Validation of VEGETATION, MODIS, and GOES+SSM/I Snow Cover Products over Canada Based on Surface Snow Depth Observations

Anita Simic[1*], Richard Fernandes[2], Ross Brown[3],
Peter Romanov[4], and William Park[2]

[1]*Noetix Research Inc. (under contract to CCRS), 588 Booth Street, Ottawa, K1A 0Y7, Ontario, Canada*
[2]*Natural Resources Canada, Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, K1A 0Y7, Ontario, Canada*
[3]*Meteorological Service of Canada, Dorval, Quebec, Canada*
[4]*Office of Research and Applications, NOAA/NESDIS, Camp Springs, MD, USA*

Abstract:

The ability to accurately map the areal depletion of snow is important for operational decision making (e.g. reservoir management), for correct specification of boundary conditions in Numerical Weather Prediction models, and for modeling atmospheric, hydrological and ecological processes. A number of satellite-derived snow cover products are available in real-time; however, these can differ considerably due to variations in sensor and platform characteristics, data pre-processing methods and the particular snow cover classification algorithms employed. This article evaluated the performance of three daily snow cover products over Canada (1) Terra Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover maps provided at 500m spatial resolution for 2001, (2) National Oceanic Atmospheric Administration (NOAA) GOES+SSM/I snow maps provided at 4km resolution for 2001 (~30km resolution SSM/I data were used for cloud covered areas), and (3) SPOT-4 Vegetation (VGT) snow maps derived at 1km resolution for 2000. An evaluation of the snow cover products with daily surface snow depth observations collected from almost two thousand meteorological stations across Canada revealed that the VGT snow product used in this study may not be suitable for snow mapping in Canada due to a significant bias towards mapping snow-free conditions. The MODIS and NOAA products showed similar reasonable levels of agreement ranging from approximately 80% to 100% on a monthly basis. Somewhat lower agreement was found in January suggesting that better correction for tree and surface shadow effects is needed in current snow cover mapping algorithms. The lowest agreement was seen during snow melt mainly in forest areas. Comparison of MODIS agreement statistics between sparse and dense conifer regions indicated that the effect of non-representativenes of surface snow depth observations was on the order of 10% disagreement. The NOAA product was found to be most consistent among land cover types and had the highest percentage of cloud-free pixels.

KEY WORDS: remote sensing; snow cover: MODIS; GOES; SSM/I; SPOT-VGT; validation;

* Natural Resources Canada, Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, K1A 0Y7, Ontario, Canada; Tel: 613.947.1254 email: Anita.Simic@CCRS.NRCan.gc.ca

INTRODUCTION

The pattern of snow cover, as determined by snow accumulation and snowmelt processes, has a significant impact upon climate processes, surface hydrological cycles and ecological processes within northern biomes. Global circulation model simulations suggest that snow within forests may exert positive radiative forcings on climate, and that these may offset negative forcings expected from associated carbon sequestration in vegetation (Betts, 2000). The evolution of snow cover is also related to basin-averaged snowmelt (Luce et al., 1998) and local hydrological processes (Cherkauer et al., 2003). The transition between the snowmelt and leaf appearance period is critical for terrestrial ecosystem functioning and management of both understory and overstory vegetation, and has an effect on annual net ecosystem productivity and forest fire processes.

The accuracy of snow cover maps is of particular importance in remote sensing applications to physical models. The unique spectral signature of snow is commonly used in snow cover classification algorithms to indicate snow distribution (Xiao et al., 2002; Maurer et al., 2003). Nevertheless, different spatial resolutions, geographic extents and snow classification algorithms affect the accuracy of satellite based snow cover maps. Cloud-snow confusion is one of the major impediments for snow classification. Certain types of clouds, such as cirrus, low stratus, and small cumulus, are hard to discriminate from snow and ice covered surfaces (Simpson et al., 1998). Forest areas represent another obstacle to accurate snow cover mapping in remote sensing applications. Forest canopies obscure snow from the view of both visible and passive-microwave satellite sensors. Ultimately, less snow is detected when the sensors view at off-nadir angles than at nadir (Hall et al., 1998). To enhance snow classification, Vikhamar and Solberg (2002) specified the narrow spectral ranges for which snow is most distinctive in forest areas. The spatial scaling effect from point to pixels plays an important role in the validation process and may explain some of the differences between satellite and in-situ snow cover distribution. Conifer canopies block understory snow cover from solar radiation and wind during snow melt and, therefore, snow persists longer than in open areas where in-situ observations are commonly performed (Vikhamar and Solberg, 2002; Brown and Goodison, 1996). In addition, snow depth and snow metamorphosis influence the reflectance of snow (Romanov et al., 2002; Vikhamar and Solberg, 2002). This also affects the validation process.

The constant comparison of satellite-derived snow maps and surface measurements is vital for improvement of snow-mapping algorithms. Yet, a lack of ground measurements commonly results in two major limitations: 1) the assessments are performed within small areas, which have available local surface measurements, and/or 2) the assessments are based on other satellite data, primarily Landsat. Maurer at al. (2003) evaluated the MODIS and the National Operational Hydrologic Remote Sensing Centre (NOHRSC) snow daily products with snow surface observations over the Columbia River basin and Missouri River basin during winter and spring of 2001. Their results suggested that the MODIS product exhibits a greater agreement rate than the NOHRSC snow daily product. Xiao et al. (2002) used Landsat Enhanced Thematic Mapper (ETM) data in the validation process of the VGT derived snow cover based on the Normalized Difference Snow/Ice Index (NDSII) approach. Snow cover dynamics were found to be consistent between the fine resolution data and the VGT product over an alpine region in Asia. Romanov et al. (2002b) recently validated snow cover distribution over the North American continent. Their automated snow mapping technique based on GOES+SSM/I sensors measurements was found to have 88% agreement with surface observations from approximately 1000 meteorological stations.

The main intent of this study is to 1) compare three daily snow cover satellite products of different resolution:

- SPOT-4 VEGETATION (VGT) – S1 product;
- Moderate Resolution Imaging Spectrometer (MODIS) MOD10A1 product (Version 3.0);
- National Oceanic Atmospheric Administration (NOAA) combined product of the Imager instrument onboard the Geostationary Operational Environmental Satellites (GOES) and the Special Sensor Microwave Imager (SSM/I);

with surface snow depth observations during winter and spring season over Canada, and 2) to highlight the difference in agreement between satellite and surface snow cover data within different land cover types. The validation is based on surface snow depth observations from almost two thousand meteorological stations across Canada. The assessment has been performed on a daily basis for the period of 160 days from January to June of 2000 (SPOT-4) and 2001 (MODIS and NOAA).

DATA AND RELEVANT ALGORITHMS

Snow depth surface data

Ruler-based measurements of snow depth are made on a daily basis at climate stations across Canada (Brown and Braaten, 1998). Data from almost 2000 sites were available for 2000 and 2001 for use in this study, and the spatial distribution of the observations is shown in Figure1. The data tend to be concentrated in southern populated regions of the country, and are biased to lower elevations. In addition, the observations are made at open, grassy sites, and may not be representative of snow cover conditions in surrounding vegetated areas. The difference is likely to be greatest in the spring when open areas melt faster, and will be most pronounced in heavily forested regions of the country. Approximately 27% of in-situ sites are contained within the evergreen forest areas. Almost half of these points (48%) are located within closed-canopy evergreen forest. Over 65% of in-situ sites are located within the herb dominated land cover. Snow depth is reported to the nearest cm except for the snow depth values less than 1 cm, which were considered to be 'trace' values.

Land cover map

A land cover image at 1km resolution, derived and provided by Canada Centre for Remote Sensing (CCRS) (Cihlar and Beaubien, 1998), was used in the analysis to draw attention to the difference in agreement between satellite and surface snow cover data within different land cover types. Twelve original land cover types were combined into four: evergreen forest, deciduous forest, herb dominated and lichen land cover types. Evergreen forest includes both conifer and mixed forest. A similar technique was used to study the accuracy of global snow mapping from space (prior to the MODIS launch) by Hall et al. (2001) whereby the 17-class International Geosphere-Biosphere Program

(IGBP) map was combined into 7 classes and snow-mapping errors were estimated for each class.

VGT – S1 product

VGT S1 products (Passot, 2000) consisting of red, near-infrared (NIR) and shortwave infrared (SWIR) apparent surface reflectance channels, gridded at 1km resolution, form the input to the snow cover mapping method used to produce the VGT snow cover maps. The VGT-S1 imagery corresponds to maximum normalized difference vegetation index (NDVI) composite products corrected to at surface reflectance using the SMAC (Rhaman and Didieu, 1994) algorithm with nominal atmospheric parameters. Published snow cover maps were used in this validation study (Lissens et al., 2000). These maps were produced using a three-step process:

1. Mapping snow versus no-snow irrespective of cloud cover, and cloud versus land using conservative thresholds defined by a genetic algorithm.
2. Separating snow versus cloud in remaining uncertain pixels using a neural-network post-processor.
3. Applying a cloud shadow mask developed from the mapped cloud mask, reflectance data and acquisition geometry.

MODIS – MOD 10A1 product

MODIS, an imaging spectroradiometer aboard the Earth Observing System (EOS) Terra and Aqua satellites, provides global coverage within visible and infrared spectral bands on a daily basis. MODIS operates at finer spectral and spatial resolutions (36 spectral bands; 500m at nadir for most “land” bands) than previous sources of daily imagery. The MOD10A1 snow cover product (Version 3) (Hall et al., 2002) was evaluated in this study. This product relies on advanced cloud screening (Ackerman et al., 1998) and snow detection (Klein et al., 1998). The product was archived as 500m gridded resolution daily tiles of approximately 1200km x 1200km in size including both snow cover flags and extensive quality control information. Sixteen tiles (12v02, 13v02, 14v02, 15v02, 9v03, 10v03, 11v03, 12v03, 13v03, 14v03, 9v04, 10v04, 11v04, 12v04, 13v04, 14v04) containing the in-situ snow cover sites, were used for this study. The MODIS snow product classification is based on the normalized difference snow index (NDSI), which is utilized in the fully automated algorithm through a series of thresholds (Hall et al., 2002). The process of classification starts with mapping snow covered pixels applying a threshold to the normalized difference snow index (NDSI), and separating snow from water applying a threshold to NIR band. In order to increase snow cover extent within forest areas, where snow is commonly obscured by the canopies, both NDSI and the normalized vegetation index (NDVI) are used for forest designated pixels. This differentiates snow-free and snow-covered forest pixels. Since many snow-covered forests have NDSI <0.4, a higher NDVI value for forest areas is used to separate these areas from surrounding snow cover open land areas. An additional threshold of 10% green spectral band reflectance is used to reduce commission errors over forests. As well, a thermal mask using infrared bands 31 (10.78-11.28um) and 32 (11.77-12.27um) is used to further differentiate snow from clouds (Hall et al., 2002).

NOAA – GOES+SSM/I product

The NOAA daily snow cover product is an automated product that uses a combination of GOES and SSM/I sensors to map snow cover south of 66 degrees and NOAA AVHRR imagery north of this latitude where GOES does not provide coverage (Romanov et al., 2000). Our validation study only used the GOES+SSM/I outputs due to the sparse nature of the snow depth network north of 66 degrees. The GOES data stream includes observations at 30-minute intervals from GOES Imagers of both GOES East and West geostationary platforms. The spectral coverage of the imager used for the snow detection includes a visible (VIS) channel centered at 0.6 um, a SWIR channel centered at 3.9um, and an IR channel centered at 11um. The GOES Imager provides spatial resolutions at 1km for the VIS channel and 4km for the SWIR and IR channels. The SSM/I imager onboard the Defense Meteorological Satellite Program (DMSP) satellites provides continental coverage on a daily basis with resolution footprints of 38x30km at 37 GHz and 70x45km at 19 GHz (Deblonde et al., 2002). Two characteristics of the NOAA product reduce the impact of clouds on mapped snow cover patterns. These are 1) GOES provides frequent views during the day and 2) SSM/I is able to sense through clouds since clouds do not present a significant source of contamination within the 19GHz and

37GHz bands used (Romanov et al., 2000). The recently improved ability of GOES Imagers to measure in shortwave-infrared regions makes them useful for snow versus cloud screening (Xiao et al., 2002; Maurer et al., 2003). The snow data are mapped onto Plate Carree projection with 4 km resolution over North America. The GOES component of the NOAA snow cover algorithm involves two stages of thresholds. One threshold distinguishes snow versus no-snow surfaces, while the other distinguishes clouds and land within no-snow surface. A snow index (SI) is derived using the ratio of the angle-corrected[1] visible (VIS') and SWIR reflectance to map snow versus no-snow surfaces. A VIS' threshold is then set to eliminate cloud shadows and small water bodies. For SWIR reflectance, the threshold is set to distinguish snow from most of clouds. To discriminate snow from clouds with ice tops and cirrus, two temperature brightness of IR band (T_{IR}) thresholds are used: 1) A temperature threshold based on land surface temperature separates bright warm surfaces such as deserts from snow, and 2) another threshold screens for melted regions within forest areas or/and mountainous areas in spring when the heating of tree canopies or rock increase IR brightness temperature above freezing (Romanov et al., 2000). To differentiate clouds from land within no-snow surface, VIS', SWIR and T_{IR} thresholds are used. All of these thresholds are applied to cloud-screened daily composites derived by selecting the least cloudy sub-daily hourly observation (Romanov et al., 2000). The GOES snow mapping algorithm was later improved (Romanov et al., 2002).

Snow cover maps at 30km resolution, derived by SSM/I, are used to replace gaps within the GOES product created during the cloud-covered observations since clouds do not present a significant source of contamination within the 19GHz and 37GHz bands used (Romanov et al., 2000).

METHODS

Daily MODIS snow cover maps were reprojected in Plate Carree projection to be consistent with the VGT and GOES+SSM/I snow cover products and in situ

---

[1] VIS equivalent reflectance normalized to 45 deg solar zenith angle, 45 deg satellite zenith angle and 0 deg relative azimuth

measurements. Surface and satellite data that included no measurements were excluded from the statistical analysis. Ground data were represented as vector points, and were assigned values of either “snow” (snow present) or “no-snow” (snow not present). These data were then compared to their corresponding locations (pixels) in each satellite image product for each observation date in question. The pairs of data that included pixels labeled as cloud or water were also excluded. Furthermore, the disagreement flags were separated into omission[2], and commission[3] errors. Commission errors are typically expected to occur where the open area bias in the surface observations is evident. Land cover over data points were aggregated into four classes (evergreen forest, deciduous forest, herb dominated and lichen) to produce sufficient points per month to report sufficiently precise agreement/disagreement statistics. Percentage agreement and disagreement were calculated separately for each land cover type on a monthly basis.

A snow cover fraction curve was produced for each product to provide a summary of the depletion of snow cover across Canada. The curve is an approximation over the large area and does not exhibit spatial nor temporal variations. Regional curves and accuracy assessments are also provided for three of the MODIS tiles representative of distinct ecozones within Canada: the Pacific Coast region (Tile 10v03), Central Boreal Forest region (Tile 12v03), and Boreal Shield region (Tile 12v04). Other regions in the south showed similar performance and are not included here.

An initial estimate of the contribution of scaling uncertainty to observed differences between point in-situ and areal (satellite-based) snow cover estimates was performed. To account for the open area bias in surface snow depth observations, the evergreen forest cover type was divided into open- and closed-canopy forest using the initial land cover classification (Cihlar and Beaubien, 1998). Separate validations were performed for each forest cover type and the percentages of differences were compared on a monthly basis over the same population of surface sites. We assume that the scaling error for sparse forest cover is negligible as accuracy over this cover type did not differ substantially than over bare regions for any given product. The observed difference (as shown later) in

[2] Snow on ground not seen by a satellite
[3] Satellite sees snow when none observed on the ground

error rates between open and closed forest cover serves as an upper bound on the contribution of scaling effects to the overall disagreement. The analysis was conducted within forest areas where the most prominent differences were expected.

The sensitivity of our results to the snow/no-snow threshold depth in the in-situ data was quantified by assessing the MODIS product accuracy using 3cm and 'trace' depth thresholds in addition to the baseline 1cm threshold[4].

RESULTS

A typical VGT snow map (March 21, 2000; Figure 1) shows only a narrow band of snow cover due in part to extensive cloudiness in the Canadian north and extensive snow free mapped areas in the south. Figure 2 indicates the monthly trend in agreement and snow cover fraction across Canada for all mapped VGT pixels. The overall agreement for the study period was 83%. Forests exhibit lower levels of agreement than other cover types within the VGT map, dropping to 41% in January. We propose that this lack of agreement is related to the VGT mapping approach and not scaling differences since all sites are typically uniformly snow covered early in the year. Rather, the relatively low agreement, especially for forest areas during first three months, results in a considerably high percentage omission error (Figure 3). High ratios of omission errors are also observed within the herb dominant and lichen cover types. This indicates that the classification algorithm employed in the VGT snow product used in this study may not be suitable for snow mapping in Canada.

The MODIS product appears to classify a relatively high proportion of the area as clouds, for March 22, 2001 (Figure 4). The MODIS product exhibits an average percentage agreement of 93% over the entire 160 days (Figure 5). Evergreen forests show the lowest percentage agreement throughout the whole period with a minimum of 80% during snow melt. All cover types demonstrate lower percentage agreement during January and all, except lichen, exhibit the lowest agreement during snow melt (March-April).

---

[4] Thresholds of 'trace', 1cm and 3cm designate snow cover presence when the snow depth is ≥ trace depth, ≥1cm depth and ≥3cm depth, respectively.

Figure 6 illustrates a relatively high ratio of the commission error within evergreen forests for the MODIS product. This is not in accordance with the findings of Hall et al. (2002), in which the snow cover within a forested area near Tenant Swamp was found to be underestimated. However, the same study suggested that the MODIS snow-mapping algorithm overestimated the snow cover where snow was patchy. The MODIS mapping method showed more snow mapping in forest areas than some other methods in a study of Bitner et al. (2002). In respect to the regional variations, Figure 7 shows that the Pacific Coast region exhibits lower percentage agreement than both Boreal Forest and Boreal Shield regions, ranging from 78% to 96%. The percentage agreements for Boreal Forest and Boreal Shield regions range from 84% and 86% to 100%, respectively. To address the scaling issue, an assessment was performed based on the forest cover density with both MODIS and NOAA products. For the MODIS product, closed-canopy evergreen forests exhibit consistently lower percentage agreement than open-canopy evergreen forest until snow-free conditions (Figure 8).

Figure 9 shows the NOAA snow cover map for the date corresponding to the MODIS map shown in Figure 4. An initial visual assessment indicates that the NOAA map includes no no-data regions and provides a reasonable representation of regional snow cover patterns during the onset of melt in southern Canada. Figure 10 shows the average percentage agreement of 92% for the NOAA product. The lowest agreement is seen within evergreen forests (81%). All land cover types show the similar trend, lower percentage agreement in January and during snow melt (March and April). Observational behaviors of both sensors contribute to the final product. Snow melt and precipitation clouds are major obstacles to the microwave observations due to high emissivity of the water-coated snow particles and to high scattering, respectively (Romanov et al., 2000). Relatively equal omission and commission errors are evident with all land cover types except deciduous forest, which shows higher omission error (Figure 11). The percentage commission error slightly overpowers the percentage omission error during the snow melt period for all land cover types. This is generally in accordance with the previous findings by Romanov et al. (2000) and Romanov et al. (2002b). Romanov et al. (2000)

also found that GOES+SSM/I showed the agreement of 85% when compared with surface observations, and showed similar or higher agreement than the NOAA operational (non-automated) product. In contrast to the MODIS product, the percent agreement between open- and close- canopies of evergreen forest within the NOAA product did not differ substantially as indicated in Figure 12.

Figures 13a and 13b demonstrate the difference between the statistical analysis based on the reference threshold of 1cm and thresholds of 3cm and ‘trace’ depths, respectively using the MODIS product. The difference is approximately within the range between -2% and +4%. Generally, more differences are positive suggesting that the 1cm threshold is most representative of areal snow cover within the pixel.

All pixels within the NOAA product were used in this study for the mapping; this is due to the SSM/I 30-km resolution map, which was available to use in areas that are cloud covered (Figure 14). Both the MODIS and SPOT VGT products appear to exhibit a lower percentage of obtainable days (38 and 49, respectively) than the NOAA product over the period of five months.

DISCUSSION

The validation study was performed using a biased spatial sample since most of the in-situ stations are located in southern Canada and in low elevation areas where land use is a factor. However, it is exactly these areas where validated snow cover maps are required to quantify impacts and develop management or mitigation strategies. Trends in agreement of maps with data from these sites fall in two categories. The VGT product exhibited a significant bias towards mapping snow-free conditions, especially over forest, when in fact there was known to be snow on the ground. This produced a low agreement with ground data during the period of complete snow cover and very high agreement, by default, during complete snow free periods. It is likely that the thresholds of >30% RED reflectance <24% SWIR reflectance are too restrictive for designating snow cover. This may be due to the lack of a correction for vegetation cover since the level of agreement is worst in January when solar zenith angles are low resulting in large cast shadows from vegetation and micro topography as noted with other regional studies (Xiao et al., 2002).

Both the MODIS and NOAA products show similar reasonable levels of agreement ranging from approximately 80% to 100% on a monthly basis. Better agreement was reported by Hall et al. (1998) over the boreal forest of Central Alaska using MODIS Airborne Simulator (MAS) data. They reported that 99% of the pixels that had <50% vegetation cover density and 98% of the pixels that had ≥50% vegetation cover density were correctly classified. However, this assessment incorporated only the omission error since no snow-free land existed at the time. Lower agreement was found in January, suggesting that better correction for tree and surface shadow effects is needed in current snow cover mapping algorithms, as noted also in Vikhamar and Solberg (2002). The MODIS product also exhibits a drop in accuracy over lichen areas post snow-melt suggesting its visible albedo threshold may need to be adjusted to account for this cover type. The lowest levels of agreement are found over areas with evergreen forests. This may be due to both environmental factors such as variability in cast shadows and litter on the snow pack as well as scaling differences between point snow depths at the in-situ stations and the areal snow cover over the pixel. The comparison of MODIS agreement statistics between sparse and dense conifer regions indicates that scaling errors likely contribute on the order of 10% disagreement at worst. Additionally, the low sensitivity to differences in threshold snow depth for mapping snow versus no-snow in-situ suggests that scaling errors did not have a major impact on the monthly statistics in this study.

Our assessment of regional accuracy variations was limited both by the scope of the problem and the non-uniform density of in-situ sites. The comparison of three MODIS tiles suggests that both topography (as found in the Rockies Mountains in British Columbia) and evergreen forests (found in Pacific Coast and Boreal forest tiles) result in decreased levels of agreement. Both of these factors are related to the difficulty in correcting for these effects on the surface bi-directional reflectance function (BRDF) and hence on the reflectance based snow-cover thresholds product (Romanov et al., 2000). Regional differences in agreement may also be related to the selected snow-no-snow threshold. Bussieres et al. (2002) found that the MODIS snow cover matched the SSM/I derived snow water equivalent (SWE) at the 0mm threshold over the prairie and boreal forest and at the 20mm threshold over the taiga region. Brown (2000) found that use of a 2 cm snow depth threshold to define snow/no snow in a pixel provided the highest agreement with snow covered area computed from NOAA weekly maps. The lower correlation for a 1 cm depth threshold was found to be due to the inconsistencies introduced in the reporting of trace amount of snow on the ground.

Furthermore, snow is easily confused with clouds resulting in snow cover overestimation. Although the MODIS snow algorithm is effective in eliminating most clouds, high clouds that contain ice are often confused for snow (Hall et al., 2002). This phenomenon may be amplified within high-elevation regions due to two factors: a) the amount of clouds is increased in mountainous areas, and b) on the higher plateau and on the mountainous areas, snow cover exists longer than in areas of low elevation such as river valleys (Dankers and de Jong, 2002). It was also found in this study that the British Columbia mountainous region exhibits greater snow cover overestimation over other two regions. This suggests that the snow-cloud confusion may have an effect on the snow cover mapping in addition to the complex topography of the mountainous areas. Romanov et al. (2002b) found that the observed overestimation of snow cover in the mountainous region may also be explained by the inconsistency of the satellite reference elevation and station elevation. Unlike the snow-clouds confusion and the elevation differences, a high illumination variability of the land surface and shadows over complex topography may account for the cases of the underestimation of snow cover (Xiao et al., 2002).

The comparison of MODIS and NOAA products in terms of sensitivity to forest cover and overall agreement highlight produce two interesting findings. Firstly, the NOAA product agreement level did not vary substantially as a function of forest cover while the MODIS product exhibited consistently lower agreement over dense versus sparse conifer regions. This result is partially due to an artifact of our analysis since the land cover was defined using a 1km pixel containing an in-situ site while the NOAA pixels are mapped using a nominal 4km resolution. It is likely that many of these 4km regions contained less dense vegetation outside the 1km central region. However, the analysis does suggest that the NOAA agreement levels exhibit less variability as a function of land cover type at the in-situ sites than the MODIS map simply due to the averaging effect of the coarser resolution pixels. Secondly, the 16-fold increase in spatial resolution between MODIS and GOES does not considerably change agreement statistics over large regions and monthly intervals. This is not to say that the increased MODIS resolution may not make the snow cover product more useful for applications such as distributed hydrological modelling where the spatial co-variation of snow cover and land cover parameters is important. However, the coarser resolution NOAA product may be sufficient for basin or sub-basin scale applications. More importantly, the NOAA product provides 100% retrieval rates in contrast to rates below 40% for MODIS. As previously found, the MODIS cloud mask is conservative in mapping clouds over the areas covered with snow and it tends to overestimate cloud cover (Hall et al., 2002). Version 4 of the MOD10 product is now available and it contains a more “liberal” cloud mask in the swath-level product (Riggs and Hall, 2002). Temporal coverage may be much more important than resolution in terms of using snow cover maps in support of monitoring melt-season ecosystem processes.

Both the sophisticated algorithm and 30-minute observations used in the NOAA product and the use of the microwave sensor are believed to be major factors in the high accuracy, relatively equal omission–commission errors ratio, and also high percentage of cloud-free pixels. Further progress may mostly involve the improvement of the snow-cloud confusion within the GOES snow algorithm. Romanov et al. (2002b) showed that very thick or precipitating clouds, which occur during snow storm events, represent obstacles for both GOES and microwave sensors and result in reduced snow mapping accuracy. This study shows comparable findings during the early part of the snow season. Spatial scaling from point to pixels and spatial coverage of in-situ sites are two limitations of our study. Surface measurements are commonly performed within accessible areas, limited to lower altitudes and are often subjective and neglect the sampling of varying snow depth (Brown and Goodison, 1996). To perform further validation during snow melts, it is suggested to examine the sensitivity of transition period for daily output for all points of interest across Canada in order to improve the snow algorithm. Imagery from sensors such as Landsat and ASTER could be used in the validation process to refine our analysis during the snow melt period.

Although the extent of the SSM/I contribution within the NOAA product was not determined in this study, incorporating the microwave sensor in snow cover mapping is advantageous in the performance of the snow cover product. Similar to the findings of the NOAA product, it is likely that combining the microwave sensor, such as the Advanced Microwave Scanning Radiometer (AMSR) recently launched on the Aqua satellite, and MODIS data would result in higher accuracy and better availability of the snow cover information than using MODIS data alone.

CONCLUSION

The snow ablation process and snow cover distribution have a significant impact on the hydrological cycle, terrestrial and water ecosystems, and climatologic processes. The accuracy of snow cover maps is particularly important in remote sensing applications. In this study, three satellite snow cover products were compared to surface snow depth measurements across Canada for the period between January and June. Almost 2000 surface measurements were used for the assessment. It was found that the SPOT4 VGT product used in this study was not applicable for the retrieval of snow cover in Canada due to high omission errors. Better agreement between the satellite observations and surface measurements are seen with both the MODIS and NOAA products, ranging from approximately 80% to 100%. Evergreen forests exhibit the lowest percentage agreement of all land cover types. Percentage agreement is generally reduced during beginning of snow season and during snow melt, particularly within forest areas, for both MODIS and NOAA snow product.

The capability of the snow cover algorithms to correctly identify snow-covered areas plays an important role in the validation of the products. It is likely that the thresholds within the VGT products are too restrictive for designating snow cover. The cloud-snow confusion is another factor in the validation mismatch. Further progress involves the improvement of the snow-cloud differentiation within both the GOES and MODIS snow algorithms. Advantage of the microwave sensor to observe through clouds justifies the performance of the NOAA product. Besides the snow cover mapping techniques, spatial variability within a field of view of sensors, complex topography, and land cover types are responsible for the disagreement between the snow products and surface observations. In addition, the scaling errors from point to pixels also play an important role in the validation over dense vegetation areas during snow melt. Landsat and ASTER used in the validation may provide better results for snow melt period improving the scaling issue.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the Canadian Space Agency who funded this project. We also thank to Dorothy K. Hall (Hydrological Sciences Branch, NASA/Goddard Space Flight Centre, Greenbelt, MD, USA) and George Riggs (Science Systems and applications, Inc., Lanham, MD, USA) for providing us with their valuable comments.

REFERENCES

Ackermann SA, Strabala KI, Menzel PWP, Frey RA, Moeller CC, Gumley LE. 1998. Discriminating clear sky from clouds with MODIS. *Journal of Geophysics Research* **103** (D24): 32141-32157.

Betts RA. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* **408**: 187-190.

Bitner D, Carroll T, Cline D, Romanov P. 2002. An assessment of the differences between three satellite snow cover mapping techniques. *Hydrological Processes* **16**: 3723-3733.

Brown RD. 2000. Northern Hemisphere snow cover variability and change, 1915-1997. Journal of Climate **13**: 2339-2355.

Brown RD, Braaten RO. 1998. Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. *Atmosphere-Ocean* **36** (1): 37-54.

Brown RD, Goodison BE. 1996. Interannual variability in reconstructed Canadian snow cover. *Journal of Climate*; 1915-1992.

Bussieres N, de Seve D. Walker AE. 2002. Evaluation of MODIS snow cover products over Canadian regions. In *Proceedings of IGARSS 2002*, Toronto.

Cihlar J, Beaubien J. 1998. Land cover of Canada Version 1.1. In *Special Publication, NBIOME Project*, Canada Centre for Remote Sensing and the Canadian Forest Service, Natural Resources Canada.

Cherkauer KA, Bowling LC, Lettenmaier DP. 2003. Variable infiltration capacity cold land process model updates. *Global and Planetary Change* **804**: 1-9.

Dankers R, de Jong SM. 2002. Monitoring snow cover dynamics in Northern Fennoscandia with Spot Vegetation images. *International Journal of Remote Sensing* (submitted).

Deblonde G, English S, Bell W. 2002. Stand-alone 1D-Var scheme for the SSM/I, SSMIS and AMSU: User's Guide. *NWP SAF, Meteorological Services of Canada and Met Office UK*. Document NWPSAF-MO-UD-001, Version 2.0.

Hall DK, Foster JL, Verbyla DL, Klein AG, Benson CS. 1998. Assessment of snow-cover mapping accuracy in a variety of vegetation-cover densities in Central Alaska. *Remote Sensing of Environ*ment **66**: 129-137.

Hall DK, Foster JL, Salomonson VV, Klein AG, Chien JYL. 2001. Development of a technique to assess snow-cover mapping errors from space. *IEEE Transactions on Geoscience and Remote Sensing,* **39**(2):432-438.

Hall DK, Riggs GA, Salomonson VV, DiGirolamo NE, Bayr KJ. 2002. MODIS snow-cover products. *Remote Sensing of Environment* **83**: 181-194.

Klein AG, Hall DK, Riggs GA. 1998. Improving snow-cover mapping in forests through the use of a canopy reflectance model. *Hydrological Processes* **12**: 1723-1744.

Lissens G, Kempeneers P, Fierens F, Van Rensbergen J. 2000. Development of cloud, snow, and shadow masking algorithm for VEGETATION imagery. In *Proceedings of IGARSS 2000*, Hawaii.

Luce CH, Tarboton DG, Cooley KR. 1998. The Influence of the spatial distribution of snow on basin-averaged snow melt. *Hydrological Processes* **12**: 1671-1683.

Maurer EP, Rhoads JD, Dubayah RO, Lettenmaier DP. 2003. Evaluation of the snow-covered area data product from MODIS. *Hydrological Processes* **17**: 59-71.

Passot X. 2000. VEGETATION image processing methods in the CTIV. In *Proceedings of Vegetation-2000 Symposium*, Lake Maggiore, Italy, 7.

Rahman H, Dedieu G. 1994. SMAC: A simplified method for the atmospheric corrections of satellite measurements in the solar spectrum. *International Journal of Remote Sensing* **15**: 123-143.

Riggs GA and Hall DK. 2002. Reduction of Cloud Obscuration in the MODIS Snow Data Product. *The 59th Eastern Snow Conference*, 5-7 June 2002, Stowe, VT.

Romanov P, Gutman G, Csiszar I. 2000. Automated monitoring of snow over North America with multispectral satellite data. *Journal of Applied Meteorol*ogy **39**: 1866-1880.

Romanov P, Tarpley D, Gutman G, Carroll T. 2002. Mapping and monitoring of the snow cover fraction over North America. *Journal of Geophysical Research (submitted).*

Romanov P, Gutman G, Csiszar I. 2002b. Satellite-derived snow cover maps for North America: Accuracy assessment. *Advances In Spatial Research* **30** (11): 2455-2460.

Simpson JJ, Stitt JR, Sienko M. 1998. Improved estimates of the areal extent of snow cover from AVHRR data. *Journal of Hydrology* **204**: 1-23.

Vikhamar D, Solberg R. 2002. Subpixel mapping of snow cover in forest by optical remote sensing. *Remote Sensing of Environment* **84**: 69-82.

Xiao X, Moore B, Qin X, Shen Z, Boles S. 2002. Large-scale observations of alpine snow and ice cover in Asia: Using multi-temporal VEGETATION sensor data. *International Journal of Remote Sensing* **23 (**11): 2213-2228.

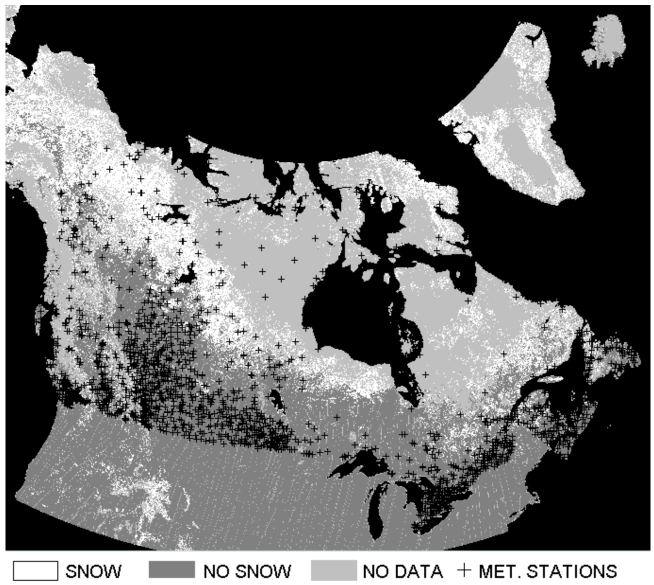


Figure 1. Snow cover extent over Canada derived by the SPOT4 VGT snow product for March 21, 2000, and locations of the meteorological stations with snow depth measurements.

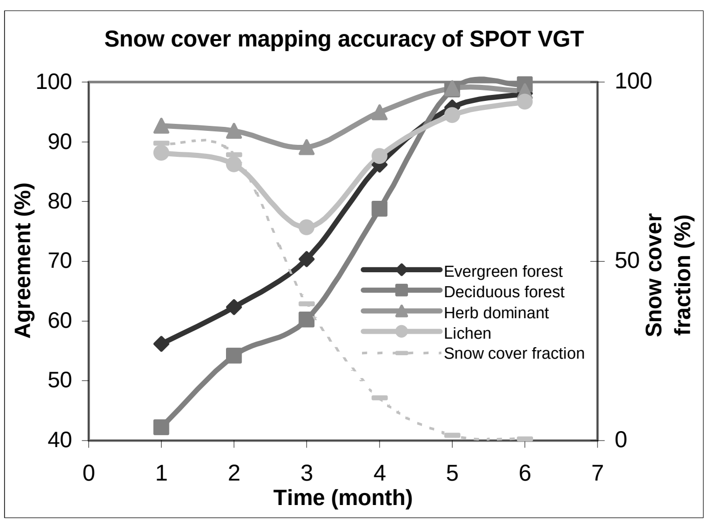


Figure 2. Snow cover mapping assessment of the VGT snow product over Canada from January to June 2000.

Back to page 4

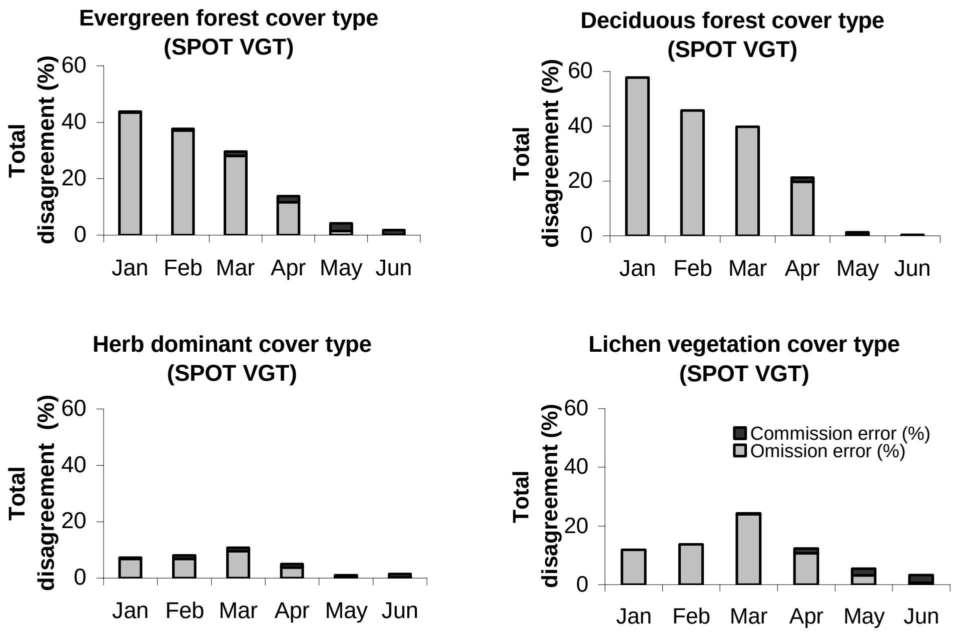


Figure 3. Ratio between omission and commission errors for the VGT snow product within four land cover types.

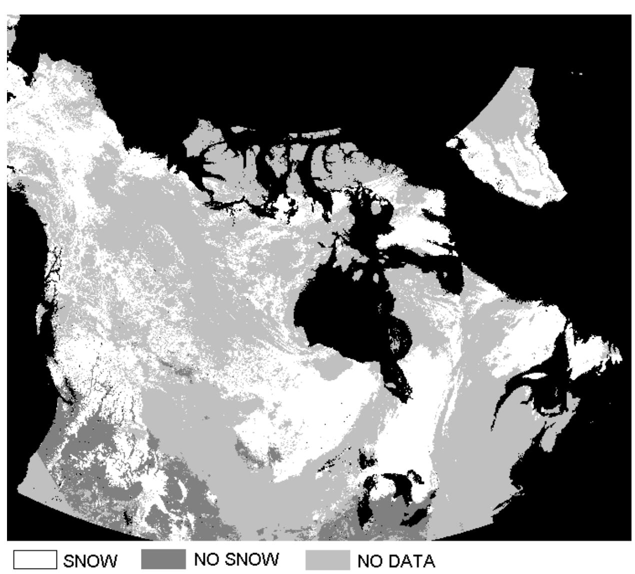


Figure 4. Snow cover extent over Canada derived by the MODIS snow product for March 22, 2001.

Back to page 9

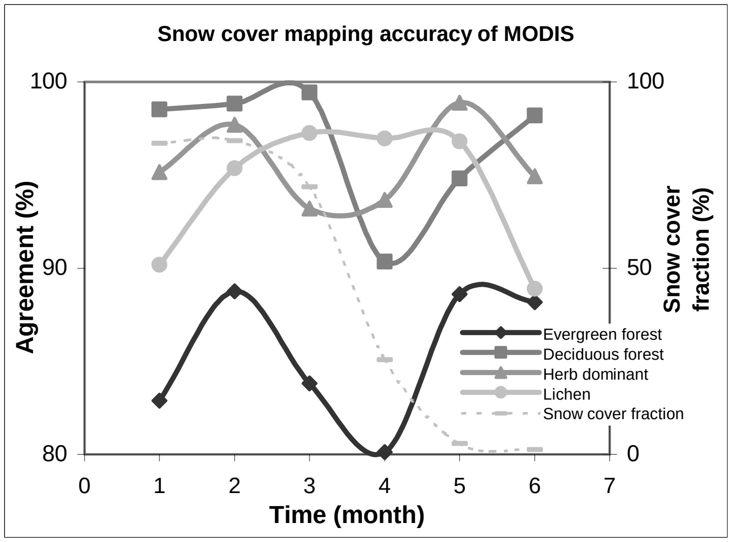


Figure 5. Snow cover mapping assessment of the MODIS snow product over Canada from January to Jun 2001.

Back to page 9

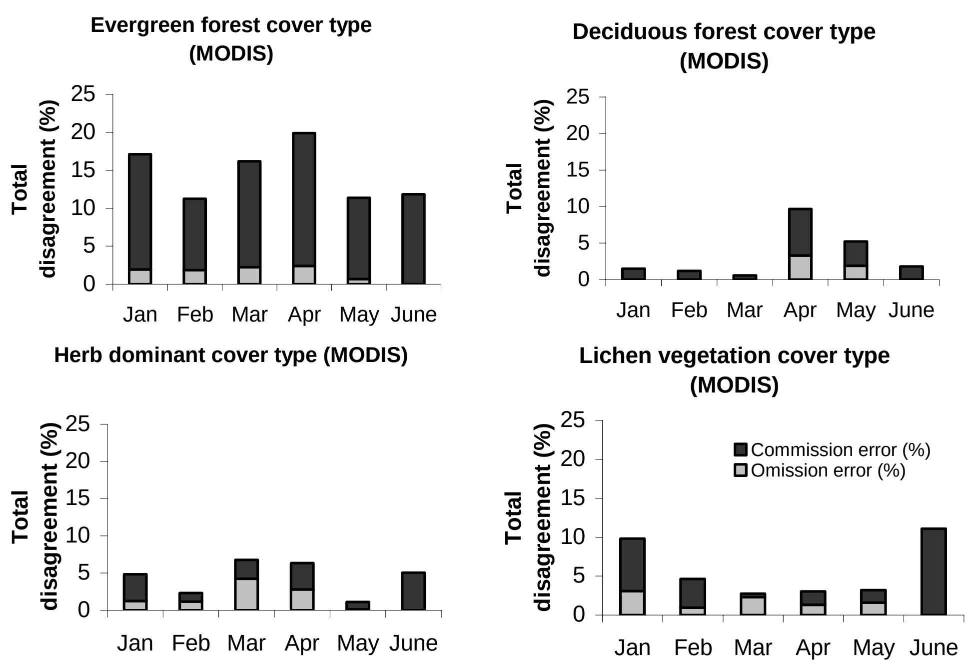


Figure 6. Ratio between omission and commission errors for the MODIS snow product within four land cover types.

Back to page 10

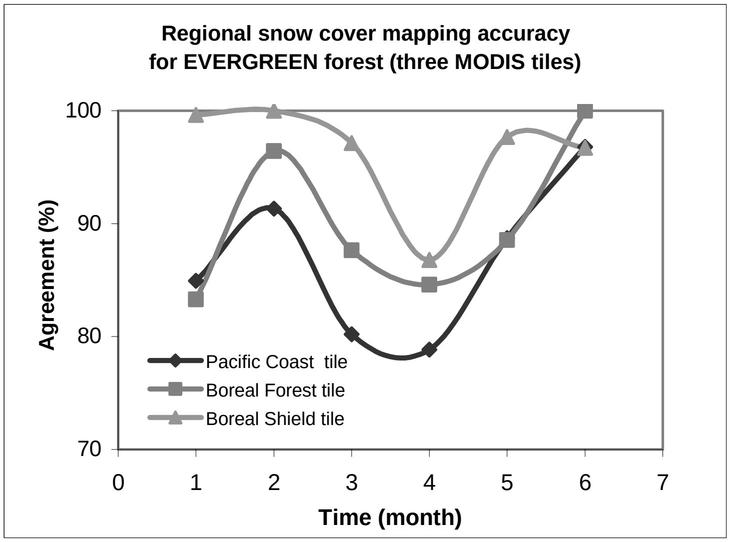


Figure 7. Regional snow cover mapping accuracy of three MODIS tiles for evergreen forest.

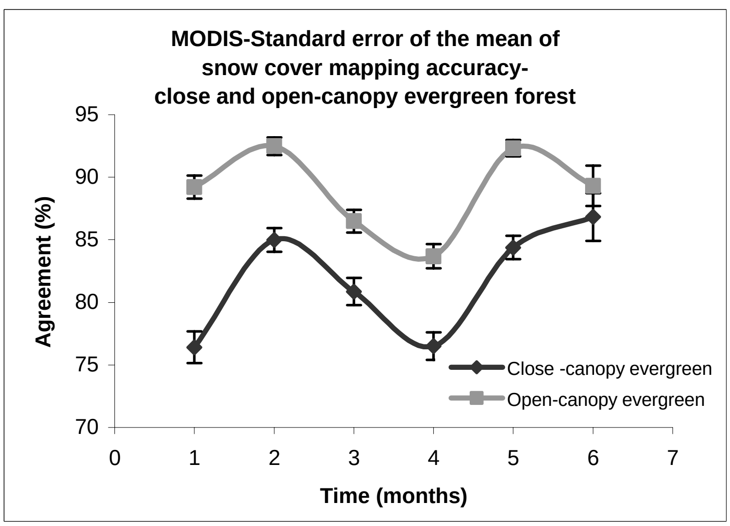


Figure 8. Snow cover mapping assessment of the MODIS snow product for close- and open-canopy evergreen forest.

Back to page 10

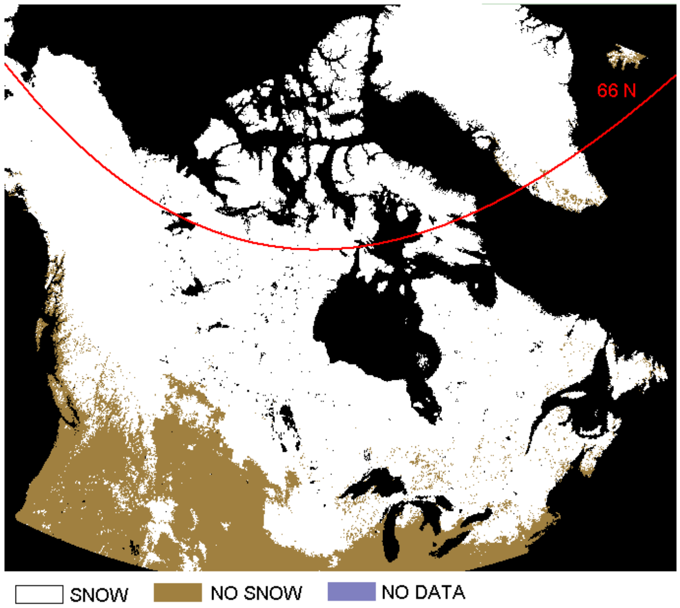


Figure 9. Snow cover extent over Canada derived by the NOAA GOES+SSM/I snow product for March 22, 2001. Note: AVHRR observations are included north of 66° latitude for the visual purpose only.

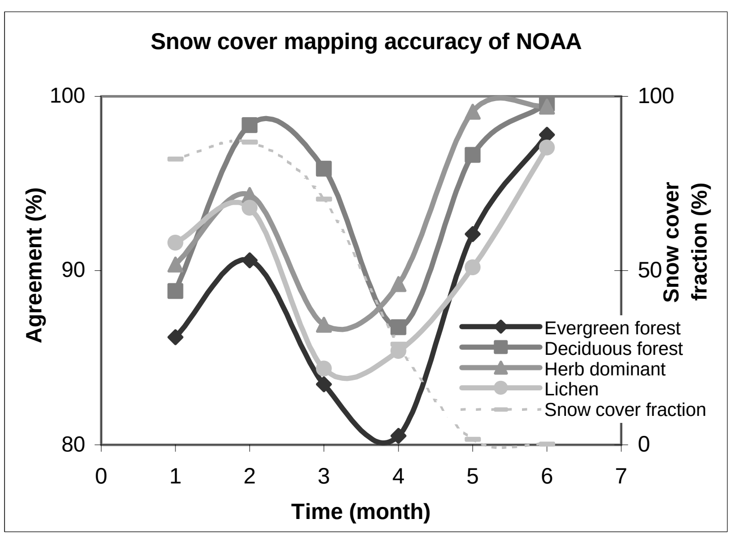


Figure 10. Snow cover mapping assessment of the NOAA GOES+SSM/I snow product over Canada from January to Jun 2001.

Back to page 10

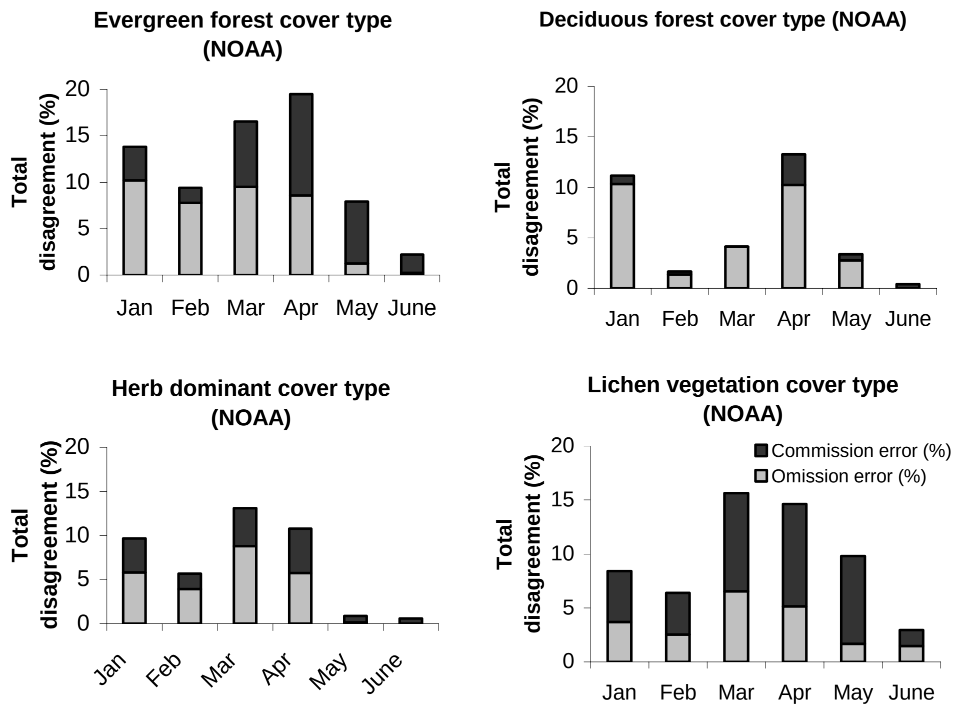


Figure 11. Ratio between omission and commission errors for the NOAA GOES+SSM/I snow product within four land cover types.

Back to page 10

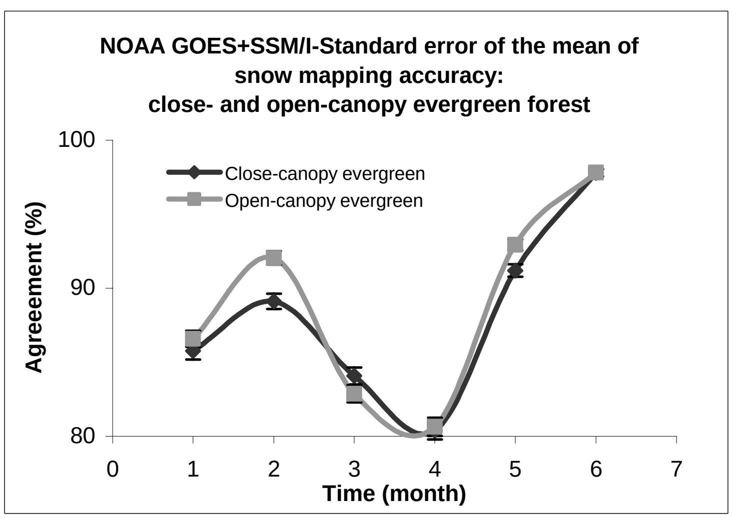
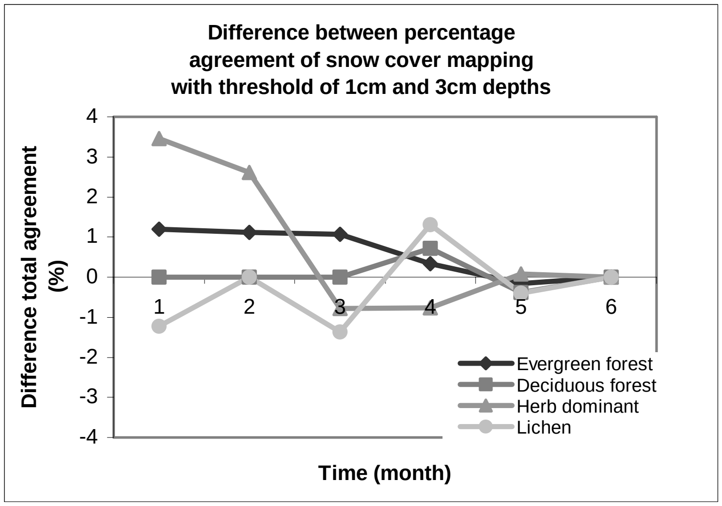


Figure 12. Snow cover mapping assessment of the GOES+SSM/I snow product for close- and open-canopy evergreen forest.

Back to page 11

a)



b)

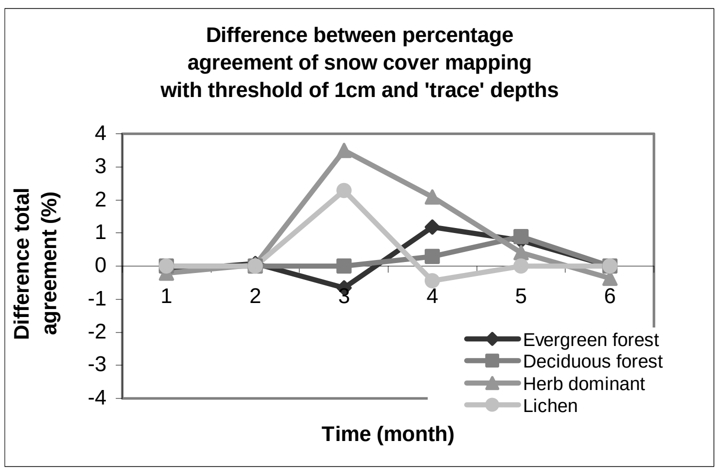


Figure 13. Difference between percentage agreement of snow cover mapping with the reference threshold of 1cm and a) 3cm, and b) 'trace' snow depth. Note: The positive difference denotes the higher percentage agreement of the reference threshold of 1cm; the negative difference denotes the lower percentage agreement of the reference threshold of 1cm.

Back to page 11

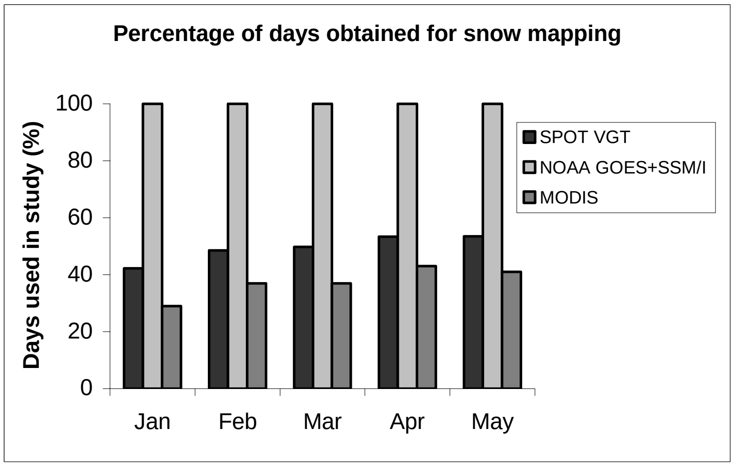


Figure 14. Percentage of days with mapped snow cover for each product. The calculations are bases on the number of pixels, which correspond to the locations of surface observations.

Back to page 11