Natural Resources Canada   Ressources naturelles Canada

GEOMATICS CANADA
OPEN FILE 33

Evaluation of multiple datasets for producing snow-cover indicators for Canada

R.A. Fernandes, F. Zhou, and H. Song

2017

Canada

GEOMATICS CANADA
OPEN FILE 33

Evaluation of multiple datasets for producing snow-cover indicators for Canada

R.A. Fernandes, F. Zhou, and H. Song

2017

https://doi.org/10.4095/300853

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation

Fernandes, R.A., Zhou., F., and Song, H.., 2017. Evaluation of multiple datasets for producing snow-cover indicators for Canada; Geomatics Canada, Open File 33, 310 p. https://doi.org/10.4095/300853

Publications in this series have not been edited; they are released as submitted by the author.

Contents

List of Figures

List of Tables

1 Abstractas

Snow Cover is an essential climate variable. Indicators of trends in the temporal and spatial patterns of snow cover are increasingly used to both monitoring climate variability and change and quantifying regional environmental conditions. However, the choice and accuracy of the indicators are often determined by the input snow cover data. A survey of snow cover indicators is performed to identify both those that would satisfy user requirements over Canada in addition to the current practices for international reporting. Four different input data sets are then used to generate snow cover indicators over a five year period (2006-2010): the Canadian Meteorological Centre snow depth analysis with systematic in-situ measurements; cloud free MODIS MOD10C1 snow cover product; NOAA Interactive Mapping Service 4km snow cover product; and CCRS/CMC snow cover product that assimilated both CMC inputs and NOAA AVHRR satellite imagery. Then snow cover indicators, including snow cover onset and melt are evaluated through their sensitivity to documented data uncertainties, by comparison to continuous monitored in-situ sites, and through inter-comparison. Recommendations for suitable indicators as a function of input dataset are provided.

2 Introduction

Snow cover is an essential climate variable and an important component of the Earth's radiation balance due to its high albedo relative to other land surface conditions [GCOS]. The high water content and low thermal conductivity of snow packs has a significant influence on ecosystem and hydrological processes [Armstrong et al., 2009]. Snow cover also impacts transportation and winter sport opportunities. Indicators of trends in the temporal and spatial patterns of snow cover are increasingly used to both monitoring climate variability and change and assessing regional environmental conditions.

Literature review suggests that a wide spectrum of studies has been conducted to assess the impact of temporal trends in snow cover on the earth's climate and earth surface elements. In these studies, a number of snow cover indicators (see Table 1 for definitions adopted in our study) including snow cover onset date (SCOD), snow cover melt date (SCMD), snow cover duration (SCD), snow cover extent (SCE), snow depth (SD), snow water equivalent (SWE), and others have been developed and used in various environmental monitoring applications. Most applications use more than one indicator in their practices. Many studies have assessed the impact of either historical or projected climate change on snow cover dynamics. These studies reveal that some snow cover indicators (e.g., SCD and SCE) exhibit substantial interannual variability when considering historical measurements over the past 100 years to the extent [Frey et al. 2006] although statistically significant decreasing trends have been found in the Arctic [Kelly et al., 2005; Brown & Mote, 2009, Vanham & Rauch, 2009; Brown et al., 2010; Campbell et al., 2010; Liston & Hiemstra, 2011]. In spite of substantial interannual variability, snow cover indicators are expected to be sensitive to projected changes in 21st century climate. A range of studies indicate that with projected climate change, SCD is expected to be shorter, SD expected to decrease, and SCMD expected to advance relative to 20th century conditions [Kelly et al., 2005; Brown & Mote, 2009, Vanham & Rauch, 2009; Brown et al., 2010; Campbell et al., 2010; Liston & Hiemstra, 2011].

The snowpack plays a significant role in ecosystem by regulating soil temperature, moisture and other biophysical or biochemical processes underneath. Studies have found that plant phenology and variation [Euskirchen et al., 2007; Wipf et al., 2009; Munoz Jimenez & Garcia Romero, 2009], and wildlife (e.g., boreal duck population) [Drever et al. 2012,] are closely associated with snow cover trends. For example, Garcia-Romero et al., [2010] observed over the xx region, a significant reduction in rainfall volume and SCD in the presence of increasing air and soil temperature, resulted in plant type replacement – herbaceous plants that are highly correlated with a long snow permanence and abundant of snow melting water have been replaced by leguminous shrubs which grow away from the influence of snow. Drever et al. [2012] used SCD as a proxy for phenological timing of wetland ecosystems to examine how SCD during spring and during the entire snow season affect population dynamics of duck species breeding in the western boreal forest of North America. They concluded that population growth rates of scaup and scoter were positively linked to spring SCD.

Snow cover and its dynamics have strong influences on hydrological process. For some regions, snow is an important source of water supply, either for river flow, ground water recharge, or soil moisture for agricultural production. Snow cover indicators are used to assess the impact of snow cover variability and change on river flow and water resources management. Studies found that shorter SCD or earlier SCMD usually results in increased water flow in winter and decrease in spring and summer, and has effect on water availability and groundwater recharge [Vanham & Rauch, 2009; Vanham et al., 2009]. Study also finds that variation in SWE represent the second largest component in variations in water supply over the arid northwestern China [Li, 1999]. Wang & Xie [2009] suggested that SCD, SCOD, SCMD and SCE together can provide critical information on spatial variation of snow conditions, and for local water agencies for planning water use and management of snow-caused disaster.

Snow cover data are also used in the study of many other areas such as ground temperature, permafrost, and tourism etc. For example, it is revealed that decreasing SCD would result in permafrost degradation [Tanarro Garcia et al., 2010], and the ground thermal regime is sensitive to variations in the timing and duration of seasonal snow cover. A modelling study over the Alaskan North Slope found that a 10-day delay in SCOD and SCMD would result in an 2degree decrease in annual ground temperature within the first 1 m [Ling & Zhang, 2003]. The presence of snow (period between SCOD and SCMD) enables the development of winter tourism and snow-related activities [Gajic-Capka, 2011]. Study also finds the interconnetions between snow cover variations, spontaneous avalanche and avalanche accidents [Valt et al., 2009].

The studies reviewed indicate consistency in the definition of the snow cover indicators used. However, there is substantial variability in the spatial and temporal resolution of input snow cover information used for these indicators. The variability is especially evident when considering observational snow cover datasets [Brown 2008] that are increasingly used for regional climate impact and trend studies. Here, we focus on the sensitivity of four snow cover indicators (SCOD, SCMD, SCD in spring, SCD in fall) to four difference input snow cover datasets for climate zones across Canada: 1) Canadian Meteorological Centre (CMC) snow depth analysis with systematic in-situ measurements (Brown and Brasnett, 2002); 2) CCRS/CMC snow cover product that assimilates both CMC inputs and NOAA AVHRR satellite imagery (Fernandes et al., 2012) 3) cloud free MODIS MOD10C1 snow cover product (Hall et al., 2002); and 4) NOAA Interactive Mapping System 4 km snow cover product (NOAA 2008). Indicators generated from the datasets are evaluated over a five year period in terms of their sensitivity to documented dataset uncertainties, by comparison to continuous monitored in-situ sites, and through inter-comparison. Recommendations based on the study for suitable indicators as a function of input dataset are discussed and provided in the following sections.

Table 1. Snow cover indicators and definitions [Arctic Climate Impact Assessment, 2006].

Indicator	Definition	Unit
Snow Cover Onset	Day of year of the first 14 day period with at least 12 snow cover days	Day of year
Snow Cover Melt	Day of year of the first 14 day period after snow cover season with at least 12 snow free days	Day of year
Snow cover duration in fall	Number of days of snow cover between August-January	Day
Snow cover duration in spring	Number of days of snow cover between February-July	Day

3 Methods and Datasets

3.1 Datasets

Three snow cover products (CCRS, NOAA, MODIS) with high spatial resolution (0.05degrees to 1km) and temporal resolution (daily) are explored for the snow cover indicator study. In addition the CMC 24km spatial resolution daily snow depth product is also used primarily as it relies on only in-situ observations rather than satellite data. The datasets are summarized in Table 2 and some detailed description can be found below.

Canadian Meteorological Centre (CMC) Northern Hemisphere daily snow depth: This data set consists of Northern Hemisphere daily snow depth analysis data processed by the Canadian Meteorological Centre. Snow depth is monitored in-situ at climate stations operated by the Meteorological Service of Environment Canada, Canadian provinces and territories and some local weather networks. Snow depth data obtained from surface synoptic observations (SYNOPS), meteorological aviation reports (METARS), and special aviation reports (SAs) were acquired from the World Meteorological Organization (WMO) information system and used in the CMC analyses. Specifically, station data from the United States of America are included within the snow depth analysis at the boundaries of Canadian Territory. These snow depth measurements are taken, usually daily, at each station using either a ruler or an automatic depth gauge. The recorded measurement corresponds to the average snow depth rounded to the nearest centimeter except where the value would fall below 2cm. In this case it is recorded as a trace snow depth. These measurements provide high accuracy but with limited spatial coverage ranging from about 25m diameter for manual methods to about 1m for automatic methods. The CMC analysis combines daily snow depth measurements with a background snow depth estimate based on the CMC daily snowpack model using a spatially weighted optimal interpolation scheme. As such, regions with dense measurement networks will tend towards the in-situ snow depth while other regions will tend to an estimate driven by output of the CMC GEM weather model analysis.

Canada Centre for Remote Sensing AVHRR/CMC snow cover dataset (CCRS): The dataset is generated by assimilation of daily cloud screened NOAA AVHRR satellite imagery and CMC snow depth analysis snow depth and density fields within an off-line version of the CMC daily snow depth model. The snow depth model is modified to include snowpack reflectance model and a surface radiative transfer scheme that relates vegetation and snowpack reflectance to top-of-canopy bi-directional reflectance. A logistic vegetation phenology model is used to parameterize temporal dynamics of canopy leaf area index. A per-pixel particle filter with a 30 day moving window is applied to assimilation observations corresponding to 1km resolution visible band directional reflectance and normalized difference vegetation index and 24km CMC daily snow depth and monthly snow density fields. The assimilation is forced using daily 2m air temperature and surface precipitation fields also used to produce the CMC snow depth analysis and satellite acquisition geometry. The system produces daily snow maps of snow cover fraction at 1km resolution over Canada that were sub-sampled at 4km to facilitate processing the multi-year dataset.

NOAA Interactive Multi-sensor Snow and Ice Mapping System North Hemisphere daily 4km snow cover products (NOAA): The dataset has 4km spatial resolution with daily coverage. NOAA consists of an interactive workstation for snow cover mapping by a snow analyst with tools for overlaying and interpolating snow cover information from a variety of data streams. The system relies mainly on visible satellite imagery but is augmented by station observations and passive microwave data [National Ice Center, 2008]. NOAA daily 4km snow cover data are only from 2004 and archived and distributed at National Snow & Ice Data Centre (NSIDC). More detailed description of NOAA snow cover mapping system can be found in Ramsay [1998] and Helfrich et al. [2007]. The main snow cover information is coded in the product as 1 (land), 2 (water), 3 (snow) and 4 (ice).

MODIS MOD10C1: MODIS snow products are provided as a suite of products beginning with a swath product, and progressing, through spatial and temporal transformations, to daily 0.05° global-gridded products. MODIS snow cover mapping algorithms, using visible, near-infrared, and thermal sensors, are automated thus reducing or eliminating biases due to human subjectivity. MODIS MOD10C1 is a daily global climate modeling grid (CMG) snow product at 0.05° resolution, which is about 5.6-km resolution at the Equator. Snow cover extent is mapped by processing the MODIS MOD10A1 products (a tile of daily snow cover maps at 500m spatial resolution), approximately 320 tiles of land data, for a day into the CMG. Snow cover extent is expressed as a percentage of snow observed in a grid cell of the CMG at 0.05° resolution based on the MOD10A1 cells at 500m mapped into a grid cell. A corresponding map of cloud cover percentage is also generated and stored. The snow and cloud percentage arrays can be used together to get a comprehensive view of snow and cloud extents for a day. Since the cells of the CMG may contain mixed features an expression of confidence in the extent of snow cover is determined and stored along with other QA data [Hall et al, 2002]. Since 2000 MODIS snow products are archived and distributed from NSIDC.

Table 2. Summary of datasets used in the generation of snow cover indicators.

Product Acronym	Description	Temporal Coverage	Spatial and Temporal Resolution	Reference
CMC	4 Snow depth (cm)	March 12, 1998 – on going	24km, daily	Brown, R. D. and Brasnett B. (2010)
CCRS	Snow cover fraction within grid cell.	2006 - 2010	1km (sub-sampled at 4km),daily	Fernandes et al. (2012)
NOAA	Snow free water, snow free land, snow covered surface or ice covered surface within grid cell.	February 23, 2004 – on going	4km, daily	National Ice Center (2008)
MODIS	Snow cover fraction of cloud free pixels within grid cell.	February 24, 2000 – on going	0.05°,daily	Hall et al. (2002)

5 Methods

The recorded snow cover or snow depth values for each product were converted to a binary daily snow cover or snow free status. The NOAA product conversion was straight forwards with class 1 (water) and class 2 (snow free land) labelled as snow free and class 3 (snow covered surface) and class 4 (ice covered surface) labelled as snow covered. Both the CCRS and MODIS products required a conversion from snow cover fraction to a binary snow cover status. Here a snow cover fraction less than 10% was assigned to a snow free status; otherwise the status was set to snow covered. The 10% threshold was selected for two reasons. Firstly, accuracy assessment of both products indicate an uncertainty on the order of 10% when 100% snow cover is mapped in open areas (Simic et al. 2003). Since both products are based on an ensemble estimate (CCRS is based on an ensemble of >100 particle filter solutions for a pixel, MODIS is based on up to 100 pixels in each 0.05degree grid cell) we expect approximately 10% of pixels to be incorrectly labelled. Ideally, the labelling error would balance out but the worst case would be a 10% bias in snow cover fraction. Secondly, the threshold is set close to 0% snow cover since all satellite products will tend to correspond to snow cover status in sub-pixel open areas rather than canopy masked areas. We assume that snow remains in canopies later than in open areas so a threshold close to 0% snow cover fraction will potentially reduce this bias. CMC represented the most ambiguous dataset to convert to a binary snow cover state variable. Firstly, the relationship between snow depth and snow cover can vary substantially with surface topography and vegetation. Secondly, the snow depth will be representative of the small (<25m radius) spatial support in-situ measurements that are typically taken in open areas where a zero snow depth may not be representative of snow conditions in nearby forests. Thirdly, the 24km CMC grid cells indicates substantial potential for topographic effects causing sub-grid biases in snow depth. Based on Brown et al [2008] we use a 2cm threshold below which the grid cell is assumed snow free. But, recognizing the potential for substantial local uncertainties with this threshold we only compare CMC based indicators to other products' indicators at the climate zone level. The assumption being that the uncertainties will tend to cancel when aggregated over thousands of 24km grid cells.

In this study, snow cover indicators are first generated for every grid, and then spatially averaged into the eleven climate regions spanning Canada (Fig. 1). Climate regions were selected for comparison units for three reasons. Firstly, each product will have random uncertainties related to input datasets that will propagate to the indicator derived for a single grid cell. Such random errors may average out over a long (e.g. 30 year) temporal interval but may persist in our limited 5 year study period if spatial averaging was not performed. Secondly, it is expected a priori that climate zones will tend to have similar snow cover indicator trends so averaging within a zone will tend to amplify rather than smooth systematic differences between products. Finally, as our review indicates, snow cover indicators are increasingly used for regional applications. The use of climate zones represents a first level of spatial partitioning into geographical units of relevance for impact studies. As such, our results may indicate regions where there is consistency between indicators (and hence greater confidence in using any one of the indicators) and regions where lower consistency may indicate need for more details (perhaps longer term) evaluation of the input products. With these averaged indicators for each climate zone, we conducted the detailed analysis and inter-comparison of the indicators to reveal the spatial and temporal of trends of snow cover indicators over the Canadian climate regions within the 5-year period (2006-2010), which are described in Section 3.

Figure 1. Canadian climate zones.

After conversion to binary snow cover status using the rules provided in Table 3, each product was reprojected into the 4km resolution Lambert conformal conic projection used for the CCRS product. Considering the differences in spatial resolution and projections between products comparisons of derived indicators were then either performed qualitatively when dealing with maps or quantitatively at a climate zone level.

Table 3. Snow cover definitions.

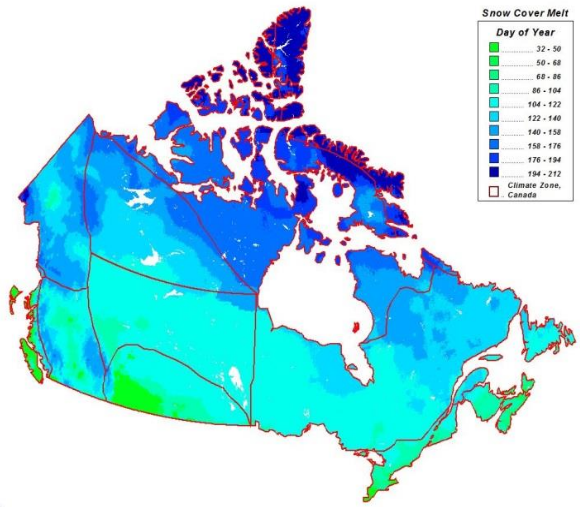
	Snow Cover Product			
	CCRS	NOAA	MODIS	CMC
Snow cover	> 10% fraction of snow cover	3 (snow)	10% fraction of snow cover	>= 2 cm snow depth
Snow free	<= 10% fraction of snow cover	1 (land)	<= 10% fraction of snow cover	< 2 cm snow depth

6 Result Analysis and Discussion

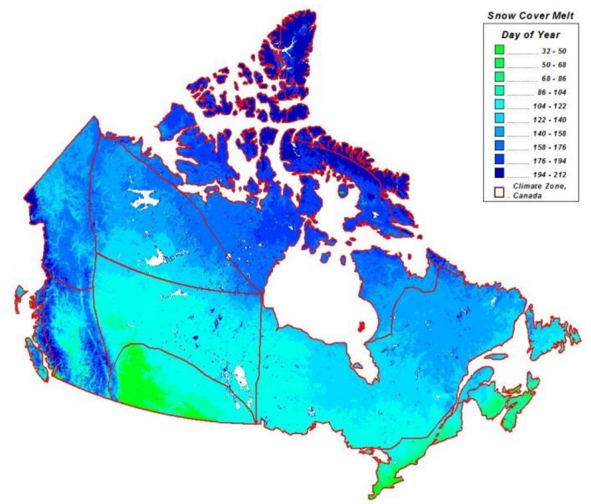
In this section, we present both a qualitative comparison of snow cover indicator maps generated from the snow cover products (CCRS, NOAA, and MODIS) and a quantitative annual averages of indicators from these products as well as the CMC product over Canadian climate regions.

6.1 Visual interpretation of spatial distribution

Figures 2 and 3 show SCMD for 2006 and SCOD for 2007 respectively. Although only one set (one year) of snow cover melt and onset maps are shown, the spatial distributions of these indicators of other years are very similar. The maps show a general agreement for the relative between climate zone patterns of both indicators. For all three products SCMD (SCOD) shows a transition from early (late) dates in the southern zones (Atlantic Canada, Great Lakes St. Lawrence and Prairies) to later (earlier) dates in the forested climate zones and the interior lower lying regions of the South British Columbia a)



b)



c)

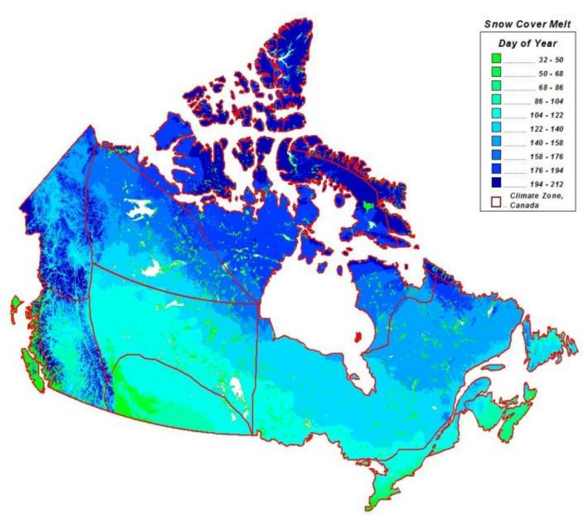


Figure 2. Spatial distribution of snow cover melt date in 2006 generated from a) CCRS b) IMS c) MODIS

a)

b)

c)

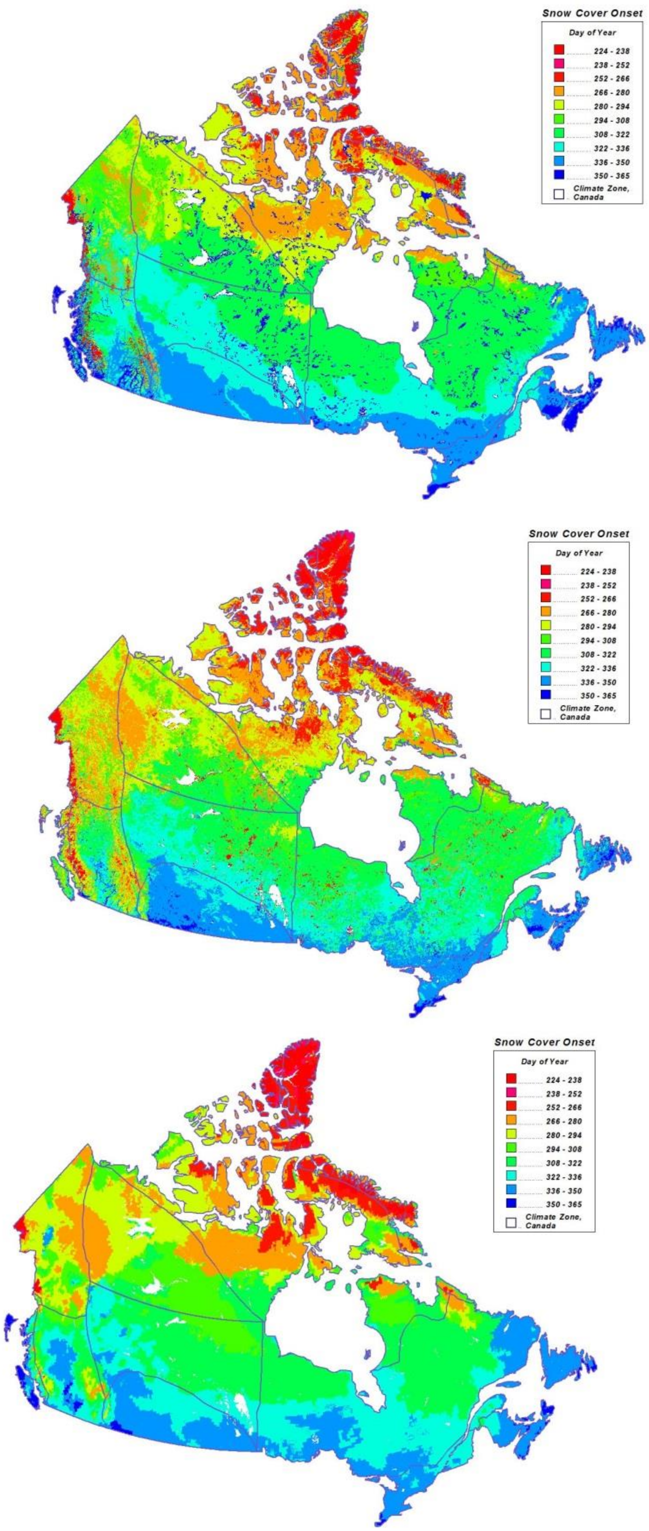


Figure 3. Spatial distribution of snow cover onset date in 2006 generated from

Mountains zone to the latest (earliest) dates in the Arctic zones. However, there are some differences evident between products. Firstly, the CCRS indicators have much less spatial detail than the NOAA and NASA products suggesting they do not put sufficient weight on AVHRR inputs. Moreover, the CCRS indicators show early (late) melt (onset) over the Rocky and West Coast Mountain ranges compared to NOAA and NOAA. Examination of the CMC snow depth fields (not shown) indicate that they also show this artifact due to the absence of in-situ stations at high altitudes. Again, the CCRS product seems to be placing insufficient weight on the locally relevant higher resolution AVHRR inputs in favour of the 24km CMC snow depth and climate inputs. The CMC product also tends to show an unrealistically late onset over the north east coast (Labrador Peninsula). Again, this may be due to the reliance on in-situ measurements on Newfoundland for CMC snow depth model estimates of snow depth over this region that, in-turn, propagate to the CCRS indicators. Other systematic biases tend to be related to land cover related issues. The NOAA product shows an unrealistically late (early) melt(onset) date over regions near waterbodies and lakes. This may be due to an overemphasis on visual interpretation over regions that are dominated by lake or river ice phenology or, for onset, due to the use of coarse (>20km) resolution passive microwave imagery that will respond strongly to ice cover within a pixel. In summary, the visual assessment suggests the least potential for artifacts in the MODIS based indicators if one is concerned about within climate zone SCMD or SCOD while there is general agreement between the three indicators across climate zones except in areas dominated by mountains.

6.2 Snow cover indicator inter-comparison over Canadian climate regions

Figures 4 and 5 show the deviation from the annual climate zone mean SCMD and SCOD across all products. For clarity the deviations are discussed in terms of the three major climate zone groupings ("southern zone" 1,2,5; "forest zones" 3,4; "mountainous zones" 6,7,8; and "northern zones" 9,10, 11). These deviations are of interest when assessing the potential use of these data for snow cover indicators. For example, a constant difference between two products for all (or most) years would indicate that they would both provide the same indicator trend. Random differences between products indicate that that at least one product (and possibly more) has a random error component. However, systematic trends in deviations cannot be assigned any weight both due to the relatively short five year comparison and due to the small ensemble of only four products.

6.2.1 Snow cover melt and onset

The southern zones show modest deviations in SCMD (<5days in most cases) with the larger (5 days to 10 days) values typically corresponding to systematic product deviations across most years and zones (e.g. MODIS is always ~5days above the mean in zone 1, and ~3% below the mean in zone 5; NOAA is about 5days above the mean in zone 5). CCRS and CMC products most frequently show the smallest deviation. SCOD shows larger deviations between products for these three zones than SCMD by a factor of almost 2 on average. However, the largest

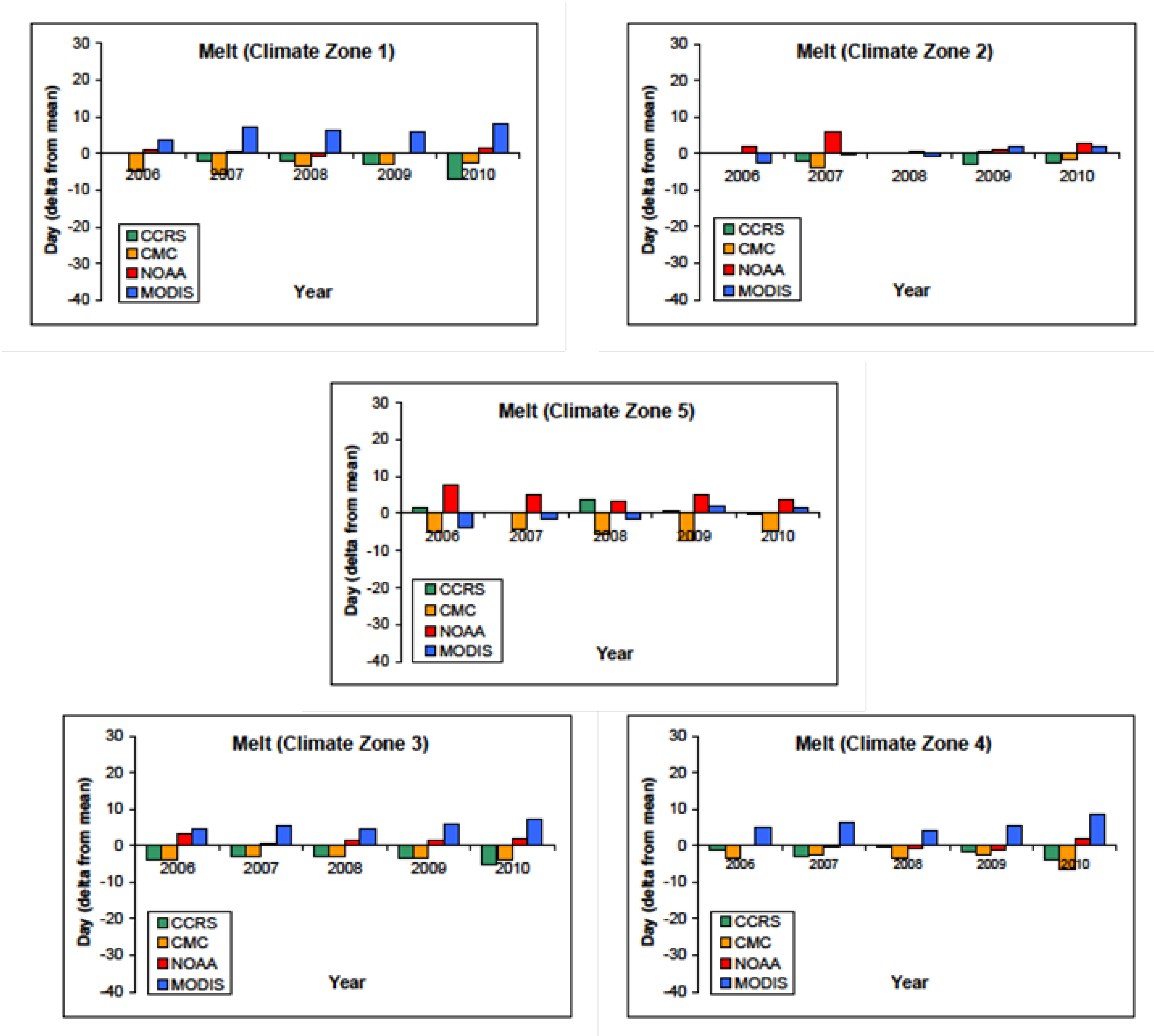


Figure 4. Deviation from the averaged snow cover melt date
(aggregated by climate zone)

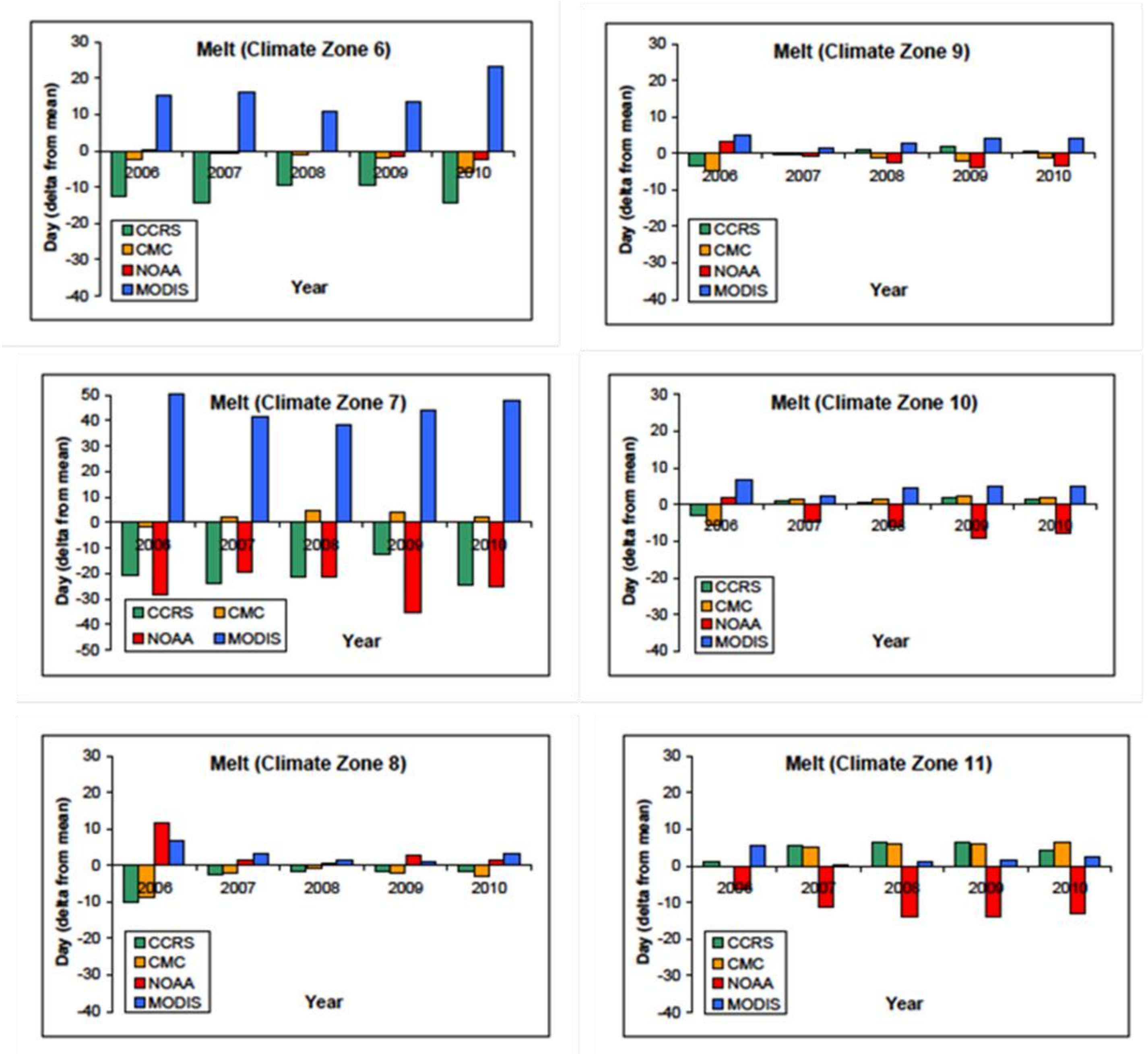


Figure 5. . Deviation from the averaged snow cover onset date (aggregated by climate zone)

deviations are almost always systematic (e.g. MODIS is biased above the mean by ~8days for zone 1); 2006 in zone 2 being the only exception (CCRS shows a positive bias and MODIS a negative bias on the order of 5days). Taken together these results suggest that all indicators are reasonably consistent for SCMD and SCOD over the southern zones with a random error of under 5 days.

The forested zones show similar magnitude deviations as the southern zones but the deviations are extremely systematic with product. For SCMD, MODIS shows a positive deviation on the order of 5 to 10 days while CMC and CCRS show negative deviations on the order of 5days and the NOAA falls close to the mean deviation. SCOD shows nearly the opposite pattern in deviations although for zone 4 the NOAA product now shares the positive deviation seen with CMC and CCRS. The systematic difference between deviations observed for MODIS versus other products clearly indicate a bias in snow cover labelling over forests between MODIS. At the same time the systematic nature of deviations across products indicates that temporal trends of indicators derived from them are expected to be stable over time.

The mountainous zones indicate large (>10d) but consistent deviations for both SCMD and SCOD between products for the southern two zones and more modest (<10d) but again consistent deviations for the Yukon and North British Columbia zone. For example, with respect to SCMD, both NOAA and CCRS differ from MODIS by between 25days to 75days in the southern two zones. Similar patterns of differences are seen for SCOD for zone 7 with the other two zones showing systematic but smaller (<10d) deviations. In contrast to the large difference to MODIS, the CCRS and NOAA deviations are generally similar (within 15days for SCMD and 10 days for SCOD). Considering that these products are based on significantly different algorithms (data assimilation versus visual interpretation) it is unlikely that the similarity is due to chance alone. These results are in some sense in opposition to the visual assessment that suggested that MODIS and NOAA were more similar than CCRS over mountainous areas. It is possible that MODIS again shows a bias to late melt and early onset seen over the forested zones but in this case the trend is pronounced. The bias may also be due to MODIS being overly conservative in cloud screening so that snow is detected later than actual onset. A third possibility is that MODIS is more accurate over mountains that all other products although this is somewhat unlikely considering that visual interpretation (NOAA) and automated mapping (CCRS) agree reasonably.

Over the Arctic zones, deviations of indicators from mean annual values are modest (<10days) for zones 9 and 10 and moderate (<15 days) for the high arctic zone 11. As with the Mountain zones, the deviations are systematic for products except for 2006 for NOAA. Moreover the CMC and CCRS products agree to within 5% in most cases. The agreement of these two products suggest that the AVHRR inputs to the CCRS assimilation scheme provide little useful information in terms of snow melt and onset. This may be due to the increased noise in the data at high latitudes due to shadowing related to acquisition geometry or simply the fact that melt and onset in the Arctic is well described using the CMC degree day model. NOAA shows a persistent 5-10day negative bias for melt and >10day positive bias for onset for the high arctic. This is possibly due to biases in visual interpretation over this region since similar biases are not seen over the more southern Arctic zones. It is noteworthy that MODIS shows an opposite early bias in onset for this zone suggesting that interpretation of satellite imagery is non-trivial at such high latitudes. In summary, the southern Arctic zone show good consistency among products for both SCOD and SCMD but the northern Arctic zone indicates relatively large biases for both NOAA and MODIS.

Even considering the potential for rather large absolute deviations in SCOD and SCMD between products the deviations need to be placed in context of the interannual variation in these indicators within versus between climate zones. . For example Figure 6 shows scatter plots with 1:1 lines for both indicators for the products based on snow cover input maps. In this case, only the Pacific Coast (zone 6) is problematic if one were to use these indicators to portray differences across climate zones rather than map within climate zone trends.

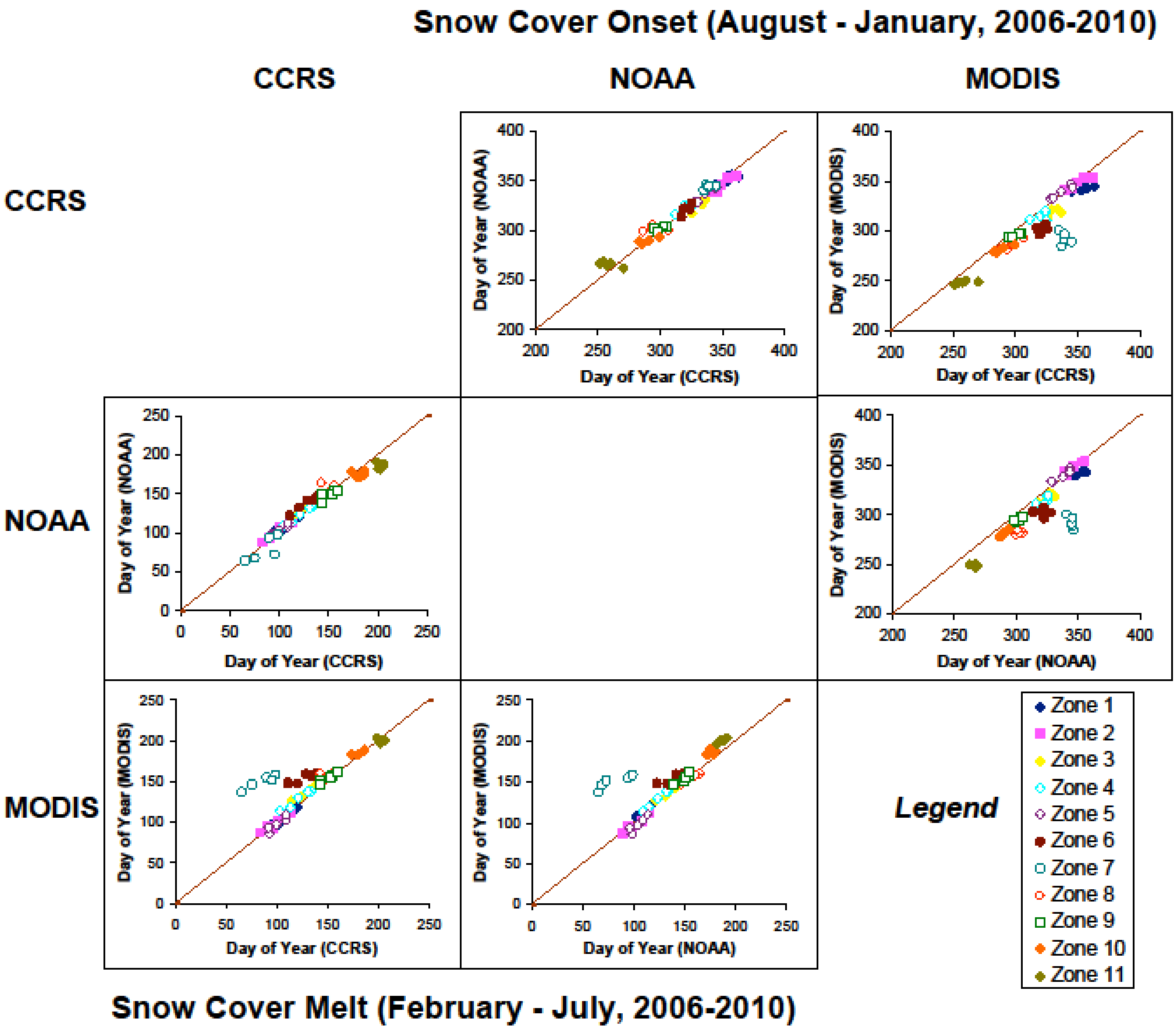


Figure 6. Inter-comparison of snow cover onset (upper right) and snow cover melt (lower left)

6.2.2 Snow cover duration in spring and in fall

Figure 7 shows the comparison of snow cover duration in fall (counted from August 1 to January 31of next year – upper right), and snow cover duration in spring (counted from February to July – lower left) of the three snow cover products (CMC is not included since strictly speaking it does not map snow cover). Unlike SCMD and SCOD, snow cover duration counts all dates in the period rather than looking for the earliest or latest consecutive set of snow covered or snow free mapped grid cells. In this sense we expect better agreement between products for duration versus SCOD and SCMD. As expected, the duration of snow cover is shorter in the south, and longer in the north, both for snow cover duration in fall and in spring. Across all products, climate region 11 (Arctic Mountains & Fiords) has the longest snow cover duration, and followed by climate region 10 (Arctic Tundra). CCRS and NOAA agree within 5% for both spring and fall duration with the exception of fall duration for zone 7 (Pacific coast). Zone 7 was previously identified as being problematic considering its relative small area that spans both a maritime climate (Victoria Island in the Pacific) and a coastal mountain range. MODIS shows more scattered agreement with CCRS and NOAA for fall snow cover with larger than 10% differences for zone 1m 6 and 7. Zone 1 and 7 are Maritime regions noted for cloud cover suggesting MODIS may have issues in cloudy areas. Zone 6 includes forested mountains where the previous analysis of melt and onset dates indicated that MODIS was an outlier amongst the products. Agreement between MODIS and other products improves somewhat for spring snow cover although MODIS still shows a large difference over the Pacific Coast zone 6.

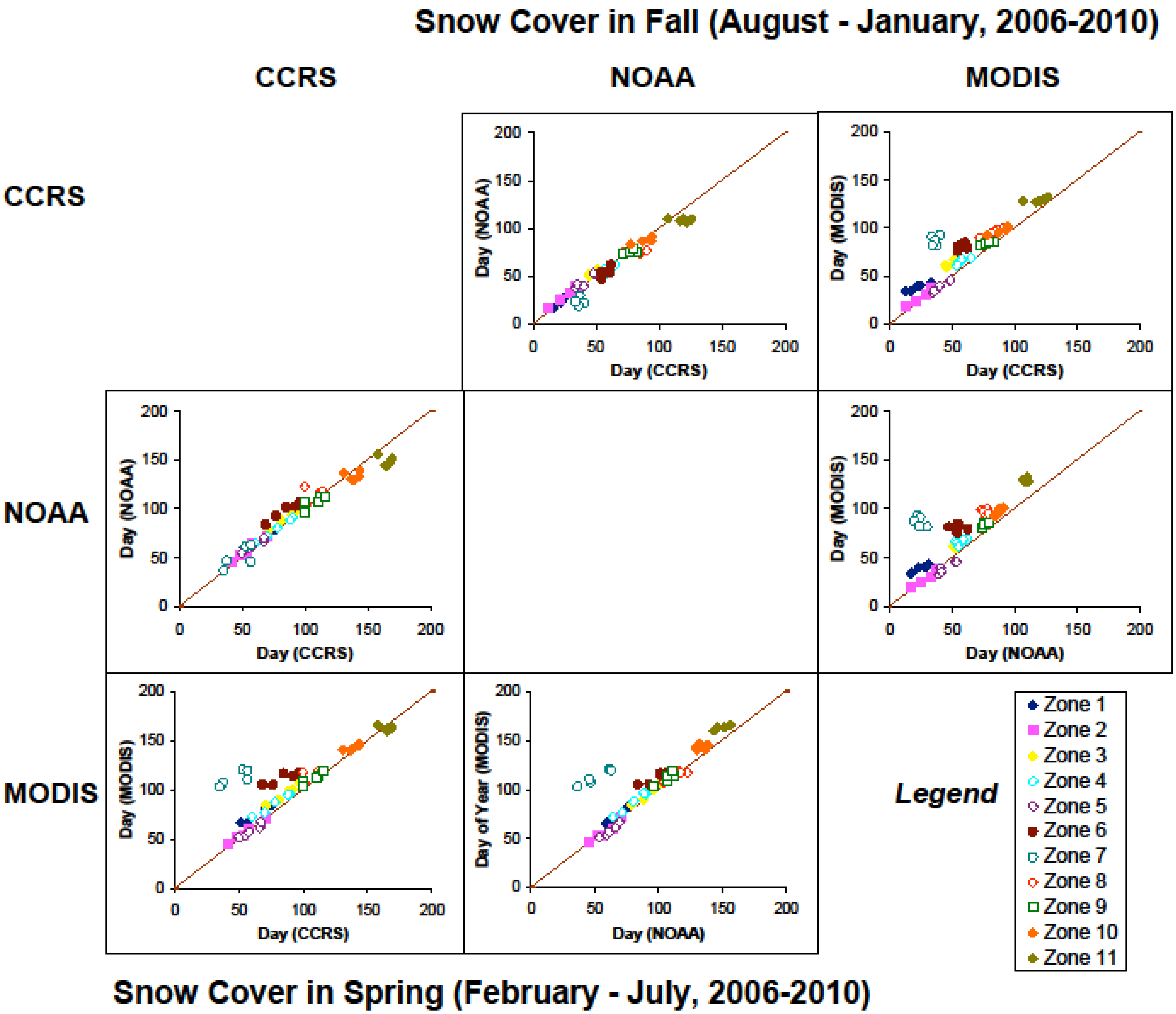


Figure 7. Inter-comparison of snow cover duration in fall (upper right) and in spring (lower left)

7 Conclusions

A comprehensive assessment of four standard snow cover indicators, snow cover onset date, snow melt onset date, fall snow cover and spring snow cover was conducted over Canada using four different input snow cover/depth datasets. A five year period was used to capture natural variability in snow cover phenology and product performance while minimizing the impact of long term changes in indicators. Comparisons were performed both visually and by climate zone.

Visual comparisons suggest general agreement for CCRS, NOAA and MODIS indicators although the CCRS indicators clearly over smoothed in areas such as the Arctic and mountainous regions. The over smoothing may be due to a combination of biases in the input CMC snow depth analysis due to the low-lying location of most in-situ stations and the sparse northern coverage of stations. The over smoothing also implies the AVHRR inputs to the CCRS algorithm are not exploited fully suggesting systematic issues with cloud screening of CCRS AVHRR imagery over cold surfaces. While NOAA and MODIS showed very good agreement in pattern there were clear regions (mountains, Arctic) where one product was consistently biased in comparison to the other.

Quantitative comparisons of SCMD and SCOD indicated either small (<5 day) deviations from the mean or systematic differences for a product when deviations were >5days. This is encouraging for the use of these products to generate trends in indicators since it suggests that they are relatively stable over time. However, except for the forested zones, agreement between products is not sufficient to produce within zone absolute indicators of melt and onset. Nevertheless, the relatively large difference in melt and onset between zones suggests that the agreement rates are sufficient even if absolute indicator values were required to compare between different zones. There is some concern that the MODIS based indicators produce a forward shift in the snow season considering that both the visually interpreted NOAA based indicators and the automated mapping CCRS based indicators show large (>20day and up to 75 day) differences with MODIS for melt and onset dates over mountains and in the Arctic. It is possible this is due to the very conservative MODIS cloud screening algorithm that may be preferentially missing snow cover pixels during onset and that may be relying on persistence to map melt due to cloudy conditions in this period related to increased water on the landscape.

Quantitative comparison of spring and fall snow cover durations across products show better agreement than for SCMD and SCOD since they average over a greater time period. As such, it may be useful to include both event based and duration based indicators to offer users options with differing levels of consistency across products.

In summary, with the exception of Mountainous and high Arctic zones, all three satellite based products can provide temporal trends in indicators that should be stable in comparison to natural short term (5 years in our study) variability in these quantities. Moreover, the CCRS and NOAA indicators could be combined to provide a stable estimate of between zone differences in the absolute value of these indicators. Further work is required to identify the cause of biases seen for MODIS base indicators and the lack of spatial detail of the CCRS indicators over mountainous and high arctic regions.

8 Acknowledgement

The authors thank Canada Meteorological Service, NOAA, NASA, and NSIDC for providing the snow cover products for the study.

9 References

Arctic Climate Impact Assessment (2006): ACIA Scientific Report.

Armstrong, R., Steffen K., Monteduro M. and Sessa R. (2009). Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables: Snow, *Global Terrestrial Observing System*, Rome, 2009.

Bao, Z., Kelly,R.,Wu,R. 2011. Variability of regional snow cover in spring over western Canada and its relationship to temperature and circulation anomalies. *International Journal of Climatology*, 31 (9), pp. 1280-1294.

Brown R.D., Brasnett B. & Robinson D. (2003). Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. Atmosphere-Ocean. Volume 41, Issue 1, 2003. pp.1-14.

Brown, R., Derksen C., Wang, L. (2010). A multi-data set analysis of variability and change in Arctic spring snow cover extent, 1967-2008. *Journal of Geophysical Research, D: Atmospheres* 115(16), art. No.D16111.

Brown, R.D., Mote, P.W. (2009). The response of Northern Hemisphere snow cover to a changing climate. *Journal of climate*, 22(8), pp.2124-2145.

Campbell, J.L., Ollinger, S.V., Flerchinger, G.N., Wicklein, H., Hayhoe, K., Bailey, A.S. (2010). Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire, USA. *Hydrological Processes*, 24 (17), pp.2465-2480.

Drever, M.C., Clark, R.G., Derken, C., Slattery, S.M., Toose, P., Nudds, T.D. (2012). Population vulnerability to climate change linked to timing of breeding in boreal ducks. *Global Change Biology*, 18(2), pp. 480-492.

Fenandes R. et al. (2013). Continuous Daily Snow Cover Mapping Through Joint Assimilation of NOAA AVHRR Imagery and CMC Snow Depth Analysis in a Daily Snow-Albedo Model. *Manuscript submitted to RSE*

Ellis, A.W., Leathers, D.J. (1998). A quantitative approach to evaluating the effects snow cover on cold airmass temperatures across the U.S. Great Plains. *Weather and Forecasting*, 13 (3 part 2), pp.688-701.

Euskirchen, E.S., Mcguire, A.D., Chapin, F.S. (2007). Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming. *Global change Biology*, 13 (11), pp.2425-2438.

Fernandes R., Miller J.R., Chen J.M., & Rubinstein I.G (2004). Evaluating image-based estimates of leaf area index in boreal conifer stands over a range of scales using high-resolution CASI imagery. *Remote Sensing of Environment*. Volume 89, Issue 2, 30 January 2004, Pages 200-216.

Fernandes R. & Zhao H. (2008). SNOWCOVER: An approach for continuous daily snow cover Estimation from AVHRR and MODIS Imagery, *Eos Trans. AGU*, 89(53), Fall Meet. Suppl., Abstract C31A-0435.

Fernandes, R. and Zhou, F., (2012) CCRS Snow Data Assimilation System, technical report, in preparation, Remote Sensing Science Programme, Natural Resources Canada.

Garcia-Romero, A., Munoz, J., Andres, N., Palacios, D. (2010). Relationship between climate change and vegetation distribution in the Mediterranean mountains: Manzanares Head valley, Sierra De Guadarrama (central Spain). *Climatic Change*, 100(3), pp.645-666.

Gajic-Capka,M. (2011) Snow climate baseline conditions and trends in Croatia relevant to winter tourism. *Theoretical and Applied Climatology*, 105(1), pp.181-191.

GCOS. http://gosic.org/ios/MATRICES/ECV/ECV-matrix.htm.

Hall D. K., Riggsb G.A., Salomonsonc V.V., DiGirolamob, N.E., & Bayrd K.J. (2002). MODIS snow-cover products. *Remote Sensing Environment*, Vol. 83, Issues 1-2, Nov. 2002, pp181-194.

Helfrich, S. R., D. McNamara, B. H. Ramsay, T. Baldwin, and T. Kasheta (2007), Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (NOAA), *Hydrological Processes*, 21, pp.1576–1586.

IPCC (2007). Climate Change 2007: Synthesis Report.

Li, P. (1999). Variation of snow water resources in northwestern China, 1951-1997. *Science in China, Series D: Earth Sciences*, 42 (supplement), pp. 72-79.

Ling, F., Zhang, T. (2003). Impact of the timing and duration of seasonal snow cover on the active later and permafrost in the Alaskan Arctic. *Permafrost and Periglacial Processes*, 14(2), pp.141-150.

Liston, G.E., Hiemstra, C.A. (2011). The changing cryosphere: Pan-Arctic snow trends (1979-2009), *Journal of climate*, 24(21), pp.5691-5712.

Munoz Jimenez, J., Garcia Romeo, A. (2009). Plant colonization in condesa nivation hollow, sierra de guadarrama (Spanish central system) Geografisca Annaler, *Series A: Physical Geography*, 91(3) pp.189-204.

National Ice Center (2008). updated daily. NOAA daily Northern Hemisphere snow and ice analysis at 4 km and 24 km resolution. Boulder, CO: National Snow and Ice Data Center. Digital media.

Ramsay, B. (1998). The interactive multisensor snow and ice mapping system, *Hydrological Processes*, 12, pp.1537–1546.

Tanarro Garcia, L.M., Palacios Estremera, D., Zamorano Orozco, J.J., Gomez Ortiz, A. (2010). Snow cover, permafrost and skin flows formation in a detritic talus of the High Mountain, Cuadernos de Investigacion. *Geografica*, 36(2), pp.39-59.

Valt, M., Cianfarra, P., Moro, D., Zasso, R. (2009). Recent snow over variations and avalanche activities in the Southern Alps. *ISSW 09 – international Snow Science Workshop, Proceedings*, pp.229-233.

Vanham, D., Rauch, W. (2009). Retreating snow packs under climate change: implications for water resources Management in the Austrian Alps. *IAHS-AISH Publication*, 330, pp.231-238.

Vanham, D., Fleischhacker, E., Rauch, W. (2009) Impact of snowmaking on alpine water resources management under present and climate change conditions. *Water Science and Technology*, 59 (9), pp.1793-1801.

Wang, X., Xie, H. (2009). New methods for studying the spatiotemporal variation of snow cover based on combination products of MODIS Terra and Aqua. *Journal of Hydrology*, 371(1-4), pp.192-200.

Wipf, S., Stoechli, V., Bebi, P. (2009). Winter climate Change in alpine tundra: Plant responses to changes in snow depth and snowmelt timing. *Climate Change*, 94 (1-2), pp.105-121.

Ye, H., Bao, Z., Feng, X. (2005). Connections of Siberian snow onset dates to the following summer's monsoon conditions over Southeast Asia. *International Journal of Climatology*, 25 (12), pp.1567-1584.

Zhao, H., Fernandes R. (2009). Daily snow cover estimation from advanced very high resolution radiometer polar pathfinder data over Northern Hemisphere land surfaces during 1982–2004, *J. Geophys. Res*., 114, D05113, doi:10.1029/2008JD011272.

Zhou, F., Zhang, A. (2013). Methodology for estimating availability of cloud-free image composites: A case study for southern Canada. *International Journal of Applied Earth Observation and Geoinformation*, 21 (2013) pp.17–31.