MODIS-derived Snow Metrics Algorithm

Version 1.0

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Introduction

The National Park Service and Geographic Information Network of Alaska (GINA) are developing an algorithm to derive snow cover climatology for Alaska using the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover daily product. The algorithm is two-fold and involves both data processing and the derivation of snow cover metrics. Terra MODIS snow cover daily 500m grid data (MOD10A1) are processed to reduce cloud obscuration through iterations of cloud reduction methods that include spatial, temporal, and snow cycle filtering. MRT tool is used to mosaic daily tile files and re-sample the data. A total of 12 metrics (e.g. date of first snow, date of persistent snow cover) for each pixel are calculated. IDL with ENVI subroutines were used to develop the algorithm.

Input dataset

The MODIS Terra Snow Cover Daily L3 Global 500m Grid data (MOD10A1) from the National Snow and Ice Data center (NSIDC) are used to calculate the snow metrics for a snow year. A snow year is defined as August 1 of the previous year to July 31 of the year in which it ends. For example, 2010 snow year is from August 1 of 2009 to July 31 of 2010.

MOD10A1 data contains snow cover, snow albedo, fractional snow cover, and Quality Assessment (QA) data in compressed Hierarchical Data Format-Earth Observing System (HDF-EOS) format along with corresponding metadata. MOD10A1 consists of 1200 km by 1200 km tiles of 500 m resolution data gridded in a sinusoidal map projection. The MODIS snow cover data is based on a snow mapping algorithm that employs a Normalized Difference Snow Index (NDSI) and other criteria tests. (See http://nsidc.org/data/mod10a1v5.html).

For our purposes, we download 26 daily tile files covering all of the Alaska region (Figure 1).

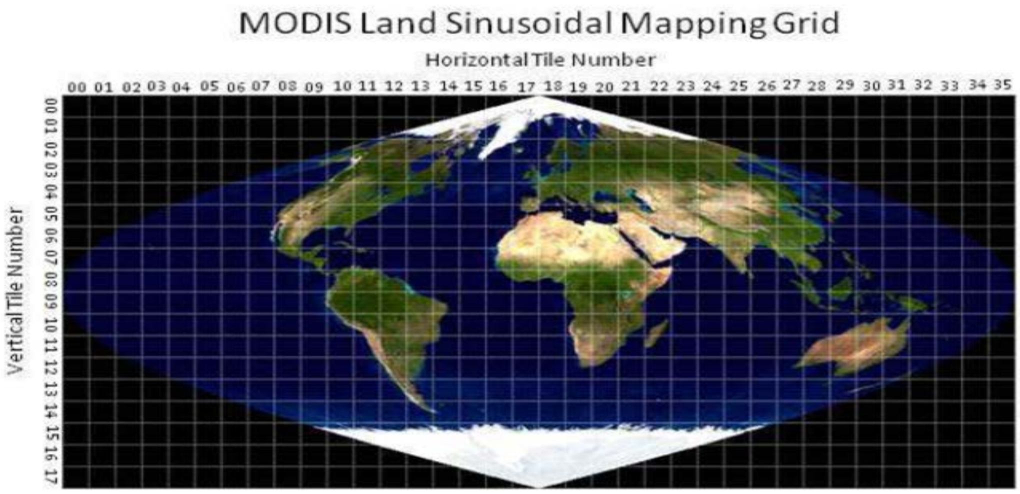

Figure 1. 26 tiles files are downloaded from NSIDC.

The 26 tiles are h06v03, h07v03, h08v03, h09v02, h09v03, h10v02, h10v03, h11v02, h11v03, h12v01, h12v02, h13v01, h13v02, h14v01, h20v01, h21v01, h22v01, h23v01, h23v02, h24v02, h25v02, h26v02, h26v03, h27v03, h28v03, h29v03.

Each tile file includes four scientific fields such as snow_cover, fractional_snow_cover, Snow_albedo, and snow_cover_spatial_quality to indicate the attributes of the pixels in the tile. The the snow_cover, snow_fraction, snow_albedo, and snow_spatial_QA fields are defined in Tables 1 to 4, respectively.

Table 1. Local attributes for the Snow_Cover field of tile data

Value	Description
0=missing data	data missing
1=no decision	no decision
11=night	Darkness, terminator, or polar night
25=no snow	Snow-free land
37=lake	Lake or inland water
39=ocean	Open water
50=cloud	Cloud obscured
100=lake ice	Snow-covered lake ice
200=snow	Snow-covered land
254=detector saturated	Detector saturated
255=fill	Fill

Table 2. Attributes for Fractional_Snow_Cover Field of tile data

Value	Description
0-100=fractional snow	In percent
200=missing data	Missing data
211=night	Darkness, terminator, or polar night
225=land	Snow-free land
237=lake	Lake or inland water
239=ocean	Open water
250=cloud	Cloud obscured
254=detector saturated	Detector saturated
255=fill	Fill

Table 3. Attributes for the snow-albedo field of tile data

Value	Description
0-100=snow albedo	In percent
101=no decision	no decision
111=night	Darkness, terminator, or polar night
125=no snow	Snow-free land
137=lake	Lake or inland water
139=ocean	Open water
150=cloud	Cloud obscured
250=missing	Missing data
251=self-shadowing	Self-shadowing
252=landmask mismatch	Landmask mismatch
253=BRDF_failure	Bidirectional reflectance distribution function failure
254=non-production-mask	Non-production-mask

Table 4. Attributes for the Snow_Spatial_QA field

Value	Description
0	Good quality
1	Other quality
252	Antarctic mask
253	Land mask
254	Ocean mask
255	Fill

Daily tile files are mosaicked and re-projected using the MRT tool into the Alaska Albers Projection (NAD83), and converted into four single band GeoTIFF files. For example, the four TIFF files for 2009/02/28 are: 2009-059.Snow_Albedo_Daily_Tile.tif, 2009_059.Fractional_Snow_Cover.tif, 2009_059.Snow_Cover_Daily_Tile.tif, and 2009_059.Snow_Spatial_QA.tif.

Snow metrics algorithm

Calculation of snow metrics for a snow year (Aug 1 to July 31) is divided into two stages: processing data to reduce cloud pixels and deriving the snow metrics. Figure 2 shows the scheme of the algorithm. Data processing includes spatial, temporal, snow-cycle filtering methods to reduce the cloudy days. Snow metrics processing produces snow metrics. Finally, the algorithm outputs the snow metrics as well as the modified snow cover.

Daily data are composed of four TIFF format files. The value of a pixel in the cover file is defined in Table 1.

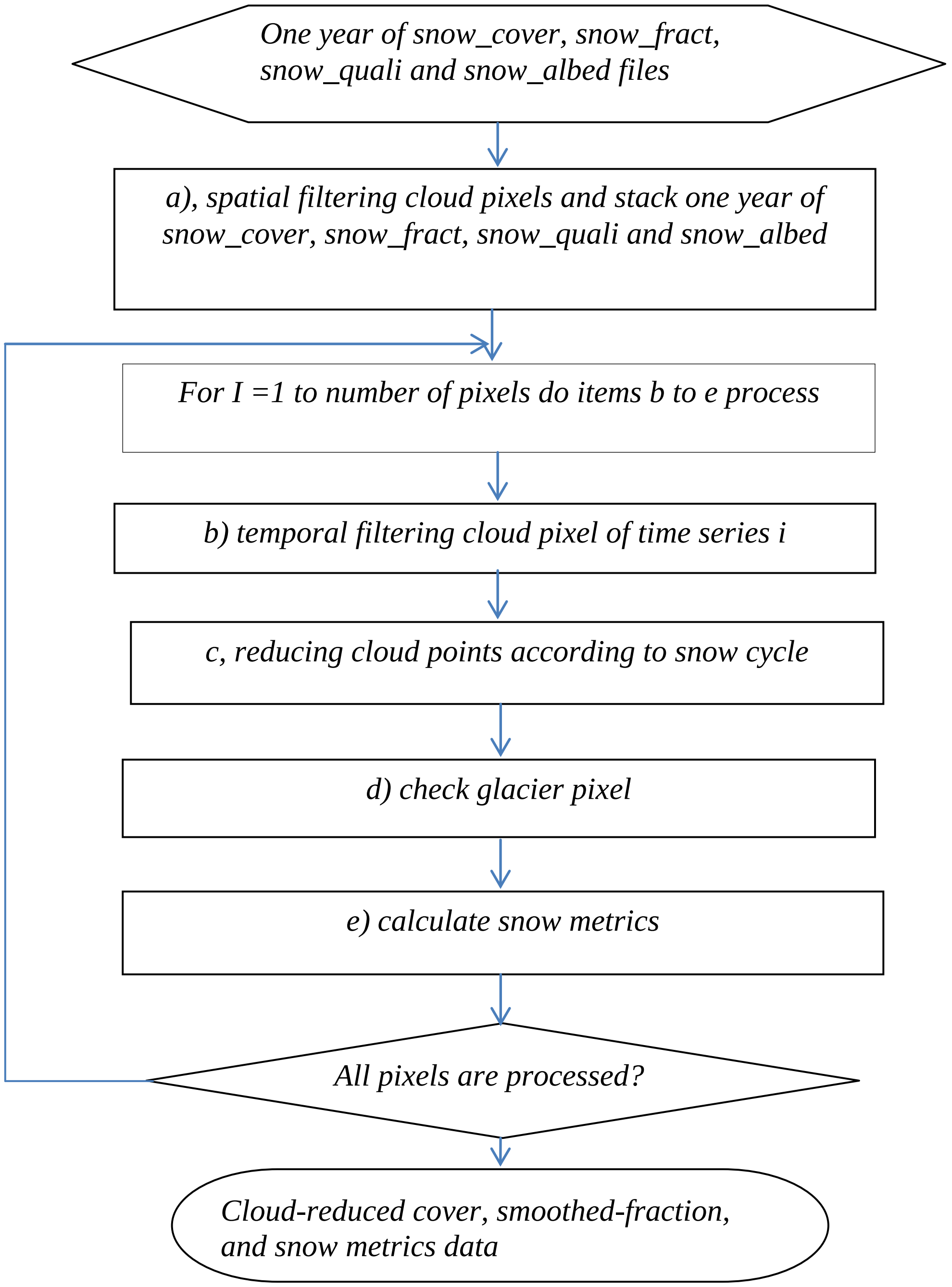

Figure 2. Flowchart for data processing and metrics calculation.

a) Spatial filtering cloud pixels and stacking one-snow-year data

Each day of cover file is processed with the spatial filtering cloud pixels algorithm. Check each cloud pixel, if ¾ of its orthogonal neighbor pixels are snow, then re-classify the cloud pixel as snow pixel; if ¾ of them are no-snow, re-classify the cloud pixel as no-snow pixel.

All daily files that are available for the snow year (Aug 1 to Jul 31) are stacked, resulting in four stacked files - one for each of the scientific data sets (cover, albedo, quality, and fraction).
For example, 2009 snow year has four stacked files, which are: 2009_snow_cover, 2009_frac, 2009_albed, and 2009_quali.

Within a snow year, there are few days of missing data. We do not interpolate the missing days when deriving snow metrics. For example, 2009 snow year has 351 days. Days from 2009-275 to 2009-287 are missing. Appendix A lists days with data for the 2009 snow year. Note that data of a snow year are processed from August 1 of the first year to July 31 of next year, but that the metrics days are reported as day of year, starting with Jan 1 of the first year. That is, we report the first and last snow cover days, and the first and last days for the longest consecutive snow cover period in terms of the number of days from Jan 1 of first year to July 31 of the following year. So, the range of the metrics days is from 213 to 577 (578 in leap year).

b). Temporal filtering to reduce the cloud pixels

Each pixel is described by its cover, fraction, quality, and albedo vectors. A temporal filter is applied for each pixel using the following steps. For example, Figure 3 presents the raw data for the cover time series at pixel (sample 3249 and line 3435) for snow-year 2009. Please notice that the total days for available satellite data for this snow-year (from August 1 to next year July 31) are 351 days.

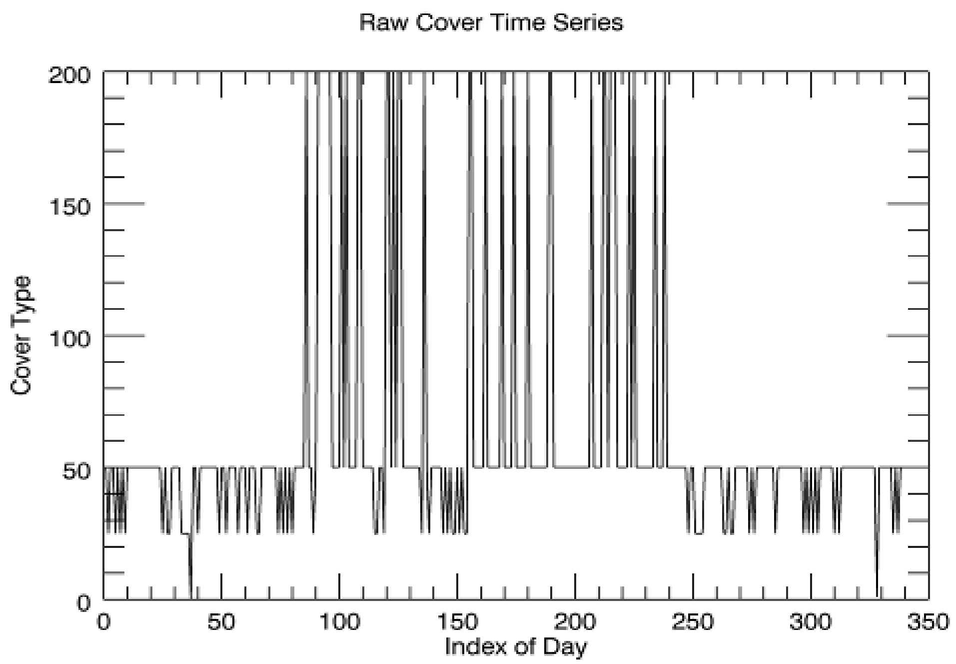

Figure 3. Raw cover time series at pixel (sample 3249 and line 3435).Value 200 is snow, 50 is cloud, 25 is no-snow, and 0 is no-data.

The temporal filtering method includes following steps. First, we determine what the pixel is (ocean, land, or lake/inland water) by counting the number of the types information in the cover time-series produced in step b. If more than 10 points in the cover time-series are ocean, the pixel is classified as ocean, if more than 10 points are lake/inland water the pixel is classified as lake/inland water, otherwise it is classified as land. Second, we check the snow flag in the cover time-series to determine if the pixel is snow covered or not. Then, we check each cloud day in the cover time-series produced in step b. If one day before and after the cloud day are snow, the cloud day is reclassified as snow day; if one day before and after the cloud day are no-snow, the cloud day is reclassified as a no-snow day.

Figure 4 shows the temporal filtered time series for the same time series that was shown in Figure 3.

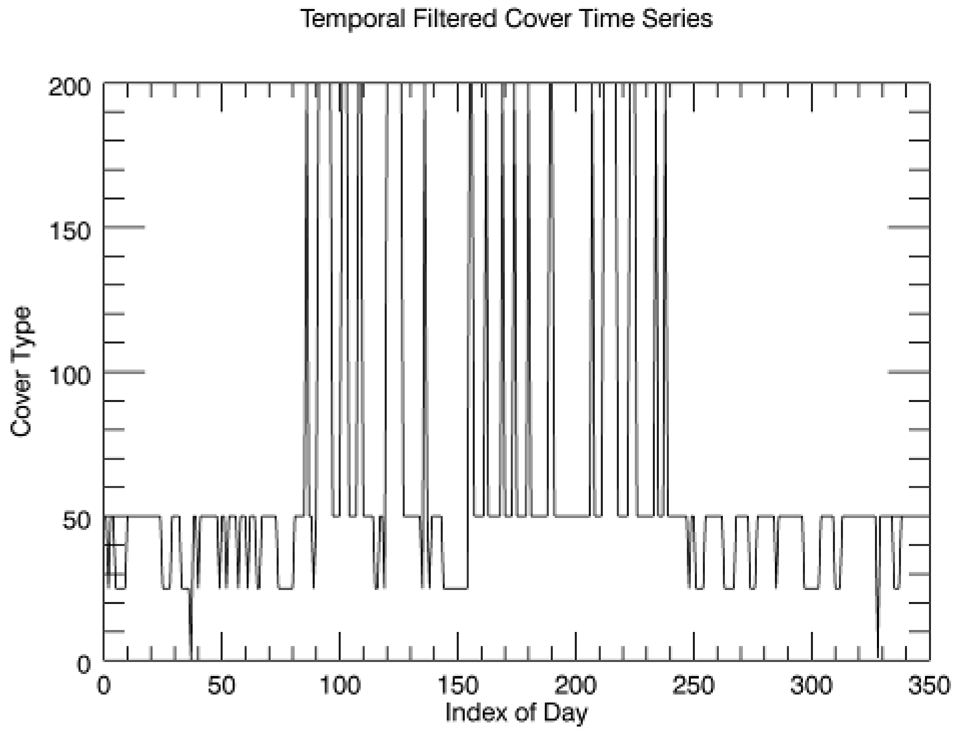

Figure 4. Temporal filtered time series.

c). Snow cycle filtering

We define a snow year (or cycle) as having three segments: snow accumulation, snow cover, and snow melt. During the snow accumulation segment, cloud days that occur before a no-snow day can be assumed to be no-snow days. During the snow cover segment, cloud days that are bound by snow days are assumed to represent snow days. Cloud days that occur after a no-snow day in the snow melt segment are assumed to be no-snow days. Therefore, we apply different cloud re-classifying methods to each of the different segments of the snow year. We first use a method to estimate the snow cycle of the *cover* time-series and then apply different cloud filtering methods to each segment of the time series.

- Segment1 is defined as the first day of snow calendar year (August 1st) to the estimated start of consecutive snow season (SOCSS) day ;

- Segment 2 is defined as the estimated SOCSS day to the estimated end of consecutive snow season(EOCSS) day, and
- Segment 3 is defined as the estimated EOCSS day to the last day of the snow calendar year (July 31st).

In order to estimate the SOCSS day, candidate SOCSS days and their related location indexes in the time series are found by identifying snow pixel points whose fractions are equal to or greater than 50% and whose albedos are equal to or greater than 30%.

The estimated SOCSS day is evaluated by forward checking candidate SOCSS days - starting from the first candidate SOCSS day with the smallest location index in the time series. If the estimated SOCSS day and following days meet the consecutive snow period requirements (the following days must not be classified as no-snow/lake/ocean and the number of these kinds of days (num_threshold) must be greater than 14 days) then this is the estimated SOCSS day. Otherwise, we continue to evaluate the next SOCSS day in the remaining candidate SOCSS days until we find a SOCSS day that meets the requirement for the consecutive snow season. If none of the candidate SOCSS days meet the requirement, then Dec 31st of the first year is picked as the estimated SOCSS day.

For example, consider a cover time series (Table 5) with fractional snow cover of all snow days greater than 50% and albedo values of all snow days greater than 30%. In this table, we present that s—snow, n—no snow, f—fill, c—cloud, t—night, l—lake, o—ocean, m—missing data.

Table 5. Example for estimating the first day of consecutive snow season.

0	1	2	3	4	5	**6**	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
n	n	f	S	c	n	***s***	*s*	*s*	*t*	*t*	*t*	*t*	*c*	*c*	*f*	*t*	*s*	*s*	*c*	c	c	f	c	s	n	n	n	n
						x																						

By using above method, we determine that day 6 is the first day of the consecutive snow season because the day 6 is the first of more than 14 consecutive days that are not classified as no-snow/lake/ocean days (in Table 5 it is actually the first of 19 consecutive days).

A similar method is used to determine the EOCSS day, except backward checking is used to determine the EOCSS day from the candidate EOCSS days.

After determining the SOCSS day and the EOCSS day, the time series is divided into three segments:
Segment 1: first day (first_idx) to SOCSS day - 1
Segment 2: SOCSS day to EOCSS day
Segment 3: OCSS day + 1 to the last day (last_idx)

These segments are then filtered to reduce cloud days using the following steps. During filtering, we treat the missing, night, or fill days as cloud days. So, it appears that there are only three kinds of days in the cover time series: snow, no-snow, and cloud days.

Backward filtering segment 3

Beginning with the last day, if day *i* is a snow day and the preceding consecutive days (i-1,i-2,..., i-n) are cloud days, then we re-classify the preceding consecutive days (i-1,i-2,..., i-n) as snow days. Table 6 illustrates how the hypothetical time series are processed by the backward process for segment 3. The second row represents a hypothetical segment 3 (end of season), and the third row is the result produced by backward filtering of segment 3. The letters used are the same as those in Table 5 and changes are shown in red.

Table 6. Segment 3 and the result of backward filtering.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
n	n	n	n	s	c	n	c	c	c	f	f	f	c	c	c	n	s	c	c	s	s	c	c	f	s	t	t	c
n	n	n	n	s	c	n	c	c	c	f	f	f	c	c	c	n	s	s	s	s	s	s	s	s	s	t	t	c

The result of backward filtering segment 3 for the time series shown in Figure 4 is presented in Figure 5. Because backward filtering did not change anything in this case, the plot shown in Figure 5 is identical to that in Figure 4.

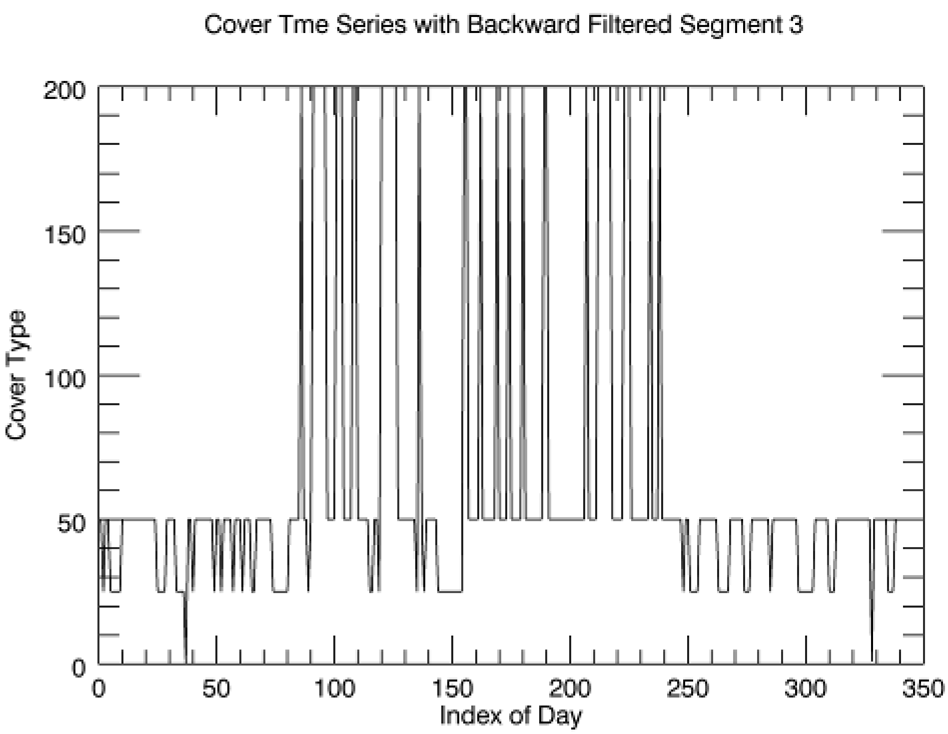

Figure 5. Backward filtering of segment 3.

Backward filtering segment 2

Beginning with the last day of segment 2, if day *i* is snow and the preceding consecutive days (i-1,i-2,...,i-n) are cloud, then we reclassify the preceding consecutive days (i-1,i-2,...,i-n) as snow. Figure 6 shows the result of backward filtering segment 2 for the same time series that is presented in Figure 5.

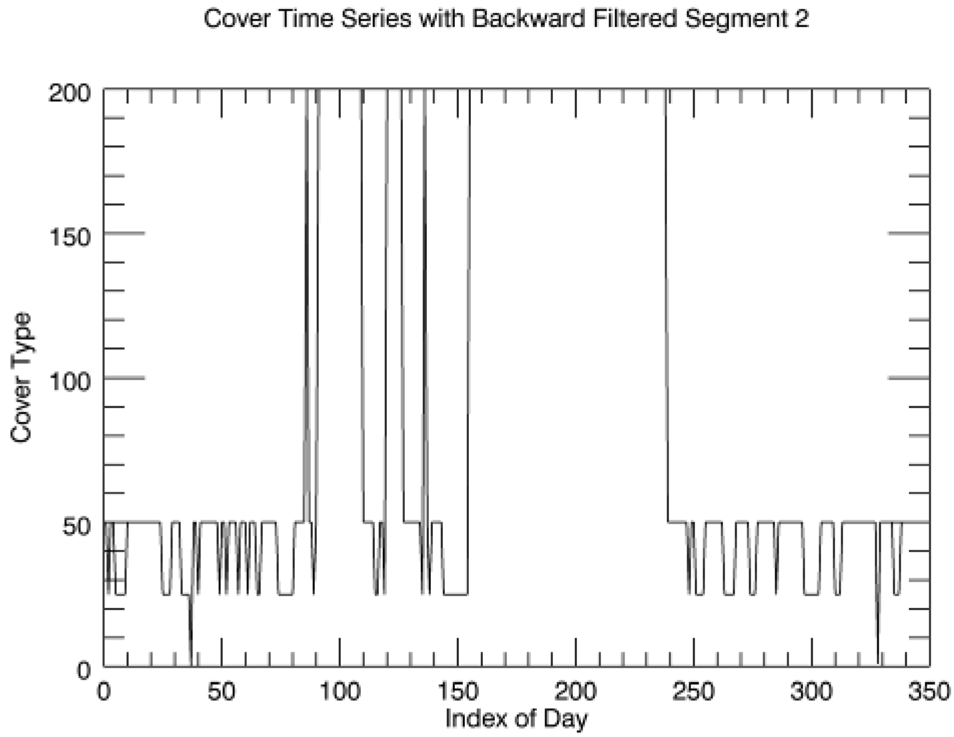

Figure 6. Backward filtering segment 2.

Backward filtering segment 1

Beginning with the last day of segment 1, if day *i* is no-snow and the preceding days (i-1, i-2,.., i-n) are cloud, then we reclassify the preceding consecutive days (i-1,i-2,...,i-n) as no-snow days. Figure 7 presents the results of backward filtering segment 1.

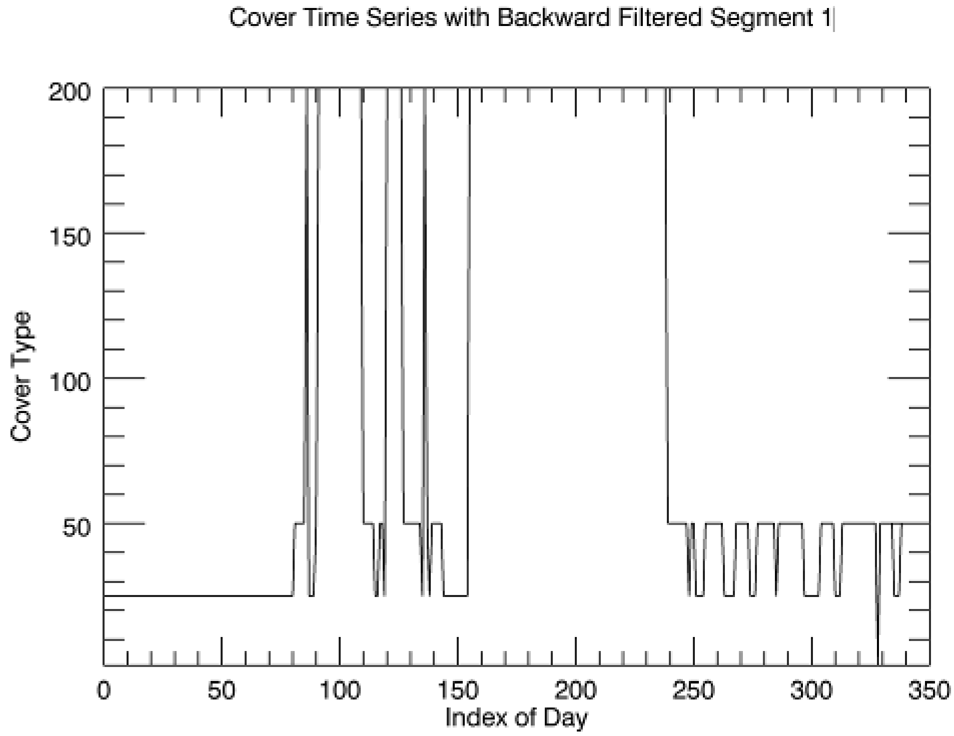

Figure 7. Backward filtering segment 1.

<u>Forward filtering segment 1</u>

Beginning with the first day of segment 1, if day *i* is snow and the following consecutive days (i+1,i+2,...,i+n) are cloud, then we reclassify the following consecutive days (i+1, i+2,..., i+n) as snow. An example is shown in Table 7. The second row represents a hypothetical segment 1 time-series. The third row is the result of forward filtering of the second row. The reclassification of clouds is indicated by red-colored characters. The result of forward filtering segment 1 is shown in Figure 8. Because forward filtering did not change anything in this case, the plot shown in Figure 8 is identical to that in Figure 7.

Table 7. Example of forward filtering segment 1.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
n	n	n	n	s	c	n	c	c	c	f	f	f	c	c	c	n	s	c	c	s	s	c	c	f	s	t	t	c
n	n	n	n	s	s	n	c	c	c	f	f	f	c	c	c	n	s	s	s	s	s	s	s	f	s	t	t	c

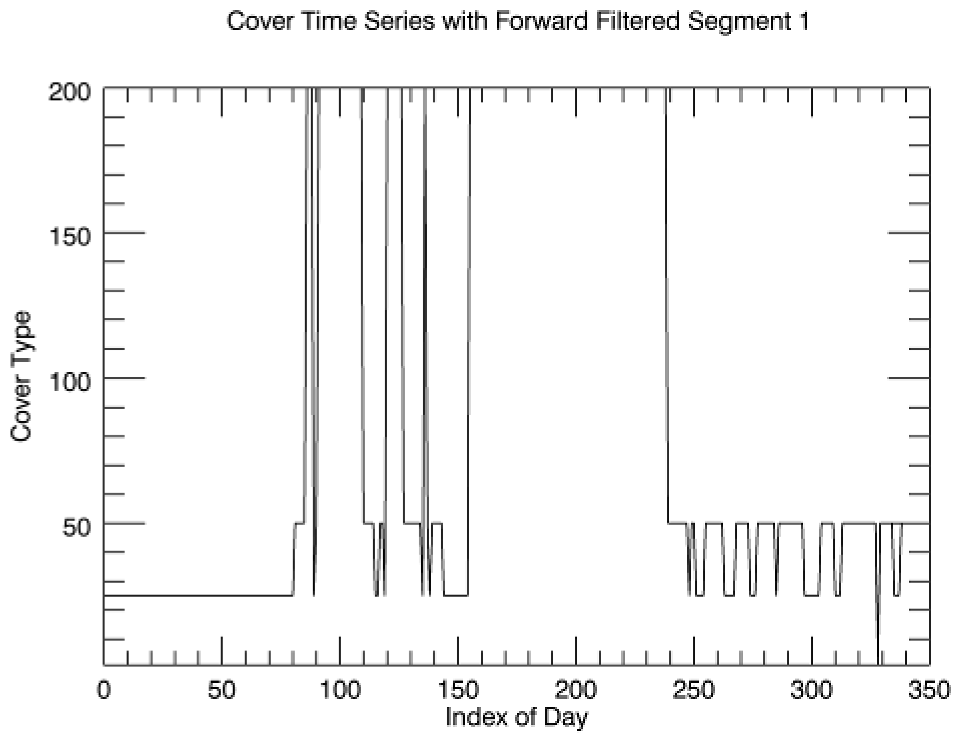

Figure 8. Forward filtering segment 1.

<u>Forward filtering the Segment 2</u>

Beginning with the first day of segment 2, if day *i* is snow and the following consecutive days (i+1,i+2,..., i+n) are cloud, then we reclassify the following consecutive days (i+1,i+2,..., i+n) as snow. Figure 9 displays the result of forward filtering segment 2. In this case, forward filtering did not change anything so the plot shown in Figure 9 is identical to that in Figure 8.

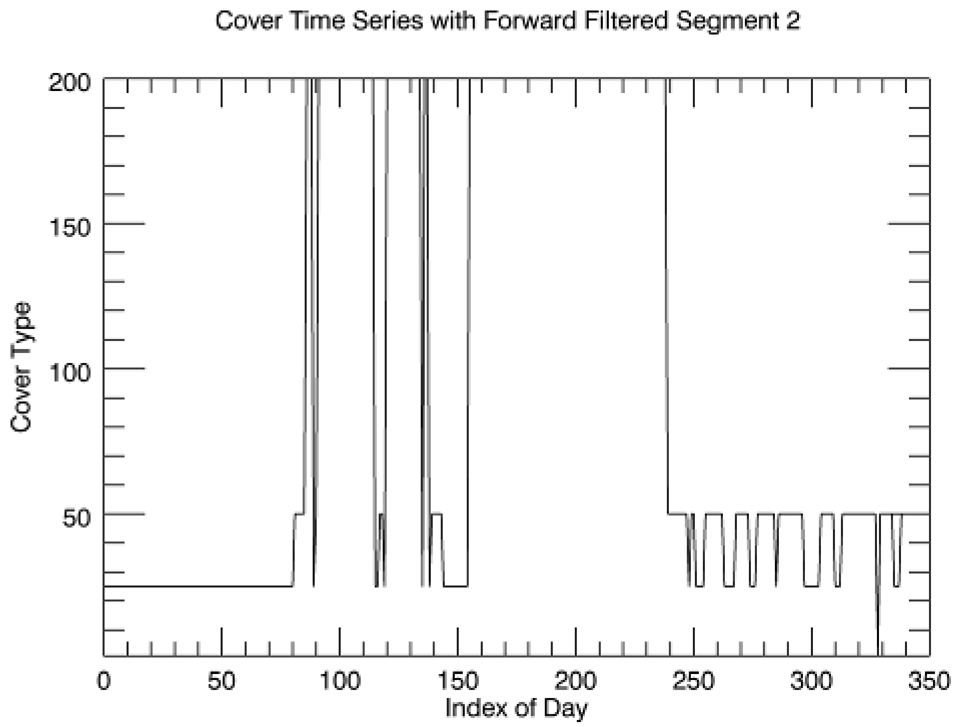

Figure 9. Forward filtering segment 2.

Forward filtering segment 3

Beginning with the first day of segment 3, if day *i* is no-snow and the following consecutive days (i+1,i+2,...,i+n) are cloud, then we re-classify the following consecutive days (i+1,i+2,...,i+n) as no-snow. Figure 10 illustrates the result of forward filtering segment 3.

After cloud filtering the snow cycle there are still some cloud days left in the time series. There is no reasonable way to get rid of these remaining cloud days in the time series because they primarily occur in the transition period between segment 1and segment 2 and/or segment 2 and segment 3.

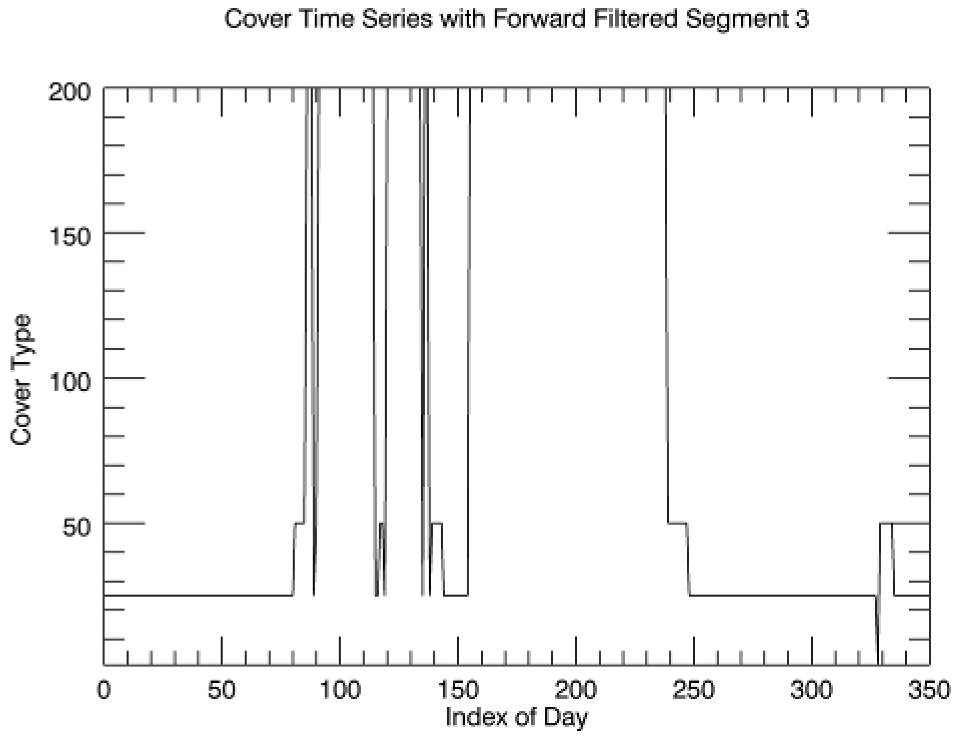

Figure 10. Forward filtering segment 3.

d) Check and re-classify the glacier pixels

The final step for snow cycle filtering is determining if the time series represents a glacier pixel. If the time series does not have any no-snow, lake, or ocean classifications, we consider the time series to represent a glacier pixel. For the time series of a glacier pixel, we reclassify all days the as snow days. The time-series shown in Figures 2 - 10 is not for a glacier pixel, so the results of filtering this time series are not shown.

e) Calculation of snow metrics

After finishing the spatial, temporal, and snow-cycle filtering, the time-series is ready for calculating snow metrics (Figure 1, Step e).

<u>Finding the first snow day (FSD) and the last snow day (LSD):</u>

Obtain the index for the first snow day and index for the last snow day in the cover time-series (refers to the first column in Appendix A). We do not consider the cloudy days before the first snow day and after the last snow day as possible snow days. That means that FSD and LSD days are the same as MODIS snow_cover_field. Then locate these indices in the band name array (refers to the second column in Appendix A) to obtain the first_snow day (FSD) and the last_snow day (LSD), and calculate the day range between the first and last snow day. For example, for the time series shown in the Figure 10, we determine that the first snow cover day index = 86, and the last snow cover index =238. By locating the indices in the band name array, we get that first_snow_day=312, last_snow_cover day=464. The range from the first and last snow cover day is 153 days.

<u>Finding the first day of the consecutive snow season (FCSS) and the last day of the consecutive snow season (LCSS):</u>

Within the range of FSD and LSD, we identify the "first day for looking (FLD) for continuous snow season (CSS) segments", which is the first snow day with fraction equal to or greater than 50% and with albedo equal to or more than 30% and the "last day for looking (LLD) for CSS segments", which is the last snow day (with the same fraction/albedo qualifications). Then, we start to look for CSS segments within the range of FLD - LLD. The CSS is defined as having 14 or more consecutive days that must be "snow" or "cloud", and no more than 2 consecutive days of no-snow days. The CSS segments may include a number of cloudy days in the beginning or/and at the end of a segment. So, the first day of the CSS segment (FCD) and the last day of the CSS segment (LCD) may need to be adjusted. If the FCD is a cloud day, then we look forwards for the first snow day of the CSS segment and pick the middle day as the FCD. In a similar way, if the LCD is a cloud day, then we look backwards for the last snow day of the CSS segment, and pick the middle day as the LCD (Figure 11). Figure 12 also gives an example of how the FCD and LCD are determined.

s n c c c s s s s s c c s s s s c s s s s s c s s s s s c c c n n c c s c c s
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9

The Day 1 is the both FSD and the FLD, and the day39 is the LSD and the day 36 is the LLD. Because day 39 has snow fraction of 38% which is less than 50%, and day 36 has snow fraction of 87% and albedo 56%, day 36 is LLD.
The continuous snow season segment is initially identified as to be from the day 3 to the day 31. Because the first snow day of the continuous snow season (FCD) is the day 6, we adjust the first day of the CSS segment to the day 4. The last day of the CSS segment is the day 31, and the last snow day of the CSS segment do is the day 28, we change the last day of the un-broken segment (LCD) to the day 30.

Figure 11. Determination of CSS segment by adjusting cloudy days

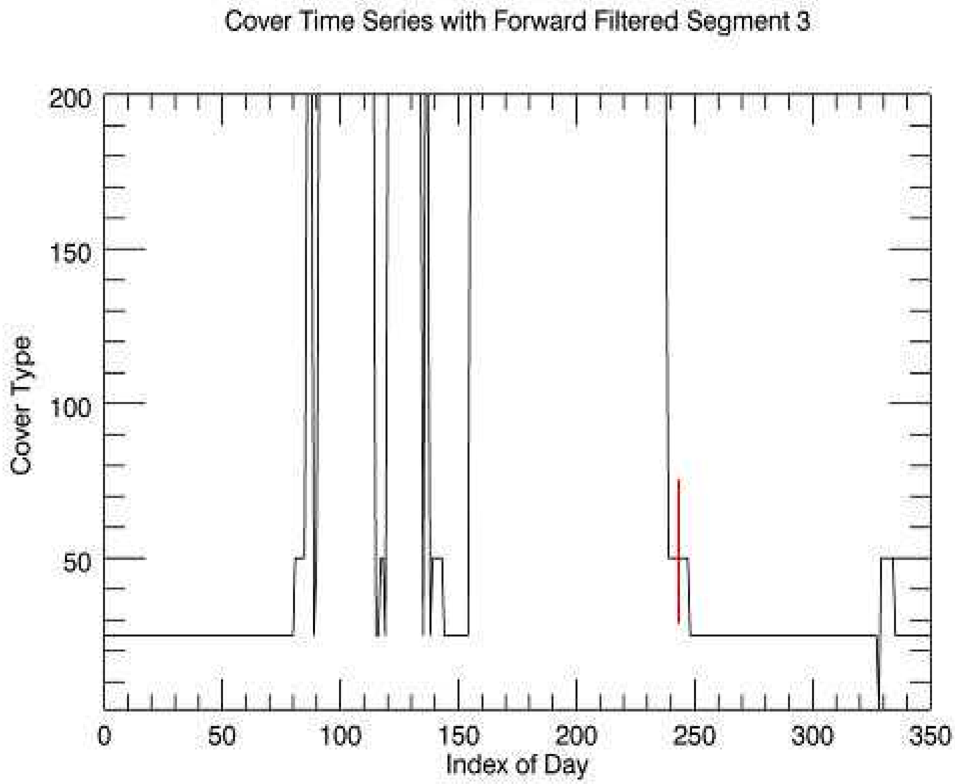

Figure 12. Extending the length of the continuous snow season segment to the middle day of cloud days. The vertical red line shows the modified date selected as the last day of the CSS segment.

After determining if there are one or more CSS segments, we count the number of CSS segments, and pick up the longest CSS segment to get the first day of the longest CSS, the last day of longest CSS, and other metrics. For the time series shown in Figure 11, the longest CSS segment is from index 155 (day of first year 381 or Jan. 16, 2010) to index 238 (day of second year 464 or Apr. 9, 2010). The FCSS day is Jan. 16, 2010, and the LCSS day is Apr. 9, 2010.

Results

The outputs of the algorithm include snow-metrics, snow-fraction, and snow-cover data files.

- Snow-metrics data file defines 12 snow metrics as following:

  01-first_snow_day, first day of the full snow season (FSS start day)
  02-last_snow_day, last day of the full snow season (FSS end day)
  03-fss_range, last_snow_day-first_snow_day +1
  04-longest_css_first_day, first day of the longest CSS segment (CSS start day)
  05-longest_css_last_day, last day of the longest CSS segment (CSS end day)
  06-longest_css_day_range, longest_css_last_day-longest_css_first_day +1
  07-snow_days, the number of snow days
  08-no_snow_days, the number of no snow days
  09-css_segment_num, the number of CSS segments
  10-mflag, pixel type (ocean, land, or lake/inland water) and type of snow (no snow, broken snow, or continuous snow)
  11-cloud_days, number of cloud days
  12-tot_css_days, total number of all days within CSS segments

  Note:
  Days reported as metrics are counted as day of year beginning on Jan.1 of the year that precedes the name of the snow year. For example, the days reported in the snow metrics of the snow-year of 2010 are counted from Jan.1, 2009.
  The mflag values and their descriptions are defined in Table 5.

Table 5. Values and their description for mflag

	Ocean (1)	Land (2)	Lake (3)
No-snow (10)	11	12	13
Broken-snow (20)	21	22	23
Css-snow (30)	31	32	33

- The snow-cover file includes after cloud filtering snow cover data. It is a multi-band ENVI image file. Each band corresponds to a day in a snow-year. The value for a day in a pixel is one of classification flags defined previously.

- The snow-fraction data file recorded cloud fraction of the smoothed time series. It is a multi-band ENVI image file. Each band corresponds to a day in a snow-year, and the value for a day in a pixel fraction of snow cover from 0 to 100.

Reference

1. http://nsidc.org/data/docs/daac/modis_v5/mod10a1_modis_terra_snow_daily_global_500m_grid.gd.html

2. Bradley Reed, Michael Budde, Page Spencer and Amy Miller, 2006. Satellite-Derived Measures of Landscape Processes DRAFT Monitoring Protocol for the Southwest Alaska Network.

3. Keshav Prasad Paudel and Peter Andersen, 2011. Monitoring snow cover variability in an agropastoral area in the Trans Himalayan region of Nepal using MODIS data with improved cloud removal methodology, Remote Sensing of Environment, 115, 1234-1246.

4. Dorothy Hall, George Riggs and Vincent Salomonson, 2006 (updated daily). MODIS/Terra Snow Cover Daily L3 Global 500m Grid V005, [1 August 2009 to 31 July, 2010]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Appendix A. Days of 2009 snow year

Index	year-days of the year	days from the Jan. 1 of 2009
0	2009-213	213
1	2009-214	214
2	2009-215	215
3	2009-216	216
4	2009-217	217
5	2009-218	218
6	2009-219	219
7	2009-220	220
8	2009-221	221
9	2009-222	222
10	2009-223	223
11	2009-224	224
12	2009-225	225
13	2009-226	226
14	2009-227	227
15	2009-228	228
16	2009-229	229
17	2009-230	230
18	2009-231	231
19	2009-232	232
20	2009-233	233
21	2009-234	234
22	2009-235	235
23	2009-236	236
24	2009-237	237
25	2009-238	238
26	2009-239	239
27	2009-240	240
28	2009-241	241
29	2009-242	242
30	2009-243	243
31	2009-244	244
32	2009-245	245
33	2009-246	246
34	2009-247	247
35	2009-248	248
36	2009-249	249
37	2009-250	250
38	2009-251	251
39	2009-252	252
40	2009-253	253
41	2009-254	254
42	2009-255	255
43	2009-256	256
44	2009-257	257
45	2009-258	258
46	2009-259	259
47	2009-260	260
48	2009-261	261

49	*2009-262*	*262*
50	*2009-263*	*263*
51	*2009-264*	*264*
52	*2009-265*	*265*
53	*2009-266*	*266*
54	*2009-267*	*267*
55	*2009-268*	*268*
56	*2009-269*	*269*
57	*2009-270*	*270*
58	*2009-271*	*271*
59	*2009-272*	*272*
60	*2009-273*	*273*
61	*2009-274*	*274*
62	*2009-288*	*288*
63	*2009-289*	*289*
64	*2009-290*	*290*
65	*2009-291*	*291*
66	*2009-292*	*292*
67	*2009-293*	*293*
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