into various land types, the correlation between the IMS product and the NCDC snow depth data is determined for each land category. Once again, the correlation percentage is plotted on a daily basis from January 2006 – February 2010. The daily correlation percentage is determined as follows:

$$\text{Correlation (\%)} = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100$$

in which Match = Σ stations in either of:

Situation I: station snow depth > 0 and IMS = snow

Situation II: station snow depth = 0 and IMS = land (no snow)

and Mismatch = Σ stations in either of:

Situation I: station snow depth > 0 and IMS = land (no snow)

Situation II: station snow depth = 0 and IMS = snow

Observing stations having a missing snow depth value (i.e. no record was made that day) are not taken into the calculation of the correlation (%). In such an event, it is impossible to classify the event as a match or mismatch situation.
3.2.1 METHODOLOGY

The global 1 kilometer spatial resolution AVHRR land classification dataset was downloaded and opened as a GeoTIFF file using both Geomatica and ENVI. The global image was cropped to the study area of 30 – 60 degrees North latitude and 60 – 140 degrees West longitude. The cropped image was then saved an ASCII file. This ASCII file was used for the remainder of the data processing. The land classification image may be seen in Figure 8 below.

![Land Classification Image](image)

**Figure 8** A processed global AVHRR land cover classification dataset image. The processing involves cropping the original image down to the study area of interest.

Latitude and longitude grids corresponding to the cropped land classification dataset were created in order to determine the proper pixel in the land classification dataset given a station’s latitude longitude coordinates. In creating the latitude grid, the total number of rows in the cropped land classification image was used in combination with the latitude values of the first
and last rows of the cropped land classification image (i.e. 30° N and 60° N) to determine the proper spacing of the latitude values for the latitude grid. Similarly, in creating the longitude grid, the total number of columns in the cropped land classification image was used in combination with the longitude values of the first and last rows of the cropped land classification image (i.e. 60° W and 140° W) to determine the proper spacing of the longitude values for the longitude grid.

After both the latitude and longitude grids have been created, the cropped land classification pixel corresponding to a particular station’s latitude and longitude coordinates may be determined. The procedure has been previously discussed, but is reviewed once more below. In order to determine the proper land classification grid cell corresponding to a particular station’s latitude and longitude coordinates, one may follow these steps:

1. The absolute difference between the station latitude coordinate and the latitude grid of the cropped land classification image are calculated for each grid cell. In mathematical terms:

   \[ A = |\text{station latitude coordinate} - \text{latitude value for particular grid cell}| \]

   to be performed over all grid cells, resulting in matrix A.

2. The absolute difference between the station longitude coordinate and the longitude grid of the cropped land classification image are calculated for each grid cell. In mathematical terms:

   \[ B = |\text{station longitude coordinate} - \text{longitude value for particular grid cell}| \]
to be performed over all grid cells, resulting in matrix B.

3. The average of the two calculated values from steps 1 and 2 are calculated for each grid cell. In mathematical terms:

\[
C = \frac{A + B}{2}
\]

to be performed over all grid cells, resulting in matrix C.

4. The grid cell corresponding to the minimum value of the entire grid obtained from Step 3 is determined to be the cropped land classification pixel corresponding to the latitude and longitude coordinates of a particular observing station. In mathematical terms:

\[
D = \text{minimum value of matrix } C
\]

in which D is a single value.

This procedure is repeated for each of the 8659 observing stations.

Once the corresponding land class grid cells have been obtained for all the observing stations, it is possible to group the observing stations by land class. The number of stations in each land class is specified in Table 1.

After the stations have been grouped by land class, an investigation into the correlation between the Interactive Multisensor Snow and Ice Mapping System images and the daily National Climatic Data Center snow depth values is made on a daily basis from January 2006 – February 2010 by land class group.
<table>
<thead>
<tr>
<th>Land Class</th>
<th>Total Number of NCDC Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>187</td>
</tr>
<tr>
<td>Evergreen Needle leaf Forest</td>
<td>391</td>
</tr>
<tr>
<td>Evergreen Broadleaf Forest</td>
<td>0</td>
</tr>
<tr>
<td>Deciduous Needle leaf Forest</td>
<td>0</td>
</tr>
<tr>
<td>Deciduous Broadleaf Forest</td>
<td>523</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>450</td>
</tr>
<tr>
<td>Woodland</td>
<td>1017</td>
</tr>
<tr>
<td>Wooded Grassland</td>
<td>1370</td>
</tr>
<tr>
<td>Closed Shrub land</td>
<td>341</td>
</tr>
<tr>
<td>Open Shrub land</td>
<td>291</td>
</tr>
<tr>
<td>Grassland</td>
<td>1260</td>
</tr>
<tr>
<td>Cropland</td>
<td>2047</td>
</tr>
<tr>
<td>Bare Ground</td>
<td>33</td>
</tr>
<tr>
<td>Urban and Built</td>
<td>749</td>
</tr>
</tbody>
</table>

Table 1  A table showing the distribution of the National Climatic Data Center stations over each land class. There are no stations identified as evergreen broadleaf forest or deciduous needle leaf forest.

For the stations in a particular land class, the daily Interactive Multisensor Snow and Ice Mapping System images are opened and its snow extent is compared to the daily snow depth values of the National Climatic Data Center in order to determine the correlation (%) for a particular land type. To determine the correlation (%), one must perform the following:

\[
\text{Correlation (\%)} = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = \( \Sigma \) stations in either of:

- Situation I: station snow depth > 0 and IMS = snow
Situation II: station snow depth = 0 and IMS = land (no snow)

and Mismatch = Σ stations in either of:

Situation I: station snow depth > 0 and IMS = land (no snow)

Situation II: station snow depth = 0 and IMS = snow

This procedure is repeated over all land types containing at least one observing station. Evergreen broadleaf forests and deciduous needle leaf forests are not investigated because no stations were found to be in these areas (see Table 1).

In addition to the correlation (%), the percentage of snow covered observing stations is recorded for each day. The percentage of snow covered observing stations may be determined by:

\[
\text{Percentage of NCDC Snow Covered Stations} = \frac{\sum \text{stations in which snow depth} > 0}{\sum \text{stations in which snow depth} \neq \text{missing}} \times 100
\]

3.2.2 ANALYSIS

According to Table 1, there is a large variation in the distribution of the stations among the land classes. While there are as many as 2047 stations found in cropland, there are no stations found in the evergreen broadleaf forests and deciduous needle leaf forests. While it may appear unusual that 187 stations are classified as water, mixed pixels or a coastal location would be a possible reason for this occurrence.

While a time series of the correlation (%) between the snow extent of the Interactive Snow and Ice Mapping system and the snow depth values of the National Climatic Data Center was plotted
for water, evergreen needle leaf forest, deciduous broadleaf forest, mixed forest, woodland, wooded grassland, closed shrub land, open shrub land, grassland, cropland, bare ground, and urban and built, only a select number receive further analysis.

Selection for further analysis is dependent upon the number of observing stations within a particular land type. More stations are preferred for analysis. Therefore, the four classes selected are woodland, wooded grassland, grassland, and cropland. The number of stations found in these land classes is found in Table 2. According to Table 2, the number of observing stations within a land class is all within the same order of magnitude.

<table>
<thead>
<tr>
<th>Land Class</th>
<th>Total Number of NCDC Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodland</td>
<td>1017</td>
</tr>
<tr>
<td>Wooded Grassland</td>
<td>1370</td>
</tr>
<tr>
<td>Grassland</td>
<td>1260</td>
</tr>
<tr>
<td>Cropland</td>
<td>2047</td>
</tr>
</tbody>
</table>

Table 2 A table showing the distribution of the National Climatic Data Center stations for the selected land classes. Selection was based on the number of stations in a particular land class. More stations are preferred for the analysis.

The correlation (%) of the Interactive Multisensor Snow and Ice Mapping system snow extent and the NCDC snow depth data for the select land classes of woodland, wooded grassland, grassland and cropland may be found in Figure 9, Figure 10, Figure 11, and Figure 12 below. The correlation (%) for all other land classes containing at least one observing station may be
found in Appendix I.

Figure 9 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as woodland.

Figure 10 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as wooded grassland.
Figure 11  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as grassland.

Figure 12  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as cropland.
With regards to correlation (%), all four land classes, woodland, wooded grassland, grassland, and cropland appear to have the same cyclical shape wherein the correlation reaches a peak of 100% during the summer months and dip into valleys during the winter months. The correlation (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the National Climatic Data Center snow depth values are higher for woodland and wooded grassland than the grassland and cropland (see Figure 9, Figure 10, Figure 11, and Figure 12). The range of correlation (%) is larger for grassland and cropland spanning between 70 – 100% and 74 – 100%, while the range of correlation (%) for woodland and wooded grassland areas spans between 80 – 100% and 78% - 100%. There is also more consistency, or correlation value clustering, in the values for both woodland and wooded grassland than grassland and cropland.

More insight as to the relation in the correlation (%) ranges for the select land classes may be determined through further investigation. Further investigation may involve the plotting of the stations for a particular land class on a latitude longitude grid on the day containing the largest number of snow-covered NCDC stations. In the plot, the stations would be colored according to the four possible results:

Result I: station snow depth > 0 and IMS = snow

Result II: station snow depth = 0 and IMS = land (no snow)

Result III: station snow depth > 0 and IMS = land (no snow)

Result IV: station snow depth = 0 and IMS = snow
A visual analysis of the plot would then reveal whether there are particular areas in which there is consistent agreement or disagreement. A plot ought to be made for each of the four land classes.

Further analysis may also include an investigation of the land classes as a function of snow depth. This would involve an investigation of the snow depths obtained by the stations in a select land class on a day containing the most snow-covered NCDC stations. It is highly probable that the snow in the land classes achieving lower correlation, grassland and cropland, is patchy, so there would be a lot of disagreement between the IMS snow extent and snow depths of the NCDC. One ought to investigate the effect of snow depth for all four of the selected classes to gain a full understanding in this situation.

Regarding the percentage of NCDC snow covered stations in Figure 9, Figure 10, Figure 11, and Figure 12, it is fairly similar in shape for woodland, wooded grassland, grassland, and cropland. There are more snow covered stations in grassland and cropland, reaching highs of around 40% than in woodland and wooded grassland, reaching highs of around 30%.

### 3.3 COMPARISON INVOLVING SNOW TYPE

An investigation is made on the effect of snow type on the correlation between the snow extent of the Interactive Multisensor Snow and Ice Mapping system images and the snow depth data obtained from National Climatic Data Center observing stations. This is made possible through the use of a global scale 270 arc second snow classification dataset obtained from Dr. Glen Liston, a senior research scientist at Colorado State University’s Cooperative Institute for Research in the Atmosphere. The global scale snow classification dataset is shown in Figure 13 below.
This data is used to classify the stations into various snow types. This snow classification dataset contains 8 snow classes. They are: water, tundra, cold taiga, maritime, ephemeral, prairie, warm taiga, and ice.

After the stations are classified into various snow types, the correlation between the IMS product and the NCDC snow depth data is determined for each snow category. Once again, the correlation percentage is plotted on a daily basis from January 2006 – February 2010. The daily correlation percentage is determined as follows:

\[
\text{Correlation (\%)} = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = \(\Sigma\) stations in either of:
Situation I: station snow depth > 0 and IMS = snow

Situation II: station snow depth = 0 and IMS = land (no snow)

and Mismatch = Σ stations in either of:

Situation I: station snow depth > 0 and IMS = land (no snow)

Situation II: station snow depth = 0 and IMS = snow

Observing stations having a missing snow depth value (i.e. no record was made that day) are not taken into the calculation of the correlation (%). In such an event, it is impossible to classify the event as a match or mismatch situation.

3.3.1 METHODOLOGY

The 270 arc second global snow classification dataset is opened in MATLAB and cropped down to the study area of 30 – 60 degrees North latitude and 60 – 140 degrees West longitude in order to improve processing time. The cropped image is shown in Figure 14 below.
While there are seven categories in the global snow classification dataset, there are only six categories in the cropped snow classification image. As seen in Figure 14, the six categories are: water, tundra, cold taiga, maritime, ephemeral, prairie, and warm taiga. No area in the study area of interest is classified as ice.

Latitude and longitude grids are created for the cropped snow classification dataset to aid in the determination of the proper snow classification grid cell for a particular station latitude and longitude coordinate. These grids were created through the knowledge of the number of rows, number of columns, cell size, and the latitude and longitude values of the grid cell located in the lowest left hand corner. The latitude grid was created through the combination of the number of rows, the latitude value of the lowest left hand corner grid cell, and the cell size. The longitude
grid was created through the combination of the number of columns, the longitude value of the lowest left hand corner grid cell, and the cell size.

The creations of latitude and longitude grids for the cropped snow classification image are used to determine the proper pixel in the snow classification image for particular station latitude and longitude pairing. Given a station’s latitude and longitude coordinates, its classification within the cropped snow classification dataset may be determined by the following:

1. The absolute difference between the station latitude coordinate and the latitude grid of the cropped snow classification image are calculated for each grid cell. In mathematical terms:

   \[ A = |\text{station latitude coordinate} - \text{latitude value for particular grid cell}| \]

   to be performed over all grid cells, resulting in matrix A.

2. The absolute difference between the station longitude coordinate and the longitude grid of the cropped snow classification image are calculated for each grid cell. In mathematical terms:

   \[ B = |\text{station longitude coordinate} - \text{longitude value for particular grid cell}| \]

   to be performed over all grid cells, resulting in matrix B.

3. The average of the two calculated values from steps 1 and 2 are calculated for each grid cell. In mathematical terms:
\[ C = \frac{A + B}{2} \]

to be performed over all grid cells, resulting in matrix C.

4. The grid cell corresponding to the minimum value of the entire grid obtained from Step 3 is determined to be the cropped snow classification pixel corresponding to the latitude and longitude coordinates of a particular observing station. In mathematical terms:

\[ D = \text{minimum value of matrix } C \]

in which D is a single value.

This procedure is repeated for each of the 8659 observing stations.

Once the corresponding snow class grid cells have been obtained for all the observing stations, it is possible to group the observing stations by snow class. The number of stations in each snow class is specified in Table 3 below.

<table>
<thead>
<tr>
<th>Snow Class</th>
<th>Total Number of NCDC Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>47</td>
</tr>
<tr>
<td>Tundra</td>
<td>10</td>
</tr>
<tr>
<td>Cold Taiga</td>
<td>41</td>
</tr>
<tr>
<td>Maritime</td>
<td>1341</td>
</tr>
<tr>
<td>Ephemeral</td>
<td>3861</td>
</tr>
<tr>
<td>Prairie</td>
<td>2795</td>
</tr>
<tr>
<td>Warm Taiga</td>
<td>564</td>
</tr>
<tr>
<td>Ice</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3  A table showing the distribution of the National Climatic Data Center stations over each snow class. There are no stations identified as ice.
After the stations have been grouped by snow class, an investigation into the correlation between
the Interactive Multisensor Snow and Ice Mapping System images and the daily National
Climatic Data Center snow depth values is made on a daily basis from January 2006 – February
2010 by snow class group.

For the stations in a particular snow class, the daily Interactive Multisensor Snow and Ice
Mapping System images are opened and its snow extent is compared to the daily snow depth
values of the National Climatic Data Center in order to determine the correlation (%) for a
particular snow type. To determine the correlation (%), one must perform the following:

\[
\text{Correlation} \, \% = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = \(\Sigma\) stations in either of:

**Situation I:** station snow depth > 0 and IMS = snow

**Situation II:** station snow depth = 0 and IMS = land (no snow)

and Mismatch = \(\Sigma\) stations in either of:

**Situation I:** station snow depth > 0 and IMS = land (no snow)

**Situation II:** station snow depth = 0 and IMS = snow

This procedure is repeated over all snow types containing at least one observing station. The ice
class is not investigated because no stations were found to be in these areas (see Table 3).

In addition to the correlation (%), the percentage of snow covered observing stations is recorded
for each day. The percentage of snow covered observing stations may be determined by:
3.3.2 ANALYSIS

The number of stations in each snow class varies greatly. The number of stations in the maritime, ephemeral and prairie classes is in the thousands, the number of stations in warm taiga is in the hundreds, and the number of stations in the water, tundra, and cold taiga class are in the tens (see Table 3). As mentioned previously, there are no stations in the ice class.

While a correlation (%) plot is created for all snow classes containing more than one observing station, only a few snow classes are selected for further analysis. Selection is based on the number of stations classified within a particular class. More stations in a snow class are desirable. This being the case, the four selected snow classes are maritime, ephemeral, prairie and warm taiga. The number of stations within each of these snow classes is listed in below.

<table>
<thead>
<tr>
<th>Snow Class</th>
<th>Total Number of NCDC Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maritime</td>
<td>1341</td>
</tr>
<tr>
<td>Ephemeral</td>
<td>3861</td>
</tr>
<tr>
<td>Prairie</td>
<td>2795</td>
</tr>
<tr>
<td>Warm Taiga</td>
<td>564</td>
</tr>
</tbody>
</table>

Table 4: A table showing the distribution of the National Climatic Data Center stations for the selected snow classes. Selection was based on the number of stations in a particular snow class. More stations are preferred for the analysis.

A time series of the correlation (%) between the Interactive Multisensor Snow and Ice Mapping system snow extent and the NCDC snow depth data for the selected classes of maritime,
ephemeral, prairie, and warm taiga snow classes may be found in Figure 15, Figure 16, Figure 17, and Figure 18 below. The percentage of snow covered National Climatic Data Center stations are plotted on the same figures. The correlation (%) plots for all other snow classes containing at least one observing station, such as water, tundra, and cold taiga, may be found in Appendix II.

Figure 15  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as maritime.
Figure 16  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as ephemeral.

Figure 17  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as prairie.
The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as warm taiga is shown in Figure 18. The correlation (%) reaches a peak of 100% during the summer months and dips into valleys during the winter months. The correlation (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the National Climatic Data Center snow depth values is higher for the ephemeral snow class than the maritime, prairie, and warm taiga snow classes (see Figure 15, Figure 16, Figure 17, and Figure 18). The higher values of correlation (%) for the ephemeral snow class are likely due to a larger number of match situations where the NCDC observing station records 0 cm (no snow) and the IMS result is land (no snow). This is supported by the small percentages of NCDC snow covered stations plotted in Figure 16.

The range of correlation (%) is larger for maritime, prairie and warm taiga snow classes, spanning between 58 – 100%, 68 – 100%, and 62 – 100%, while the range of correlation (%) for
the ephemeral snow class is 73 – 100%, with most values above 85%. The distribution of the correlation (%) over the winter months appears to be more distributed for the maritime and warm taiga snow classes than the prairie and ephemeral snow classes.

Regarding the percentage of NCDC snow covered stations in Figure 15, Figure 16, Figure 17, and Figure 18, it varies in magnitude but is fairly similar in shape for maritime, ephemeral, prairie and warm taiga. During the winter season, the percentage of snow covered stations is larger for the maritime, prairie, and warm taiga snow classes at around 50% in comparison to the ephemeral snow class with values around 15%.

3.4 COMPARISON INVOLVING SNOW DEPTHS

An investigation is made on the effect of snow depth on the correlation between the snow extent of the Interactive Multisensor Snow and Ice Mapping system images and the snow depth data obtained from National Climatic Data Center observing stations. This is made possible through the classification of the observing stations into various snow depth intervals. Snow depth intervals are created for trace – 3 cm, 3 cm – 6 cm, 6 cm – 9 cm, and 9 cm – 12 cm. The snow depth interval of trace – 3 cm includes all observing stations reporting a trace value and up to, but not including, 3 cm. The other snow depth intervals are to be interpreted in a similar manner. The observing stations are classified on a daily basis over the study period of January 2006 – February 2010.

After the stations are classified by snow depth into various snow depth intervals, the percentage of correct agreement between the IMS product and the NCDC snow depth data is determined for each snow depth interval. The percentage of correct agreement is plotted on a daily basis from
January 2006 – February 2010. The daily percentage of correct agreement is determined as follows:

\[
\text{Percentage of Correct Agreement} (\%) = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = \( \Sigma \) stations in:

**Situation I:** station snow depth > 0 and IMS = snow

and Mismatch = \( \Sigma \) stations in either of:

**Situation I:** station snow depth > 0 and IMS = land (no snow)

**Situation II:** station snow depth = 0 and IMS = snow

Observing stations having a missing snow depth value (i.e. no record was made that day) are not taken into the calculation of the correlation (%). In such an event, it is impossible to classify the event as a match or mismatch situation.

**3.4.1 METHODOLOGY**

It is necessary to convert the NCDC snow depth values from inches to centimeters since the measurement for the classification groups is in centimeters. This is performed for all stations over the entire study period.

The snow depth records of the National Climatic Data Center are opened in MATLAB for a given day. The stations are then categorized based on their snow depth values into the intervals of trace – 3 cm, 3 cm – 6 cm, 6 cm – 9 cm, and 9 cm – 12 cm. After the stations in each snow depth interval have been identified, the Interactive Multisensor Snow and Ice Mapping system
image is opened and the proper pixel within the IMS product image is identified for each station classified in the same snow depth interval. The value of the IMS pixel and the NCDC snow depth record for a given station are then compared to determine whether it is a match or mismatch situation. This is performed for the stations in the same snow depth interval. The percentage of correct agreement (%) is then determined for each of the snow depth intervals. This procedure is performed on a daily basis. The number of stations in each snow depth interval is recorded on a daily basis as well.

In order to determine the percentage of correct agreement (%) for a particular snow depth interval, one must determine the proper pixel within an IMS product image for each station classified in the same snow depth interval. This is necessary in order to determine whether a scenario is a match or a mismatch situation. The proper pixel is determined by the following:

1. The absolute difference between the station latitude coordinate and the latitude grid of the Interactive Multisensor Snow and Ice Mapping system images are calculated for each grid cell. In mathematical terms:

   \[ A = |\text{station latitude coordinate} - \text{latitude value for particular grid cell}| \]

   to be performed over all grid cells, resulting in matrix A.

2. The absolute difference between the station longitude coordinate and the longitude grid of the Interactive Multisensor Snow and Ice Mapping system images are calculated for each grid cell. In mathematical terms:

   \[ B = |\text{station longitude coordinate} - \text{longitude value for particular grid cell}| \]

   43
to be performed over all grid cells, resulting in matrix B.

3. The average of the two calculated values from steps 1 and 2 are calculated for each grid cell of the IMS image. In mathematical terms:

\[ C = \frac{A + B}{2} \]

to be performed over all grid cells, resulting in matrix C.

4. The grid cell corresponding to the minimum value of the entire grid obtained from Step 3 is determined to be the IMS pixel corresponding to the latitude and longitude coordinates of a particular observing station. In mathematical terms:

\[ D = \text{minimum value of matrix } C \]

in which D is a single value.

This procedure is performed for the observing stations in the same snow depth interval.

A comparison between a daily Interactive Multisensor Snow and Ice Mapping System image and the daily National Climatic Data Center snow depth values is performed. Each of the daily IMS images is opened one by one, followed by the determination of the pixel location for each of the stations in the same snow depth interval. The pixel value of the daily IMS image is then compared to the NCDC station snow depth value for these stations.

In each of the comparisons between the pixel value of the daily IMS image to a NCDC observing station snow depth value for a particular day, the situation is classified as either ‘match,’ ‘mismatch,’ or ‘missing.’ Details for each of the situations follow. A ‘match’ event occurs under the following situations:
Situation I: station snow depth > 0 and IMS = snow

A ‘mismatch’ event occurs under the following situations:

Situation I: station snow depth > 0 and IMS = land (no snow)

Situation II: station snow depth = 0 and IMS = snow

A ‘missing’ event occurs if the station snow depth is ‘missing.’ Comparisons to the IMS are not performed for those ‘missing.’

For a given Interactive Multisensor Snow and Ice Mapping system daily image, a percentage of correct agreement between the image and all the NCDC observing stations in the same snow depth interval are calculated through the summation of the ‘match’ events and ‘mismatch’ events. The formula for the percentage of correct agreement was described earlier as:

\[
\text{Percentage of Correct Agreement (\%)} = \frac{\text{Match}}{\text{Match} + \text{Mismatch}} \times 100
\]

in which Match = Σ stations in either of:

Situation I: station snow depth > 0 and IMS = snow

and Mismatch = Σ stations in either of:

Situation I: station snow depth > 0 and IMS = land (no snow)

Situation II: station snow depth = 0 and IMS = snow

The number of stations in each snow depth interval is recorded on a daily basis as well.
3.4.2 **ANALYSIS**

A time series of the percentage of correct agreement (%) between the Interactive Multisensor Snow and Ice Mapping system snow extent and the NCDC snow depth data for the snow depth intervals of trace – 3 cm, 3 cm – 6 cm, 6 cm – 9 cm, and 9 cm – 12 cm may be found in Figure 19, Figure 20, Figure 21, and Figure 22 below. The number of NCDC stations in each interval is also plotted on each of these figures.

![Figure 19](image_url)

*Figure 19* The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between trace – 3 cm.
Figure 20 The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between 3 cm – 6 cm.

Figure 21 The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between 6 cm – 9 cm.
The agreement between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations having a snow depth between 9 cm – 12 cm.

With regards to the percentage of correct agreement (%), all four snow depth intervals, trace – 3 cm, 3 cm – 6 cm, 6 cm – 9 cm, and 9 cm – 12 cm appear to have the same cyclical shape wherein the percentage of correct agreement reaches a peak during the winter months and dips down to no percentages during the summer months. There are no percentages during the summer months because there are no stations with snow depths of trace – 12 cm at that time. This can be seen in the number of stations plotted in Figure 19, Figure 20, Figure 21, and Figure 22.

It may be interpreted from these figures that the percentage of correct agreement (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the snow depth values of the National Climatic Data Center observing stations increases with increasing snow depth. In looking at Figure 19, Figure 20, Figure 21, and Figure 22, there are more days in which the percentage of correct agreement (%) reaches 100% for the larger snow depth intervals.
(i.e. 6 cm – 9 cm and 9 cm – 12 cm) than the smaller snow depth intervals (trace – 3 cm and 3 cm – 6 cm).

The plots for the number of NCDC stations in each snow depth interval follow the same cyclical shape. They reach a peak in the winter months and drop down to no stations during the summer months. As mentioned earlier, there are no stations with snow depths of trace – 12 cm at that time.
The correlation (percent) between the Interactive Multisensor Snow and Ice Mapping system snow extent and National Climatic Data Center snow depth records range from 79% - 100%. Therefore, the correlation between the two overall is in good agreement all year long during the said study period.

In a land type analysis, the correlation (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the National Climatic Data Center snow depth values are higher for woodland and wooded grassland than the grassland and cropland (see Figure 9, Figure 10, Figure 11, and Figure 12). The range of correlation (%) is larger for grassland and cropland spanning between 70 – 100% and 74 – 100%, while the range of correlation (%) for woodland and wooded grassland areas spans between 80 – 100% and 78% - 100%. There is also more consistency, or correlation value clustering, in the values for both woodland and wooded grassland than grassland and cropland.

More insight as to the relation in the correlation (%) ranges for the select land classes may be determined through further investigation. Further investigation may involve the plotting of the stations for a particular land class on a latitude longitude grid on the day containing the largest number of snow-covered NCDC stations. The stations would be color coded according to the four possible combinations of snow-snow, snow-no snow, no snow-snow, no snow-no snow. The snow-no snow combination would mean that the IMS product pixel value was snow and the NCDC snow depth was a value greater than zero. A visual analysis of the plot would then reveal whether there are particular areas in which there is consistent agreement or disagreement.
Further analysis may also include an investigation of the land classes as a function of snow depth. It is highly probable that the snow in the land classes achieving lower correlation, grassland and cropland, is patchy, so there would be a lot of disagreement between the IMS snow extent and snow depths of the NCDC.

In the snow type analysis, the correlation (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the National Climatic Data Center snow depth values are higher for the ephemeral snow class than the maritime, prairie, and warm taiga snow classes (see Figure 15, Figure 16, Figure 17, and Figure 18). The higher values of correlation (%) for the ephemeral snow class is likely due to a larger number of match situations in which the NCDC observing station records 0 cm (no snow) and the IMS result is land (no snow). This is supported by the small percentages of NCDC snow covered stations plotted in Figure 16.

In the snow depth analysis, it may be interpreted from Figure 19, Figure 20, Figure 21, and Figure 22, that the percentage of correct agreement (%) between the snow extent of the Interactive Multisensor Snow and Ice Mapping system and the snow depth values of the National Climatic Data Center observing stations increases with increasing snow depth. There are more days in which the percentage of correct agreement (%) reaches 100% for the larger snow depth intervals of 6 cm – 9 cm and 9 cm – 12 cm than the smaller snow depth intervals of trace – 3 cm and 3 cm – 6 cm.


Liston, G. (2010). Global Snow Classification Dataset Email C. Chen. Fort Collins, CO.


The figures below are the correlation (%) time series for the following land types: water, evergreen needle leaf forest, deciduous broadleaf forest, mixed forest, closed shrub land, open shrub land, bare ground, and urban and built.

Figure 23  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as evergreen needle leaf forest.
Figure 24  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as deciduous broadleaf forest.

Figure 25  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as mixed forest.
Figure 26 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as closed shrub land.

Figure 27 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as open shrub land.
Figure 28  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as bare ground.

Figure 29  The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as urban and built.
The figures below are the correlation (%) time series for the following snow types: water, tundra, and cold taiga. The percentage of snow covered NCDC stations are also plotted in the same figure.

![Correlation (%) time series for snow types](image)

Figure 30 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as tundra.
Figure 31 The correlation between the snow extent of the interactive multisensor snow and ice mapping system product and snow depth values of the National Climatic Data Center for the stations identified as cold taiga.