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A comparison of optical-band based snow extent products during spring over North America

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ABSTRACT

We compare the performances of two widely used hemispheric scale snow products during April, May, and June over North America. The Interactive Multisensor Snow and Ice Mapping System (IMS), based primarily on optical-band remotely sensed images, is the latest incarnation of a product that dates back to the 1960s and has been used as input to operational weather forecasting models as well as for establishing the historical climatology of snow extent over land surfaces. NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) has been used for numerous applications since it was launched aboard the Terra satellite platform in 1999. The MODIS snow product is based primarily on optical-band reflectances. We include in our analysis only observations that are largely unobstructed by clouds as determined using the MODIS cloud detection algorithm. Then, after removing the influences of terrain and projection errors, we identify regions and land surface types where discrepancies between these two products occur. We also compare IMS and MODIS to the snow reanalysis produced by the Canadian Meteorological Center (CMC).

We find that on seasonal time scales, the most pronounced differences between the IMS and MODIS snow products occurs during the ablation season over North America. Our results corroborate earlier studies showing pronounced differences over the northern tundra in June, where MODIS appears to be in agreement with other observations; as well as differences in April and May in the boreal forest, where evidence suggests that both products may be biased (although MODIS biases may be smaller) in comparison with the CMC product (which is based on station observations). The influence of clouds may be a factor even though the analysis includes only clear days. Another possible explanation for these discrepancies involves the impact of numerous small lakes over the North American landscape on the interpretation of satellite retrievals in the visible band, although there are other potential sources of error in both products. For example, comparison to the CMC reanalysis suggests that MODIS may be overestimating snow during the ablation season in the boreal forest. The resolution of these discrepancies may affect our understanding of the seasonal snow cover cycle, the evaluation of and development of parameterization schemes for climate models, and the development of a climate data record for snow cover.

1. Introduction

Recent dramatic changes in earth's cryosphere (ACIA, 2004; Hanna et al., 2008; Serreze et al., 2009; Stroeve et al., 2007) have highlighted it as an early indicator of global change. In fact, a figure showing a time series of Northern Hemisphere snow extent, the subject of this study, figured prominently along with temperature and sea level in the recent Fourth Assessment Report of the Intergovernmental Panel for Climate Change (Soloman et al., 2007). However, observational uncertainties in snow extent remain, and the refinement of our ability to observe these variables with quantifiable confidence limits has taken on increased importance.

Snow cover over Northern Hemisphere lands is the component of the cryosphere with the largest seasonal change in spatial extent (Gutzler & Rosen, 1992; Robinson et al., 1993; Robinson & Frei, 2000). On decadal time scales, snow variations over Northern Hemisphere lands have also been significant (Barry et al., 1995; Brown, 2000; Derksen et al., 2004; Frei et al., 1999; Mote, 2006; Ye, 2000). Furthermore, our expectation is that upcoming changes in this century will be even more dramatic (Frei & Gong, 2005; Raisanen, 2007; Ye & Mather, 1997) and spatially and temporally complex (Brown & Mote, 2009; Nolin & Daly, 2006). In addition to its role as a climate indicator, snow cover plays a significant role as a climate driver through its role in modulating the earth's radiative, thermal, and water balance (Zhang, 2005). The use of snow observations in studies of climate feedbacks (e.g. Fernandes et al., 2009; Ge & Gong, 2009; Sturm et al., 2005), in the evaluation of climate models (e.g. Brown & Frei, 2007; Frei et al., 2005; MacKay et al., 2006; Roesch,

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2006, 2007), and in the development of long-term records of climatic variations (Robinson & Estilow, 2008) underscore the importance of documenting the accuracy of snow observations.

The data set that has been most widely used for operational charting for daily input to weather forecasting models, as well as for historical climatological analysis of large scale snow cover extent (SCE), was historically produced by the US National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite and Data Information Service (NESDIS), and has recently been transferred to the National Ice Center (NIC) (Helfrich et al., 2007; Matson & Wiesnet, 1981; Ramsay, 1998; Robinson et al., 1993). In 1997 NOAA changed the production of snow charting, and began using the Interactive Multisensor Snow and Ice Mapping System (IMS), with improved spatial and temporal (daily) resolutions. IMS is a Geographic Information System based platform with which trained analysts evaluate a variety of real- and near-real time fields, including primarily optical-band satellite observations from NOAA satellites, to estimate the spatial distribution of snow over land surfaces for daily input into weather forecasting models. (They also analyze sea ice, but that is not the subject of this study.) A number of technological advancements since 1999 have led to even higher resolution and more accurate snow mapping (Helfrich et al., 2007). As an operational necessity, the IMS product includes the analysts' best estimates of snow extent even over land surfaces that are cloud-covered and therefore obscured from the view of optical-based instruments. These estimates are based on ancillary sources, such as station reports, and on the most recent clear-sky image. A key feature of the IMS product is that human input remains an integral part of the process.

Another widely used product for recent SCE observations is NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). In 1999, NASA's Earth Observing System (EOS) Terra satellite was launched, containing five instruments including MODIS. MODIS snow cover products are derived using an algorithm that includes the Normalized Difference Snow Index (NDSI) along with other threshold tests. They provide high spatial resolution (500 m), cloud detection, and frequent coverage (daily at mid to high latitudes) (Hall et al., 2002; Hall & Riggs, 2007; Riggs et al., 2006). MODIS products include no estimate of snow cover over cloud-obscured surfaces, with the exception of a recently released cloud-gap filled product (Hall et al., 2010) which fills in cloud-obscured grid cells with information from previous days. While both IMS and MODIS are based largely on optical-band remote sensing, and their time domains are similar (both span most of the last decade), their methods of production contrast markedly: IMS is dependent on human intervention; while MODIS is fully automated, based on algorithms developed and applied globally.

Although these and other observational products, including both remotely sensed and station-based, have been compared and evaluated in a number of studies, no one product can be said to be definitively "best" (Armstrong & Brodzik, 2001; Basist et al., 1996; Bitner et al., 2002; Brown et al., 2007; Derksen et al., 2003; Drusch et al., 2004; Foster et al., 1997; Mialon et al., 2005; Mote et al., 2003; Romanov et al., 2002; Savoie et al., 2007; Tait & Armstrong, 1996). There are two key impediments to a conclusive evaluation. First, the answer depends on spatial scale, so that a single or even several surface observations may not be representative of snow across the satellite footprint (Brubaker et al., 2005; Chang et al., 2005; Kelly et al., 2004; Riggs et al., 2005). The second, and related, reason is that in most cases there is no definitive "ground truth." In general, the biggest discrepancies between products are found during the accumulation and ablation seasons, under forest canopies, over rugged terrain, and in areas of persistent clouds, patchy snow, or wet snow (Armstrong & Brodzik, 2001; Basist et al., 1996). With regards to optical-band products in particular, cloud cover presents the most significant difficulties, but land surface characteristics may play a role as well.

The IMS and MODIS products are both daily, global, automated or partially automated, and freely available. The objectives of the producers of these products are not identical, but are similar enough so that any conclusions drawn from a comparison at large spatial scales is reasonable and appropriate. This is in contrast to comparisons which use regionally-tuned products in comparison to global products: the results of such comparisons may be more difficult to interpret. The IMS and MODIS products, and many of the issues mentioned here, are reviewed in more detail by Frei (2009) and references therein.

Two recent studies have identified a discrepancy between IMS and other remotely sensed and station observations in the central Canadian Arctic (Brown et al., 2007; Wang et al., 2005) (their studies did not include MODIS). They found that the timing of snow ablation in June was delayed in the IMS product by several weeks compared with other observations. Although a definitive study identifying the reason for this offset has not been published, Fernandes et al. (2009) speculate that the presence of numerous small lakes in this region may be a possible reason. We address this issue in the Discussion section.

Our preliminary comparison of IMS and MODIS across the all Northern Hemisphere lands during all seasons (not shown here) indicates that, on seasonal time scales, the most pronounced differences are during the ablation season, including April, May, and June, over North America (although other locations during individual months do have significant differences); hence, this is the focus of our study. We remove, as much as possible, the influence of clouds, topography, and reprojection errors, as described in the Methodology section, and then identify regions and land surface types where discrepancies between these two products are found. Analyses at smaller spatial scales for smaller regions of interest, that utilize higher resolution versions of these products, and possibly higher resolution ancillary information including both remotely sensed (e.g. AVHRR) and surface observations, and possibly the recently released cloud-gap filled MODIS product (Hall et al., 2010) are left for subsequent studies.

2. Data and model output

The time domain of our analysis includes the months April, May, and June for the period 2001–2009. For IMS we choose the 24 km, rather than the more recent 4 km, product because it is available for a longer period of record, and is appropriate for large scale analyses. IMS is produced daily on a Northern Hemisphere polar stereographic (PS) projection. IMS maps and data can be found at http://www.natice.noaa.gov/ims and nsidc.org.

MODIS is available in a variety of spatial scales and geographic projections (Hall et al., 2002, 2005; Riggs et al., 2005). MODIS products are available at 500 m, but many of the products are scaled up. We choose the.05° daily Climate Modelers Grid (CMG) (MOD10C1), which is produced on a geographic (latitude/longitude) projection, because it has higher spatial resolution than the IMS 24 km product and also includes fractional snow and fractional cloud coverage. We utilize the cloud fields to identify days with views that are sufficiently unobstructed by clouds for inclusion in our analysis. To facilitate comparison of the two products, MODIS snow and cloud fields are reprojected onto the IMS 24 km PS grid as described in the Methodology section. MODIS maps and data can be found at modis-snow-ice.gsfc.nasa.gov/modis.htm and nsidc.org.

2.1. Land cover

To identify the surface types over which the two products disagree, we utilize the MODIS-based International Geosphere–Biosphere Programme (IGBP) 1-kilometer land cover classifications produced by the Boston University Department of Geography and Environment (Friedl et al., 2002) (available at http://www-modis.bu.edu/landcover/). This product includes seventeen land cover types of which several are important for our study (Table 1).

Because the prevalence of lake-covered terrain over the formerly glaciated North American landscape may be important for some of our

Table 1
IGBP land cover classifications based on MODIS (Friedl et al., 2002) and geographic relevance for this study.

#	Land cover classification	Geographic relevance for this study
0	Water	Prevalence of lakes across the North American boreal forest and tundra regions
1	Evergreen needleleaf forest	North American boreal forest
2	Evergreen broadleaf forest	
3	Deciduous needleleaf forest	
4	Deciduous broadleaf forest	
5	Mixed forest	Southern and eastern boundary of the North American boreal forest
6	Closed shrubland	
7	Open shrubland	North American Tundra, or low Arctic
8	Woody savannas	
9	Savannas	
10	Grasslands	
11	Permanent wetlands	
12	Croplands	
13	Urban and built-up	
14	Crop/natural vegetation	
15	Snow and ice	
16	Barren or sparsely vegetated	High Arctic, mostly Canadian Archipelago
17	Unclassified	

results (see Discussion section), we also include the 1-km resolution land surface water-fraction product for Canada produced by the Canada Centre for Remote Sensing (Fernandes et al., 2001). This product is fractional, and includes more of the smaller lakes, resulting in a higher (and more accurate) estimate of the portion of the land surface covered by water. When reprojected onto the coarser IMS PS grid we can estimate the fractional coverage of each land surface type within each cell.

2.2. Elevation

We use the GTOPO30, global digital elevation model (DEM) with a horizontal grid spacing of 30 arc sec (approximately 1 km). GTOPO30 is developed by U.S. Geological Survey's EROS Data Center in Sioux Falls, South Dakota by merging several regional and continental DEM products. In our study, when the finer resolution GTOPO data set is reprojected onto the coarser IMS PS grid, we estimate the topographic variation within each cell to remove areas with potential errors associated with reprojection, as discussed in Section 3. The GTOPO30 DEM product can be found at http://www.webgis.wr.usgs.gov/globalgis/gtopo30/gtopo30.htm.

2.3. CMC model output

Snow depth from the Canadian Meteorological Center (CMC) Daily Snow Depth Analysis includes a hybrid modeling/observational approach based on optimal-interpolation of daily snow depth observations from over 8000 stations from the US and Canada, with snow density estimated from a simple snowpack model (Brasnett, 1999). This model output is considered most dependable over regions with significant station coverage, which is generally south of 55° North. Over most of the Arctic, where there are few observations, the analysis is based mostly on model results, and is skewed towards snow depth observations at coastal locations with observing sites at open areas near airports. Snow at these sites tends to be shallower and to melt out earlier than snow in surrounding terrain. Nevertheless, this analysis is considered to be a reasonable estimate of snow over data-poor Arctic regions, and has been used in a number of studies (Brown & Mote, 2009).

3. Methods

Our methodology is designed to minimize the influences of: clouds and terrain; the differing production methodologies, spatial resolutions, and geographic projections of the two products; as well as our reprojection procedure. We also make every effort to test the sensitivity of our results to our quantitative assumptions; as described in this section, the results are robust. The comparative analysis is performed, and all results are presented, on the IMS 24 km PS projection. This requires the reprojection of all other input fields described in Section 2. The higher spatial resolution of the MODIS CMG grid results in ~80 (~15) MODIS CMG grid cells being averaged for each IMS 24 km PS grid cell near 70N (30N).

Reprojection, especially of data that has been reprojected previously, can introduce spurious errors. For this study, such errors are likely to be most significant over mountainous terrain, where a small spatial displacement can result in a very different elevation, slope, aspect, and snow regime. To remove this problem, we mask out regions with "variable" terrain, and consider only those results that are widespread over large, coherent regions of relatively flat terrain. We experimented with a number of different criteria to define "variable terrain", with consistent results. The results presented here have a variable terrain mask that includes all IMS PS grid cells within which the GTOPO 30 DEM elevation field has a standard deviation >100 m.

The goal is to make the comparison between the IMS and MODIS snow products under clear-sky conditions. To eliminate, as much as possible, the influence of clouds, we utilize the fractional cloud cover field provided with the MODIS product. At each grid point, we choose only days that are "clear" according to the MODIS cloud mask. We performed this analysis using a number of different criteria for "clear", with consistent results. However, a too-strict definition of "clear" (e.g. including only 100% cloud free images) leaves few days available for analysis in most regions, making a meaningful comparison impossible; a too-loose definition includes images that are significantly obscured by clouds, defeating our purpose. The results presented here include MODIS cells that are considered clear if their fractional cloud cover is <20%. Then, as the reprojection procedure maps numerous MODIS cells onto each IMS cell, we retain for analysis only those IMS cells within which >80% of the MODIS cells are considered clear. Note that the MODIS cloud mask is considered conservative, in the sense that it overestimates cloud amount, so that our choice of "clear" days is likely to be robust.

Subsequently, we convert the MODIS higher resolution results into a binary (i.e. snow/no snow) product for comparison to the IMS 24-km binary product. We perform the conversion using two different methods, with virtually indistinguishable results. In the first method, the MODIS fractional snow cover in each IMS grid cell is calculated as the mean snow fraction of all clear MODIS cells. For comparison to the IMS binary (i.e. snow/no snow) product, each MODIS regridded value is considered "snow" if >=50% of the clear portion of the cell is snow covered; it is considered "no snow" otherwise. This is equivalent to assuming that, on average, the cloud-obscured portion of the cell has the same fractional snow cover as the clear portion. In the second method, each MODIS regridded value is considered "snow" if >=50% of the MODIS cells have a snow cover fraction of >=50%. All results presented here use the second method, which is likely more akin to the actual production of the IMS 24-km product, which is derived from the IMS 4-km binary product.

We also compare both IMS and MODIS to the CMC snow analysis. Because the CMC model estimates snow depth at each point, rather than a binary "snow" or "no snow" designation, we must choose a threshold value below which we assume that the satellite sensors see no snow, and above which they see snow. We ran the analysis using both a 2.5 cm, as used in earlier studies (Frei et al., 2003), and a 5 cm threshold value, with consistent results. The figures show results using the 2.5 cm cutoff.

4. Results

Fig. 1 shows, for each month, the average number of clear days per month across our study domain. During April and May, significant

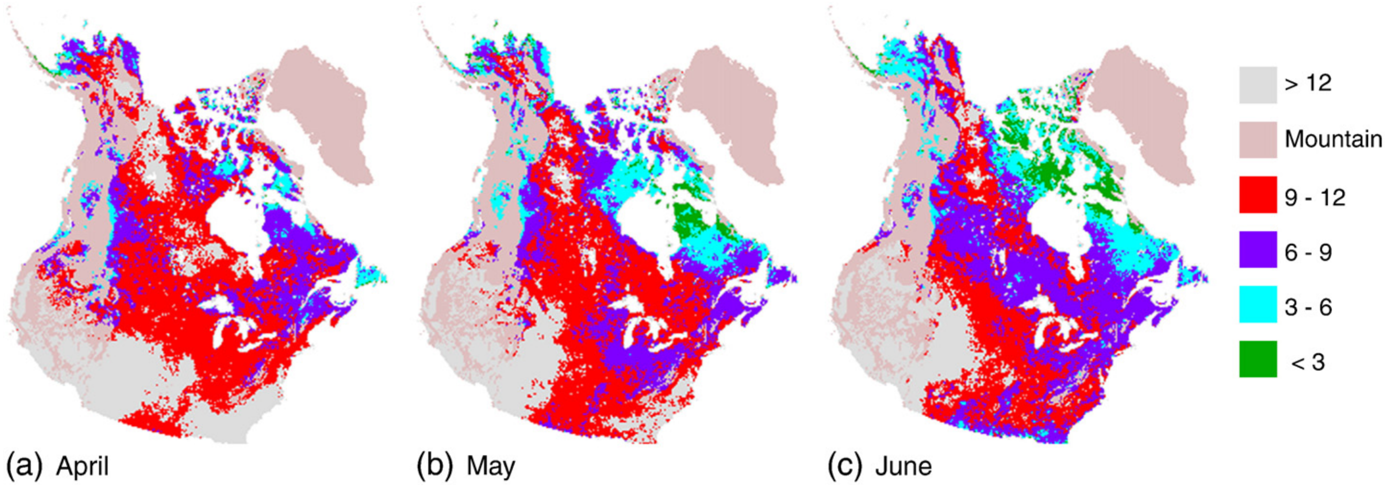

Fig. 1. Average number of clear days per month for April, May, and June 2001–2009. Clear days are identified as described in the text using the MODIS snow product cloud mask. Mountainous terrain (as defined in text) and Greenland are excluded from this analysis.

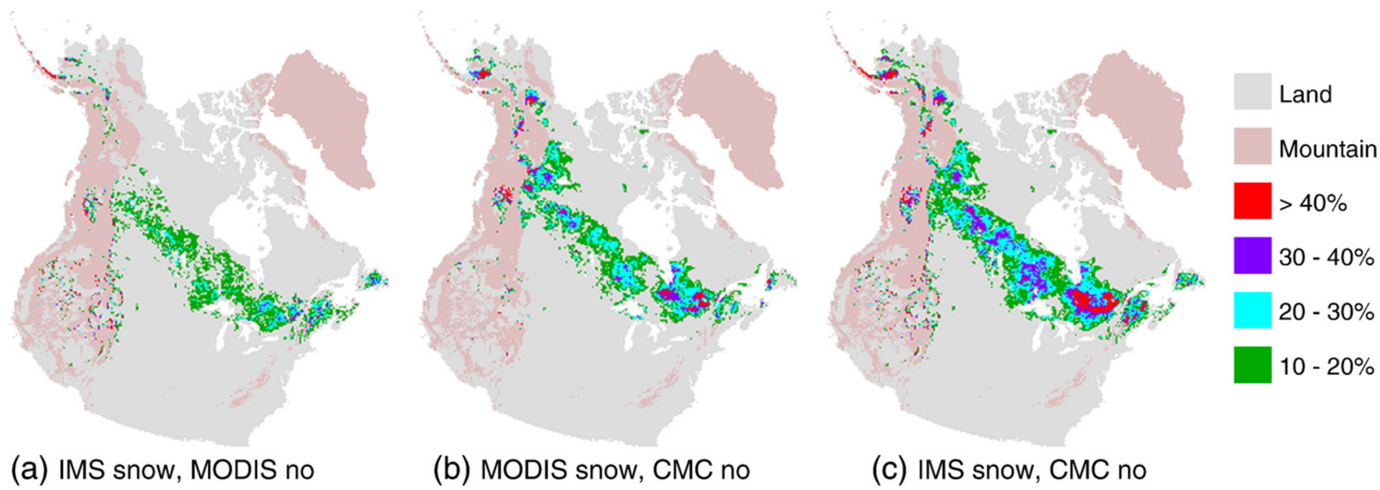

Fig. 2. Results from April 2001–2009. (a) Percentage of clear days when IMS has snow and MODIS has no snow. (b) Percentage of clear days when MODIS has snow and CMC has no snow. (c) Percentage of clear days when IMS has snow and CMC has no snow. Grid boxes with significant elevation gradients ("mountain"), as well as Greenland, are excluded in this analysis.

portions of the continent experience an average of 9–12 clear days per month. June tends to be cloudier, with significant regions experiencing 6–9 clear days per month. The Arctic portion of the continent tends to be cloudier than more southerly regions in each month. Nevertheless, a substantial number of days during our 2001–2009 time domain are available to evaluate product differences.

Figs. 2, 4, and 6 (one figure for each month) each shows three maps. Panel a in these figures shows the percentage of clear days during which IMS detects snow but MODIS detects no snow. Panel b shows the percentage of clear days during which MODIS detects snow and CMC detects no snow. Panel c shows the percentage of clear days during which IMS detects snow and CMC detects no snow. The same set of clear days is used in all comparisons.

We also examined maps where the biases were in the other direction (e.g. when MODIS detects snow but IMS detects no snow), but do not show them because they are essentially empty maps. This is because the differences between these products tend to be unidirectional, rather than being randomly distributed. The differences are summarized in Table 2, which shows, for each pair of products, the number of grid points where one product shows snow, and the other product shows no snow, during at least 10% of clear days. IMS shows snow in more grid cells than MODIS; and MODIS shows snow in more grid cells than CMC; and, the differences are by an order of magnitude. These results are discussed in more detail below.

4.1. Results in April

Fig. 2a shows grid points during April over which IMS shows snow to the exclusion of MODIS during at least 10% of clear days. Similarly, panel b shows where MODIS shows snow to the exclusion of CMC, and panel c shows where IMS shows snow to the exclusion of CMC. The shades denote different categories according to the percentage of clear days during which differences are found. The differences occur in a coherent region that corresponds to the southern boundary of the continental snow pack, where snow is undergoing ablation.

To evaluate the land cover categories over which these differences occur we turn to Fig. 3, which corresponds to Fig. 2a. It has four

Table 2
Number of grid points identified as "snow" in one product and "no snow" in another product during at least 10% of clear days.

	April	May	June
IMS snow, MODIS no snow	3599	4821	3307
MODIS snow, IMS no snow	345	257	20
IMS snow, CMC no snow	6655	5844	3707
CMC snow, IMS no snow	423	183	124
MODIS snow, CMC no snow	4564	2225	635
CMC snow, MODIS no snow	721	416	444

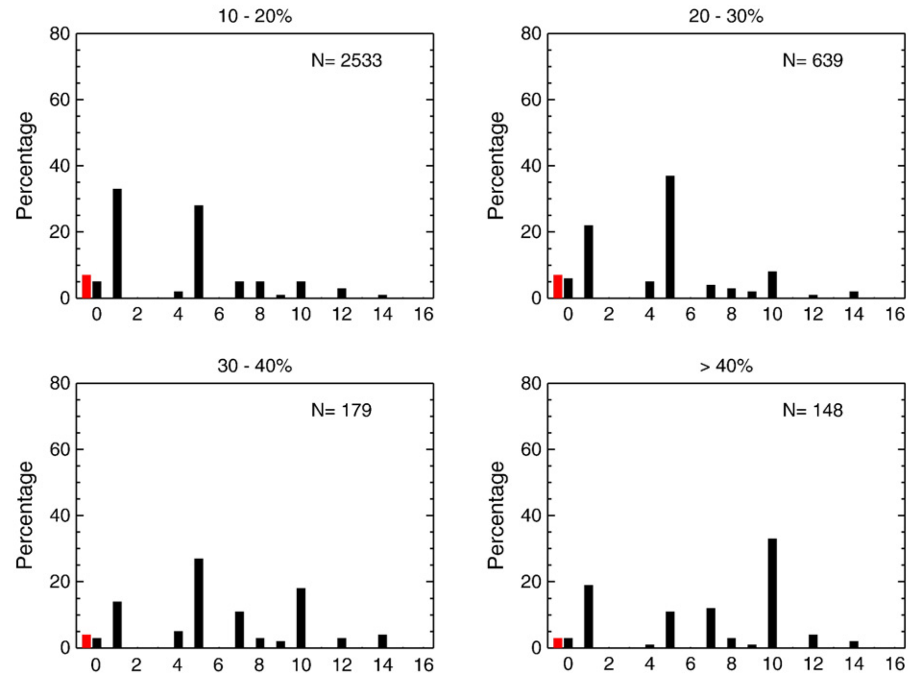

Fig. 3. Results from April 2001 to 2009. Each column chart shows the percentage of surface area covered by different IGBP land cover types (Table 1) for each category in maps from Fig. 2a (IMS has snow and MODIS has no snow). "*N*" is the number of grid cells in each category. Land cover type zero, percentage water coverage, has two values: the light shading (left) is from Fernandes et al. (2001), and the dark (right) is from MODIS. All other land cover types are from MODIS.

column charts, each of which shows the percentage of grid cells that fall within each land cover category for one of the categories in Fig. 2a. For example, the first column chart shows land cover statistics for grid cells where IMS shows snow to the exclusion of MODIS between 10% and 20% of clear days. The second column chart shows the land cover statistics for cells where IMS detects snow to the exclusion of MODIS between 20% and 30% of the time. The third and fourth charts correspond to 30% through 40%, and >40%, respectively. This figure demonstrates that in April IMS is detecting snow to the exclusion of MODIS primarily over the boreal forest (land cover type 1, the evergreen needleleaf forest) and the mixed forest (type 5) at the southern boundary of the boreal forest.

Thus, during April, when the majority of the ablation region over North America is found within the forests at the southern boundary of the continental snow pack, IMS "keeps" snow on the ground longest, and MODIS keeps snow on the ground longer than CMC. The largest differences appear in the mixed forests of Quebec rather than in the evergreen boreal forests farther north and west.

4.2. Results in May

Fig. 4 shows the results for May. As the southern boundary of the continental snow pack, along with the primary regions of ablation, moves northward from April to May, so moves the region where IMS and MODIS are biased relative to each other. In May this region includes both the boreal forest (land cover type 1) and the tundra (land cover type 7, open shrubland), or the "low arctic", but the differences are greater in the tundra (Fig. 5).

The largest differences are found in the tundra region of northeastern Canada, where IMS shows snow to the exclusion of MODIS during >40% of clear days (Fig. 5). This coincides with the region most obscured by clouds during May, averaging less than 6

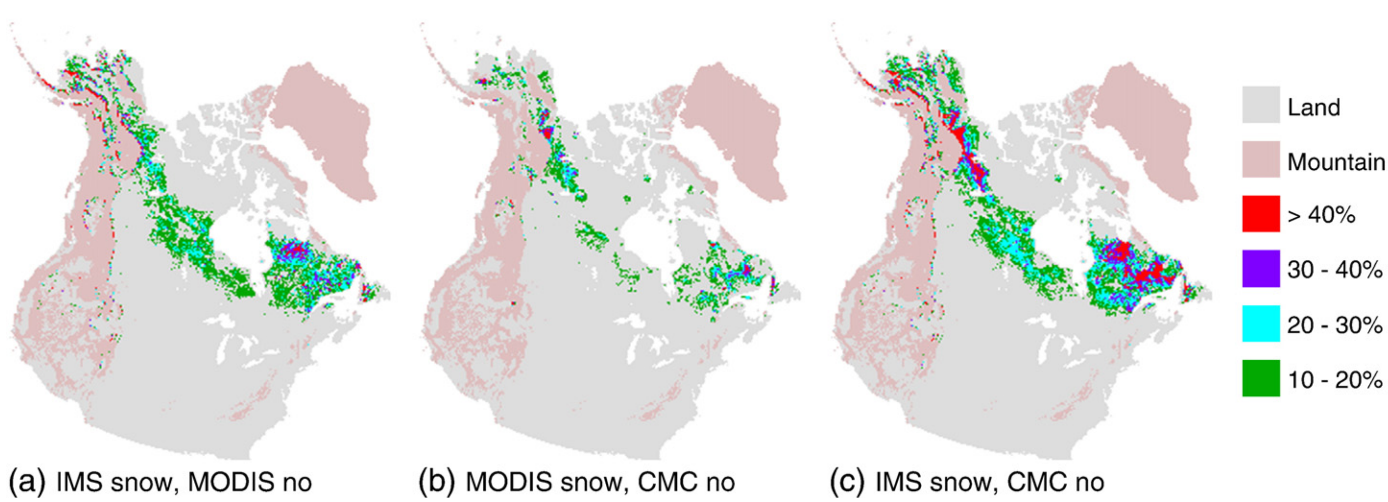

Fig. 4. Same as Fig. 2 except showing results from May 2001 to 2009.

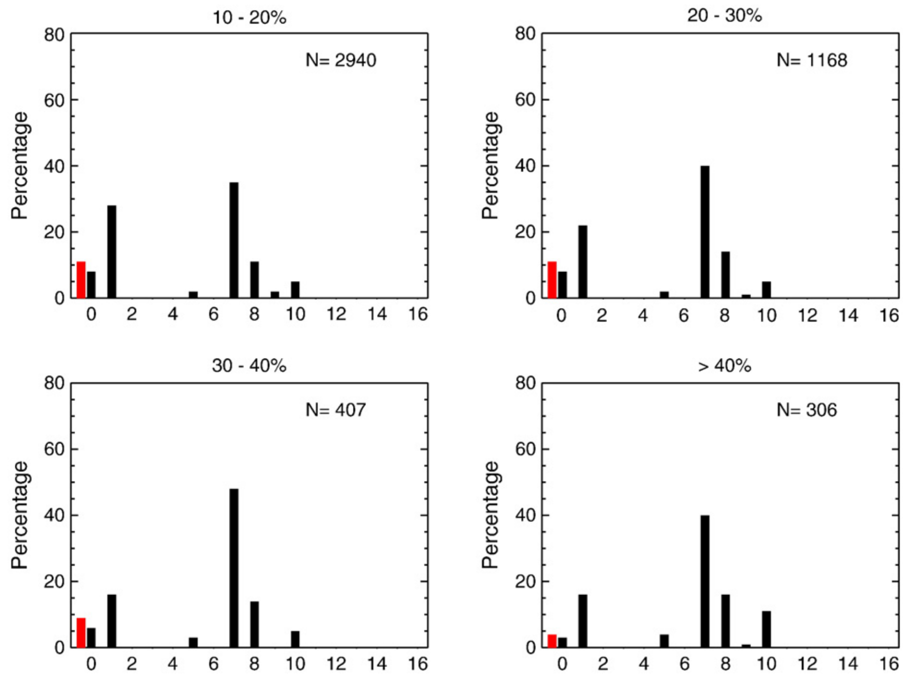

Fig. 5. Same as Fig. 3 except showing results from May.

clear days per month over many grid cells (Fig. 1b), suggesting that our method does not completely eliminate the effects of clouds (see Discussion section).

During May the discrepancies between MODIS and CMC are diminished compared to April (compare Figs. 2d and 4d). In contrast, the discrepancies between IMS and MODIS (compare Figs. 2a and 4a), and IMS and CMC (compare Figs. 2g and 4g), are not diminished in May compared to April.

4.3. Results in June

During June the continental snowpack generally ablates over the shrubland tundra of the central Canadian Arctic, with most of the remaining snow at the end of the month found in the more barren high Arctic of the Canadian Archipelago. Over a significant portion of this tundra region, IMS shows snow to the exclusion of MODIS during more than 40% of clear days (Fig. 6a), including >600 grid points (Fig. 7). The northern fringe of this region averages <6 clear days per month in June, but a majority of it experiences 6–9 clear days per month (Fig. 1c). During this month we find very little discrepancy between MODIS and CMC (Fig. 6b). The discrepancies between IMS and the other two products (Fig. 6a and g) are greater over this region than over any other region/month of our study.

5. Discussion and conclusions

In all months of our study we find differences between MODIS and IMS during clear days. These differences occur overwhelmingly because IMS detects snow to the exclusion of MODIS. As the ablation season progresses the differences appear to be more pronounced (e.g. larger percentage of clear days during which the products differ).

The differences occur over well defined regions that correspond to the ablation belt near the southern boundary of the continental snow pack, which progresses northward throughout the spring. In June, when we find the largest difference between the products, IMS detects snow to the exclusion of MODIS during >40% of clear days over a large region of the central Canadian Arctic west of Hudson Bay as well as east of Hudson Bay. During April the CMC analysis lags MODIS

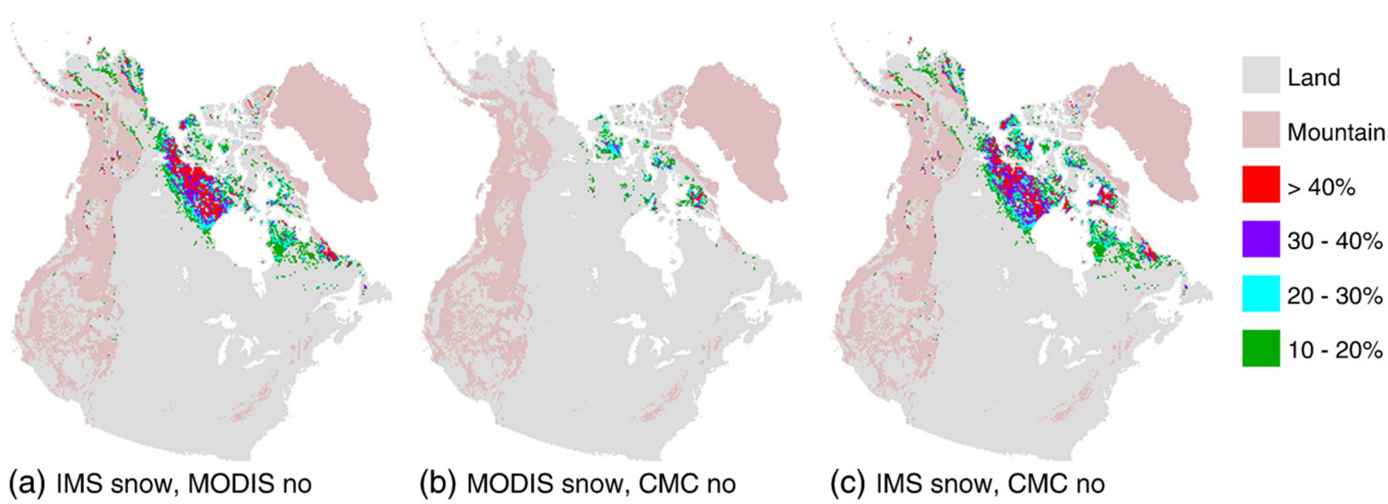

Fig. 6. Same as Fig. 2 except showing results from June 2001 to 2009.

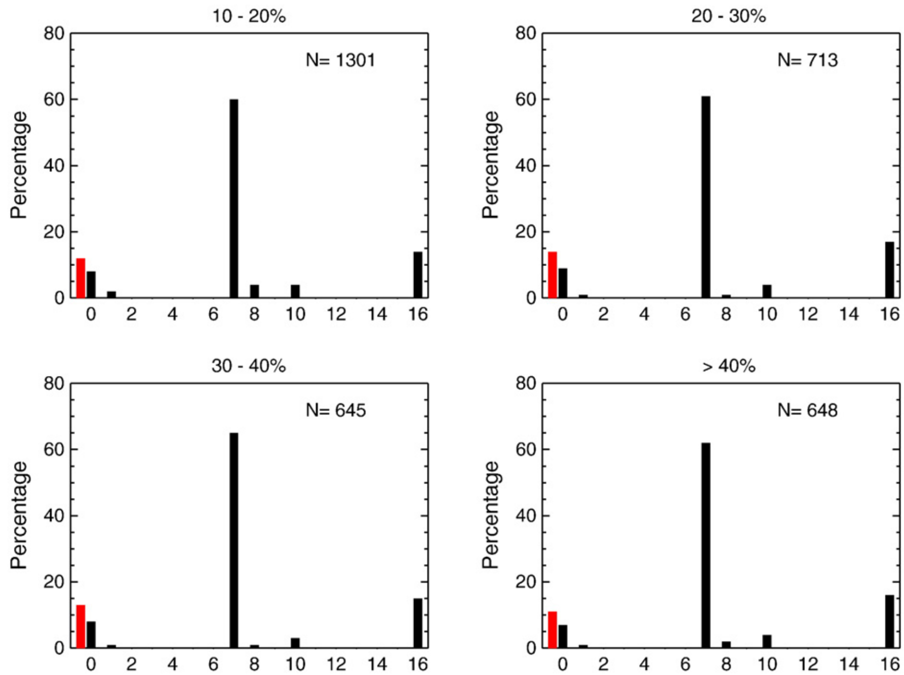

Fig. 7. Same as Fig. 3 except showing results from June.

(and therefore lags IMS by an even greater amount), but as the ablation season progresses and the ablation region progresses northward from forest to tundra, CMC and MODIS converge with each other, while diverging farther from IMS.

These monthly percentages can be used to estimate the mean time lag in snow disappearance between products, assuming that most of the days with "no snow" in a product occur after the last snow-covered day (Table 3). Using this logic, over the boreal forest in April, snow disappearance in IMS lags MODIS by 10%–20%, or 3–6 days; MODIS lags CMC by 10%–30% or 3–9 days; and IMS lags CMC by 20%–40% or 6–12 days. The differences are greatest over the forests of southern Quebec, where IMS lags CMC by >40%, or more than 12 days, over many gridpoints. In May, over large swaths of the northern boreal forest and southern tundra, IMS lags both MODIS and CMC by 10%–30%, or 3–9 days; while MODIS and CMC are largely in agreement (except over scattered grid points by 10–30%). The most pronounced differences during May are found in northeastern Canada where IMS lags CMC by >12 days over many grid points. We find the largest differences of our entire study in June, over the central and eastern Canadian Arctic, where IMS lags both MODIS and CMC by >12 days.

These results are consistent with two earlier studies which evaluated the IMS time series in June in the central Canadian Arctic (Brown et al., 2007; Wang et al., 2005). They compared IMS to other observations, including station data and remotely sensed products (MODIS was not included in those studies), finding that the timing of snow disappearance in other products was in agreement with each other, and preceded IMS by several weeks. This supports the conclusion that both MODIS and CMC more accurately discriminate between snow-covered and snow-free lands over the Canadian tundra during the June ablation period.

These other studies do not directly address the discrepancies during April and May. However, as the CMC analysis assimilates a significant number of observations south of ~55N, our results provide corroborative evidence (albeit much less certain than the conclusion for June) that in the boreal forest both IMS and MODIS may be maintaining the snow pack too long, although the bias in MODIS appears less severe.

One possible cause of these discrepancies is the presence of numerous small lakes. As a result of the glaciated history and underlying land cover of North America, much of our study domain is dotted with a density of small lakes greater than any other region in the world. According to the two land cover data sets we used, over the grid points where IMS and MODIS disagree, significant portions of the land surface is covered with water (Figs. 3, 5, and 7). The Fernandes et al. data set, which was developed specifically to include numerous small lakes that the MODIS-based land cover data set excludes, generally indicates more land covered by water in these regions, particularly during May and June (Figs. 3, 5, and 7). In contrast, the GIS lake layer used by analysts in IMS does not resolve the smallest lakes.

During the snow ablation season, lakes often remain ice covered after the surrounding land surfaces are snow-free. It is possible that lake ice is mistaken for snow on land in visible-band satellite imagery. Fernandes et al. (2001) mention this as a likely explanation, but no

Table 3
Estimated mean time lag between dates of snow disappearance in different products.

Month	Region/lags	Largest lags
April	Boreal forest: IMS lags MODIS by 3–6 days MODIS lags CMC by 3–9 days IMS lags CMC by 6–12 days	Southern Quebec forests: IMS lags CMC by >12 days
May	Northern boreal forest/southern tundra: IMS lags MODIS and CMC by 3–9 days	Northeastern Canada: IMS lags CMC by >12 days
June	Northern tundra of Central and Eastern Canada: IMS lags MODIS and CMC by >12 days	Central Canadian Arctic: IMS lags MODIS and CMC by >12 days

definitive study of this has been documented. Our preliminary analysis (not shown here) which covered the entire Northern Hemisphere during all seasons suggests that the largest discrepancies between the two products at seasonal time scales are found during the April through June period over North America, exactly when and where the ablation zone largely coincides with the lake-rich region. We speculate that the presence of lakes in the boreal forest and tundra regions of North America may be playing some role. Because neither IMS nor MODIS masks out the smallest lakes, it is possible that both products are affected by this problem. The magnitude of this effect, and whether/how much it differs between products, is unknown at this time.

However, there are likely other contributing factors. Over forested regions, it is also possible that part of the bias is associated with difficulties in identifying snow on the ground through the forest canopy (Klein et al., 1998). For example, Painter et al. (2009) present MODSCAG, an alternative algorithm to the NASA MODIS NDSI algorithm. It would be interesting to see whether alternative MODIS algorithms provide different results in the boreal forest. However, MODSCAG is tuned locally, and not currently available as a globally automated product, making the comparison somewhat problematic.

Clouds seem to play some role in these differences, despite our attempt to include only "clear" days in the analysis: some of the regions of greatest discrepancies are found in the cloudiest regions. One might think that if the snow ablates during a cloudy period, then IMS might not immediately identify the snow-free area. It is possible that IMS grid cells are not recognized by analysts as being "clear" immediately after the sky clears, although except in the cloudiest regions it seems unlikely that this would introduce a consistent delay of several weeks such as we see in June. Furthermore, our preliminary seasonal scale analysis (not shown here) indicated that during fall, even though high latitude cloud cover is more persistent than during spring, the differences between MODIS and IMS appear to be less pronounced. Clouds may be implicated in a more subtle way. It is possible that due to shading effects associated with small clearings in the cloud cover, one or both of the products may be unable to identify a change in the snow cover under a forest canopy.

One caveat is that the CMC analysis, against which the MODIS and IMS products are compared, may itself be biased. The observations on which it is based may be unrepresentative of snow ablation rates in surrounding regions (see Data section). There are some obvious ways to address this issue, but all are either inconclusive or beyond the scope of this analysis. For example, one could compare these results to a different MODIS algorithm. Such a comparison would require an algorithm that was developed and tested over the particular region of interest, which is currently unavailable. One could use higher resolution satellite images. However, the use of such high resolution imagery over a large region is impractical; and, the use of such imagery in detailed studies of one or more case study regions would be useful, but is beyond the scope of this analysis. This problem is a direct result of the paucity of snow observations at higher latitudes, for which no simple resolution is known (Brown & Armstrong, 2008).

In summary, this study presents evidence that the IMS and MODIS snow products tend to differ during the spring ablation season (April through June) over North America. IMS, in which the timing of spring ablation lags MODIS, is less consistent with other observational evidence and model results: in the tundra MODIS is very consistent with other observations, but in the forests MODIS may also be biased. The resolution of these discrepancies may affect our understanding of the seasonal snow cover cycle, the evaluation of and development of parameterization schemes for climate models, and the development of a climate data record for snow cover.

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