Interactive comment on “Screening for Snow/Snowmelt in SNPP VIIRS Aerosol Optical Depth Algorithm” by Jingfeng Huang et al.

Anonymous Referee #1
Received and published: 18 June 2018

This manuscript reports a development of an algorithm that effectively screens out snow/melting snow pixels in SNPP VIIRS aerosol optical depth product. The algorithm is described in details. Comparisons with AERONET measurements show that the algorithm works to effectively remove the snow and snow-melting pixels in the aerosol product. The paper is well written. Figures are sufficient and in general have good quality. Outcome of the study is of great importance to scientific studies that use the VIIRS aerosol product. I recommend the paper be published in the journal of AMT, before a few minor revisions are done.

Thank you very much for your very valuable and constructive comments.

1. While the "aerosol optical depth" (AOD) is used in title the "aerosol optical thickness" (AOT) is used in abstract and main text. Although AOT and AOD have been used interchangeably in literature for quite a while, I would suggest a consistent use of terminology throughout the paper. Furthermore, I prefer to use AOD.

As suggested, the paper is revised for consistent use of terminology throughout. AOD is used to replace AOT in the paper.

2. Figure 4 has low quality, although other figures have good quality. Also, three panels appear to have the same title, which is a bit confusing. I would like to suggest that they re-plot the figure with high quality. For panel (c), a different color scale may be used to better represent the difference.
Figure 4 is now revised as suggested. High quality images are used with proper titles consistent with the captions.

3. abstract, line 21: VRA appears too abruptly without any explanation. It may be suffice to say just the "default" snow-removing algorithm.
We appreciate this comment. After some deliberation, considering the VRA method is introduced in details in the main text and the VRA-based snow test are referred in many places in the paper to compare with the NDSI-based tests, we think it is better to keep the ‘VRA-based snow test’ in the abstract rather than replace it with ‘default’. This will avoid potential confusion to readers as well.

4. page 2, line 72: add "snow" immediately before "contamination"
Revised as suggested.

Interactive comment on "Screening for Snow/Snowmelt in SNPP VIIRS Aerosol Optical Depth Algorithm" by Jingfeng Huang et al.

Anonymous Referee #2
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This paper presents a modified NDSI-based snow detection scheme, which has been applied to the operational NOAA VIIRS IDPS and EPS aerosol algorithms. The proposed scheme effectively mitigated the snow contamination in AOD product by more accurately filter out pixels containing melting snow over high latitude regions. This is achieved by combining NDSI with various tests, such as brightness temperature, spatial variability, and spatial adjacency tests. Since snow contamination in the retrieval pixel even small amount could potentially lead to a significant high bias in AOD, it is important to implement more rigorous snow detection schemes in the aerosol algorithms and examine the impacts. The manuscript is well written and easy to follow. I believe that addressing the following comments would improve the quality of the paper further.

Thank you very much for your very valuable comments that are extremely helpful to improving the quality of the paper.

General comments:
1. The proposed snow detection scheme consists of several steps. I would recommend to extend Figure 2 and include AOD plots at every step, so that the readers can easily understand the impact of each step. The plot should probably be zoomed in more to better show the details. Plots of the test variables, i.e., NDSI, BT, and spatial variability, would help as well.

Thanks for this valuable comment. The new snow and snowmelt scheme work as a whole for snow and snowmelt contamination removal, so we would think that a comparison between Figure 2(a) and 2(b) are sufficient to show the significant improvements in the new scheme from the old VRA based scheme, and at the same time, it avoids potential confusion to readers by adding too many subplots.
Meanwhile, we agree readers may want to know how the three components (NDSI test, snow adjacency test, and spatial filter) play their roles in the combined effect in the new scheme. Such information is much better shown in Figure 5 with more quantitative evaluation and discussions within Section 4.

2. One can assume from Figure 4 that the proposed scheme results in some false alarm (snow detection in low latitudes, and low AOD in some snow-contaminated pixels). I would

recommend to discuss this together with potential future work to further refine the scheme, as I think retaining good pixels is as important as removing bad pixels.
This is a very good point. In the algorithm development, in addition to avoid snow and cloud contamination, we strive to avoid over-screening as well. In Section 3, we particularly discussed the complement impact of the spatial filter that it also effectively screens low level 'popcorn' cumulus clouds at low latitude regions. Since both cloud and snow conditions are unfavorable conditions for meaningful satellite aerosol retrievals, the homogeneity test provides additional quality assurances to the VIIRS aerosol retrievals in terms of both snow and cloud screenings. However we agree that residual false alarm may still remain even after the snow/snowmelt screening scheme is updated. It is a daunting challenge to verify whether the low AOD in some snow-contaminated pixels are real AOD signals or contaminated by snowmelt conditions that are not necessarily causing high AOD retrievals like snow conditions. We are adding more discussion on Page 9 in Section 5 that the algorithm should be further improved in future work: "In future work, in order to reach more quantitative statistics for a better understanding of the relative contributions from each test, more testing dates at different seasons are needed. The additional testing will not only help find seasonal variability of the tests, but also help identify any residual snow and snowmelt contaminations or any over-screened AOD retrievals, both of which are valuable for further algorithm improvement. "

3. In Figure 6, I wonder if the three data points at AERONET AOD of ~0.05 and VIIRS AOD of~0.2 are retrieval-related or snow-related.

On Line 277-282, we have discussed the two points in the red circles are retrieval-related, which was verified by our additional testing runs with the new EPS algorithm.
For the additional three points at AERONET AOD of ~0.05 and VIIRS AOD of ~0.2, we agree with the reviewer that it seems the new snow/snowmelt scheme did not screen the matchup out as snow/snowmelt contamination. Given our confidence on the performance of the new scheme, we believe the remaining bias (~0.15) are not snow or snowmelt related, and the aerosol algorithm should be improved to further reduce the retrieval bias and data uncertainty.

Specific comments I don't find further specific comments other than the other reviewers'.

Thanks.

Interactive comment on “Screening for Snow/Snowmelt in SNPP VIIRS Aerosol Optical Depth Algorithm” by Jingfeng Huang et al.

Anonymous Referee #3

Received and published: 20 June 2018

The article demonstrates that the VIIRS aerosol optical depth product contains snow/ice contamination issue over high latitude Northern hemisphere. New empirical snow and snowmelt masking was developed combining normalized differences snow index, brightness temperature threshold, snow adjacency test, and spatial homogeneity test. The impacts of the new masking were tested globally and validated against ground based AOD measurements. The topic is suitable for AMT and the contents are informative for the aerosol remote sensing community. The manuscript is well prepared. However, there are several issues that need to be addressed before this manuscript is suitable for publishing.

Thank you very much for your very detailed and thoughtful comments. Your suggestions are very valuable for us to further improve the quality of the paper. Please see below for our responses highlighted in blue. Thanks.

The manuscript indicated that there are two aerosol algorithm that applied on VIIRS sensor. It is not clear the reason to have two different coefficients of snow masks in two algorithms. Does IDPS have similar problem of masking out thick haze using the C1=0.01? Can the snow mask of EPS be applied to IDPS?

On Page 2 Line 63 – 71, we introduced the evolving IDPS aerosol algorithms and the new EPS aerosol algorithm that will replace the IDPS aerosol algorithm. The new EPS algorithm is different from the IDPS algorithm in many ways such as new AOD retrieval techniques and new screening schemes etc. If C1=0.01 is used, both IDPS and EPS aerosol products will have the same ‘thick haze over-screening’ issue. Since the IDPS aerosol product will be replaced by the EPS aerosol product, we only adjusted the C1 value for the EPS algorithm for testing purposes of the new snow/snowmelt scheme.

In our previous response to reviewers’ comments, we also had addressed this same concern before the AMTD publication:
“Because of the newly discovered over-screened thick haze issue that is attributable to the snow/snowmelt over-screening, the new snow mask was further refined by tuning threshold values, and it has been implemented in the NOAA Enterprise Processing System (EPS) VIIRS Aerosol Algorithm. Although both algorithms are currently running

operationally, one at IDPS and the other at NDE, the EPS aerosol algorithm will eventually replace the IDPS algorithm, therefore we are not seeking to further improve the snow mask in the IDPS aerosol algorithm any more. Instead, the S-NPP VIIRS aerosol products will be reprocessed by the new EPS algorithm."

Author discussed new snow mask for IDPS and EPS throughout the paper, however, in Fig. 2 the case study for EPS is missing. Without the case study the audience do know how under what boundary conditions the snow mask for EPS is different from the snow mask for IDPS.

In our previous responses to the reviewers' comment before the AMTD, we had addressed this same concern. For the aerosol retrievals in Figure 2, the EPS retrieval is very similar to the IDPS retrieval after the snow screening is updated.

The author failed to explain how five populations of pixels were generated in Fig. 3.

The explanation of five populations of pixels in Figure 3 are provided on Page 7 Line 227-230, followed by more discussions on the Figure from Lines 231-246.

Figure 5 analyzes the data loss due to different masking procedures, which is very dependent on the topography, the snow distribution and such. Only use one day as an example is not statistically significant.

Snow screening issue is more significant over boreal spring season and we choose spring dates to highlight the issue. Figure 5 demonstrates an example that is typical for spring days but not for global annual average conditions.

Figure 5 concludes that there are additional 3.44% loss of data however, in Figure 6 there are 16% (43/260) data loss for data that are collocated with AERONET. The total data loss is 37% (97/260), which is much larger than the estimates from Fig. 5.

There are fundamental difference between Figure 5 and Figure 6 statistics. Figure 5 is global evaluation but Figure 6 only counts VIIRS vs. AERONET match ups. For Figure 6, we only selected Northern North America as our region of interest, and selected boreal spring time from March to May as highlight seasons. Therefore the data loss is much larger than global evaluation in Figure 5.

Also in Fig. 5 there are different number of latitude bins after 50 degree north. It is not clear to me the physical meaning of snow adjacent percentage is 100%. It is more likely that at that latitude, there is no data available for this day.

We use 10 degree latitude bins for all figures in Figure 5. Because aerosol retrievals are only available over snow free regions, aerosol retrievals over high latitudes are very limited. Taking Figure 5c for example, there were no aerosol retrievals when latitude are higher than 75 degrees. For the 60-70 degree bin, the 100% indicates that those old retrievals that were previously contaminated because of old snow screening are now removed after the snow screening methods are updated.

Also, the author does not mention the quality of data whether they are “Good” data or all quality data in Fig. 6. Although the discussion of Fig. 6 indicates only “Good” data are used in the analyses, but the author should clearly state it.

We added ‘Good Quality’ in Page 7 Line 263 and in the Figure 6 caption as well. We only use good quality VIIRS retrievals for validation purposes. Thanks a lot for pointing this out.

The one last question is with the change of snow masking, what is the statistics of valid aerosol data that are misidentified as snow globally?

On Page 9 Line 313 to 316, for a global testing on May 18, 2014, a typical day in spring thaw season when snow and snowmelt prevail, the new snow test screened out an additional 3.44% ‘Good’ quality VIIRS AOD retrievals, which were otherwise contaminated by snow and snowmelt. This means if the snow screens are not updated, we likely have 3.44% valid aerosol data that are misidentified as snow globally for a typical data in spring thaw season. This number is lower for other seasons when snow and snowmelt are not a significant issue for VIIRS aerosol retrievals.

Interactive comment on “Screening for Snow/Snowmelt in SNPP VIIRS Aerosol Optical Depth Algorithm” by Jingfeng Huang et al.

Anonymous Referee #4

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This paper described the snow/snowmelt screening scheme for VIIRS AOD. The presentation is quite clear and the article is well-organized and concise. The method obviously works well as it has been implemented in the NOAA operation. It will be a useful documentation for the VIIRS AOD users.

Thank you very much for your very valuable comments and kind encouragement. Please see below for our responses highlighted in blue. Thanks.

Specific points:

Title: AOT is used throughout the manuscript. Why is aerosol optical DEPTH used in the title?

We have revised the paper to use AOD consistently throughout the paper.

Line 49: The word "artificial" is redundant here.

Removed as suggested.

Lines 76-78: It is stated that the snow screening tests "are designed to prevent the aerosol algorithm from making retrievals in inappropriate snow cover conditions" although true Snow/Ice products are also available (Key et al., 2013). Can the authors comment on why the VIIRS Snow/Ice products are not used in the AOD algorithm?

There could be two significant reasons. The first is the operational consideration. The operational VIIRS algorithms run in a chain. In this chain the operational snow/ice algorithm is downstream of the operational aerosol algorithm and thus the snow/ice retrievals are not yet available when the aerosol algorithm runs. The second reason is some consideration related to how the snow/ice product could be used if it was upstream before aerosol retrievals. The requirements of the snow/snowmelt contamination screening in the aerosol algorithm may be more conservative than the general snow detection in the snow/ice product. For example, we would prefer the aerosol algorithm does not retrieve

AOD over pixels with sub-pixel snow while the snow/ice product may not have the exact information of sub-pixel snow existence.

Line 99-103: They are identical to those listed in Table 1. It is better not to repeat the same words. Same for lines 149-153, 176-178.
These lines are only part of the information in Table 1. Table 1 also collects information such as AOD quality criteria and additional notes. The summary of this information in Table 1 provides organized information and better reference for readers.

Line 153: has been set 0.01 in Mx8.10 and in newer versions -> has been set to 0.01 in Mx8.10 and newer versions

Revised as suggested.

Line 170: Are the 7x7 area centered around the snow pixel?

Yes. As described in Line 172, the new snow adjacency test loops through the adjacent 7×7 pixels surrounding the central snow pixel.

Line 188: Something does not correctly show after the parenthesis.

It is ρ_{412}. It is corrected now.

Line 206: Please elaborate what are the criteria for the careful selection?
Since the test is threshold based, the unavoidable fact is, we have to achieve a balance between screening for sub-pixel snow and allowing retrievals of heavy smog. We tested different threshold values of C2, and determined C2=0.004 is optimal for minimizing sub-pixel snow over-screening to allow reasonable heavy smog retrievals at the same time.

Lines 219-281: These two paragraphs are too long. Try breaking them into short ones.
Revised as suggested. The two paragraphs are now broken into several short paragraphs.

Line 432: The sorting is not right here. This reference should be moved to Line 401.
Corrected.

Figure 1: Difficult to read. Please improve the quality of the image.
The images were replaced with high resolution ones as suggested to improve their quality.

Figure 3: The three colors for the last three populations are too difficult to differentiate. Please change them to other distinct colors.
Colors for the last three data populations are changed as suggested.

Figure 4: Difficult to read. Please improve the quality of the image.
The quality of the image is improved as suggested.

Figure 5: Some "N of Good AOD" numbers in (b) are greater than "N of Top2AOD" in some latitude bins (e.g. lat=60). Something seems wrong here.
Thank you very much for pointing out this error to us. Figure 5(a) should be 'Degraded' Quality AOD instead of 'Top 2' AOD. Top 2 AOD retrievals includes both Good and Degraded quality AOD retrievals. We have revised the Y axis label in (a) from 'Top 2' to 'Degraded' and corrected the Figure caption accordingly. The corresponding discussions are also updated.

Figure 5: Showing "-100" and "100" for Latitude Bins should be avoided.

"-100" and "100" are removed and the x-axis labels are revised as suggested.

Screening for Snow/Snowmelt in SNPP VIIRS Aerosol Optical Depth Algorithm

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Abstract. The Visible/Infrared Imaging/Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) spacecraft provides validated daily global ~~aerosol optical thickness~~aerosol optical depth (~~AOT~~AOD) retrievals; however, a close examination of the VIIRS aerosol product identified residual snow and snowmelt contamination, resulting generally in an overestimation of ~~AOT~~AOD. The contamination was particularly evident over northern hemisphere high latitude regions during the spring thaw. To improve the product performance, we introduced a new empirical snow and snowmelt screening scheme that combines a Normalized Difference Snow Index (NDSI) and Brightness Temperature (BT) based snow test, a snow adjacency test and a spatial homogeneity test (aka. spatial filter). Testing of retrievals for May 18, 2014 indicated that compared to the previous, visible reflectance anomaly (VRA) based snow test, the new NDSI and BT based snow test screened out an additional 3.44% of VIIRS ~~AOT~~AOD retrievals, most of which were over high latitudes experiencing snowmelt. The new snow adjacency test and the homogeneity test degraded another 5.57% and 0.26%, respectively, otherwise 'Good' quality ~~AOT~~AOD retrievals. For the VIIRS vs. AERONET matchups over northern hemisphere high latitude regions during three years of spring (2013-2015), the new scheme also effectively screened out a significant number of the matchups that had anomalous high positive biases attributable to snow and snowmelt contamination. The new snow and snowmelt screening scheme was transferred to the Interface Data Processing Segment (IDPS) VIIRS aerosol algorithm on Jun 22, 2015. Subsequently no significant snow and snowmelt contamination was found during spring 2016. The scheme is also implemented in the new Enterprise VIIRS aerosol algorithm in the National Oceanic and Atmospheric Administration (NOAA) Enterprise Processing System (EPS) that became operational in 2017.

1 Introduction

Nowadays with increasing public awareness of air pollution and aerosol climatic effects, satellite observations of global aerosol loading and transport provide valuable information for improving our understanding of the impact of aerosols on weather, climate and public health (Kaufman et al., 2002; Quaas et al., 2008; Al-Saadi et al., 2005; Von Donkelaar et al., 2010; Kloog et al., 2011). Although satellite retrievals of aerosol optical properties in cloud-free and even in cloudy scenes have advanced tremendously over the past decades (Lenoble et al., 2013; Jethva et al., 2016; Meyer et al., 2015; Sayer et al., 2016), aerosol observations over snow scenes are still not feasible by passive sensors.

Most over-land aerosol algorithms from passive sensors make assumptions about surface reflectance properties in the retrieval scene in order to separate the signal from aerosol scattering in the atmosphere from the signal originating from reflectance from

Earth's surface (Levy et al., 2007; Jackson et al., 2013). Snow reflectance properties vary significantly with snow grain size (Wiscombe and Warren, 1980; Warren et al., 1982) and impurities in or on the snow (Doherty et al. 2010; Hadley and Kirchstetter, 2012), all of which change rapidly in time as the snow ages, and especially as it melts. The quickly changing optical properties of snow introduce too much uncertainty for global operational aerosol retrieval algorithms (Li et al., 2005). Therefore, screening out snow pixels is a necessary procedure in almost every aerosol retrieval algorithm, yet it remains a daunting challenge, particularly if the scene is complicated with sub-pixel or melting snow. Therefore the ~~aerosol optical thickness~~aerosol optical depth (~~AOT~~AOD) retrievals adjacent to snow still have large uncertainties due to potential snow contamination (Lyapustin et al., 2012). Note that this snow contamination introduces a positive bias in the aerosol retrieval, as snow is bright in the visible and very dark in the near- and shortwave-infrared. Many passive satellite aerosol retrieval algorithms interpret the brighter-than-assumed visible surface reflectance as extra aerosol loading (Li et al., 2005). Even a small amount of sub-pixel snow in the retrieval scene can introduce ~~artificial~~ positive bias in the ~~AOT~~AOD.

The Visible/Infrared Imaging/Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (S-NPP), launched on October 28, 2011, is the first satellite in the series of the United States' next generation polar-orbiting operational environmental satellite system, the Joint Polar Satellite System (JPSS). The VIIRS aerosol products, following the aerosol products from heritage sensors such as the Moderate Resolution Imaging Spectrometer (MODIS) and the Multiangle Imaging Spectroradiometer (MISR), continue to succeed in providing daily global aerosol observations for operational and scientific user communities (Jackson et al., 2013; Liu et al., 2014; Huang et al., 2016; Zhang et al., 2016). By comparing the VIIRS aerosol products to the Aerosol Robotic Network (AERONET, Holben et al., 1998) ground measurements and the MODIS aerosol products, the validation results indicated that the ~~AOT~~AOD over land reached validated maturity on Jan 23, 2013 and the ~~AOT~~AOD over ocean reached validated maturity on May 2, 2012 (Liu et al., 2014; Huang et al., 2016).

With more than three years of the validated S-NPP VIIRS aerosol products publicly available and used in various user applications, further in-depth data analyses show that the VIIRS retrievals are consistently overestimating the ~~AOT~~AOD, when compared with AERONET, over high latitude regions in the northern hemisphere, especially during the spring thaw, when snow is melting. This implies potential snow and snowmelt contamination in the products.

The VIIRS aerosol products are generated operationally in the so-called Interface Data Processing Segment (IDPS), which is one of the segments of the NPP project that processes the raw observations into environmental data records (geophysical parameters). Versions of the system, representing increasing maturity and algorithm updates, are referred to as Mx builds in a given block (In IDPS a block is similar to a Collection in the MODIS processing.) The original at-launch snow test, summarized in the next section, was implemented in the IDPS VIIRS aerosol algorithm from Dec 9, 2011 to Jun 22, 2015, until the Mx8.8 build in Block 1.x. The new snow and snowmelt mask described in this paper, was implemented in the Mx8.10 build on Jun 22, 2015 and has been running in the IDPS ever since. The new snow mask was further refined by tuning threshold values, and it has been implemented in the National Oceanic and Atmospheric Administration (NOAA), Enterprise Processing System (EPS) VIIRS Aerosol Algorithm, which is replacing the IDPS algorithm.

This paper presents the identification of the snow contamination in Section 2, the development of a new snow and snowmelt screening scheme in Section 3, and the evaluation of the new scheme in the VIIRS operational aerosol products in Section 4, followed by summary and discussion in Section 5.

Note that all snow screening tests discussed in this paper are designed to prevent the aerosol algorithm from making retrievals in inappropriate snow cover conditions. For a true snow product, users are directed to the S-NPP VIIRS Snow/Ice products (Key et al., 2013).

2 Background and Identification of the Problem

According to Jackson et al. (2013), the snow screening in the VIIRS land aerosol algorithm consists of two parts: the snow flag from the upstream VIIRS Cloud Mask (VCM) product, and the internal snow test within the VIIRS aerosol algorithm itself. When aerosol observations are feasible under daytime conditions, the VCM uses the VIIRS Gridded Snow Cover product in conjunction with a reflectance based snow detection algorithm to check for snow surfaces. However, to avoid significant ~~AOT~~AOD overestimation caused from snow pixels or sub-pixel snow conditions, the snow screening for aerosol observations needs to be stricter than the general snow detection in the VCM. Thus an internal snow detection scheme within the aerosol algorithm becomes necessary to complement the VCM snow flag. Prior to Jun 22, 2015, the internal snow detection in the operational IDPS VIIRS aerosol algorithm is based on three tests: (1) the visible reflectance anomaly (VRA), (2) the ratio of top of the atmosphere (TOA) reflectance in the 1240 nm channel (ρ_{1240}, VIIRS band M8) to the 865 nm channel (ρ_{865}, VIIRS band M7), and (3) the surface temperature derived from the split window technique (Walton et al., 1998). This at-launch internal snow test is referred to as the 'VRA-based snow test' hereafter in the paper. VRA is defined as:

$$\mathrm{VRA} = \rho^{s}_{488} - 0.5 \times \rho^{s}_{672} \quad (1)$$

where ρ^{s}_{488} and ρ^{s}_{672} are 488 nm (VIIRS band M3) and 672 nm (VIIRS band M5) surface reflectances. Eq. 1 is based on the retrieval assumption that the surface reflectance of the blue wavelength is roughly half of the red wavelength (Kaufman et al., 1997; Jackson et al., 2013). A significant deviation from this well-established surface reflectance relationship indicates a surface outside of our range of assumptions and should not be used for aerosol retrievals.

In the VIIRS aerosol algorithm with the VRA-based snow test, as shown in Table 1, if the reflectances in the required bands are available and the following conditions are met, the internal snow test sets the snow flag and no aerosol retrievals are reported in the VIIRS aerosol product:

1. VRA > 0.02,
2. $\rho_{1240}/\rho_{865} < 0.9$,
3. Surface temperature < 278 K,
4. No cirrus, and
5. Cloud mask is confidently or probably clear.

Applying this VRA-based snow test, the ~~AOT~~AOD retrievals over high latitude geographic regions were, however, consistently overestimated during the boreal spring thaw, when snow was melting (Jackson et al., 2013; Liu et al., 2014; Huang et al., 2016). Neither the external VCM snow tests nor the internal VRA-based snow test were able to effectively detect and screen out those snow- and snowmelt-contaminated pixels, and anomalously high ~~AOT~~AODs were reported as ~~high~~ good quality retrievals. Those unfiltered snow or snowmelt pixels are usually more reflective in the visible, and thus can result in falsely high ~~AOT~~AOD retrievals if they are mistaken as aerosols. The global validation of the S-NPP VIIRS ~~AOT~~AOD product reported that such snow and snowmelt contamination frequently happened during spring thaw over high latitude geographic regions, such as northern Canada and northern Russia. This widespread residual snow and snowmelt contamination caused a significant high bias in the ~~AOT~~AOD product. Using the AERONET ground measurement, the validation of the VIIRS ~~AOT~~AOD during Feb – May of 2013-2015 showed a strong positive bias of +0.073, not meeting the requirement of ±0.06 when ~~AOT~~AOD≤0.8 (NOAA JPSS Level 1 Requirements Document, http://www.jpss.noaa.gov/pdf/L1RDS_JPSS_REQ_1002_NJO_v2.10_100914_final-1.pdf). This required an alternative internal snow test in the VIIRS aerosol algorithm to replace the VRA-based snow test.

An empirical snow detection technique using near infrared reflectances at 860 nm and 1240 nm and brightness temperature at 11 μm channel, was proposed by Li et al. (2005). This scheme was implemented in the MODIS operational aerosol algorithm beginning with Collection 5 (Levy et al., 2007, 2009, 2013). This paper explores the applicability of a similar approach in the VIIRS aerosol algorithm by using the VIIRS bands. Snow adjacency and spatial homogeneity tests complement this snow test to form a systematic snow and snowmelt screening scheme in the VIIRS aerosol algorithm.

3. The New Snow and Snowmelt Screening Scheme

The new empirical snow and snowmelt screening scheme consists of three separate tests: snow test, snow adjacency test, and spatial homogeneity test.

3.1 The NDSI and BT based Snow Test

The snow test follows the approach of Li et al. (2005). Similar to step 3 in the VRA-based snow test this snow test also uses near-infrared and shortwave infrared TOA reflectances, but instead of their simple ratio it calculates the ratio of their difference to their sum, the so called Normalized Difference Snow Index (NDSI) (defined below) and compares it to a threshold value. Normalization is used as a means to adjust for the effects of the solar and view zenith angles because the normalized form is less sensitive to changes in the two angles than the simple ratio form (i.e. Walter-Shea et al., 1997). Again, similar to step 4 in the VRA-based snow detection, it also uses a thermal-infrared brightness temperature test but with a different threshold value. In our adaptation we substitute the following VIIRS spectral bands for the MODIS bands in Li et al. (2005). We calculate the NDSI from ρ_{865} and ρ_{1240} (VIIRS bands M7 and M8), and the brightness temperature (BT) at 10.76 μm ($BT_{11\mu m}$, VIIRS band M15). To differentiate this test from the VRA-based snow test, we call this new snow test the "NDSI-based snow test" hereafter.

The theoretical basis of the NDSI-based snow test lies in the fact that the spectral dependence of snow reflectance is very different from that of vegetation and soils. The reflectance of snow decreases rapidly with increasing wavelength from visible to shortwave infrared in the 800 – 1300 nm wavelength range due to strong ice absorption features centered near 1050 and 1240 nm. The reflectance of green vegetation decreases only slightly with increasing wavelength due to weak liquid water absorption bands centered near 960 and 1180 nm. The reflectances of soil and dry vegetation however typically increase with wavelength in the same spectral region. Therefore the reflectance of snow is higher than that of green vegetation and soil at visible bands but much lower at shortwave infrared bands (Figure 3 therein Li et al. 2005). Based on the spectral properties of snow, vegetation, and soil, the NDSI, which was first used in Gao (1996), is defined as follows:

$$\mathrm{NDSI} = \frac{(\rho_{865}-\rho_{1240})}{(\rho_{865}+\rho_{1240})} \qquad (2)$$

where ρ_{865} and ρ_{1240} are reflectances at 865 nm (VIIRS M7) and 1240 nm (VIIRS M8) respectively. It is noteworthy that while the IDPS algorithm uses TOA reflectances in NDSI, the EPS algorithm uses Rayleigh-scattering and gas-absorption corrected reflectances to minimize these effects on NDSI.

Similarly to Li et al. (2005), to avoid over-screening of vegetated pixels, BT_{11} is also used for further stratification.

As Table 1 and the flowchart in Figure 1(a) show, this NDSI-based snow test will set a snow flag when the required reflectance and brightness temperature at respective bands are available and the following criteria are met:

1 NDSI > C1 (see below for threshold values used),
2 $BT_{11\mu m} < 285$ K;
3 No cirrus, and

4 Cloud mask is confident or probably clear.

C1 has been set to 0.01 in Mx8.10 and ~~in~~ newer versions of the IDPS Aerosol Algorithm. However, evaluation of retrievals over pixels with heavy smog, particularly over Eastern China during the boreal spring season, showed that this threshold value resulted in over-screening of such pixels. This happened because some heavy smog pixels also exhibited an NDSI data range (>0.01) and lower brightness temperature ($BT_{11\mu m}$<285K) similar to those for snow pixels, indicating stronger absorption of smog particles in the shortwave infrared than in the near infrared and relatively low brightness temperatures at 11µm. Thus the criteria of NDSI > 0.01 prevented potentially good ~~AOT~~AOD retrievals of these China smog events (Huang et al., 2017). Adjusting the NDSI threshold value showed that a higher threshold 0.10 helps to regain most ~~AOT~~AOD retrievals over the heavy air pollution pixels that previously went missing in the IDPS algorithm. Therefore in the EPS algorithm the higher C1 value (0.1) has been adopted. At the same time, the threshold in the spatial filter had to be adjusted as well (in Section 3.3) to ensure the new threshold values will not re-introduce artifacts due to snow contamination in other areas (Huang et al., 2017).

Because snow is one of the conditions that prevent meaningful aerosol retrievals, there are no aerosol retrievals over pixels with snow flags (Jackson et al., 2013). Therefore, in the VIIRS aerosol product, those pixels are filled with Fill Value and the quality of the retrievals over those pixels is set as 'Not Produced'.

3.2 Snow Adjacency Test

Although the NDSI-based snow test improves the snow pixel detection significantly, some residual snowmelt contamination surrounding the snow pixels still exists when we verify ~~AOT~~AOD retrievals over snow scenes. We attribute this contamination to unidentified sub-pixel snow. To minimize such contamination, a snow adjacency test is introduced as an additional quality assurance procedure in the aerosol algorithm. If the test shows a pixel is within an area of 7×7 pixels surrounding a snow pixel, the aerosol retrieval for that pixel is likely susceptible to snowmelt contamination, and the condition becomes unfavorable for meaningful aerosol retrievals.

As shown in Table 1 and Figure 1(b), the new snow adjacency test loops through the adjacent 7×7 pixels surrounding the central snow pixel. For each of the 7×7 pixels except the central pixel, the snow adjacency quality flag is set if the following criteria are met:

1 Center pixel is set as 'snow' over land,

2 No cirrus detected, and

3 Cloud Mask is confident or probably clear.

However, unlike the snow test, the snow adjacency test is designated as one of the 'Degradation' retrieval condition rather than a 'Not Produced' retrieval condition. After the snow adjacency quality flag is set for a particular pixel, the snow adjacency test continues to check whether the aerosol retrieval quality is 'Good'. If the aerosol retrieval quality is 'Good', the snow adjacency test degrades the aerosol retrieval quality from 'Good' to 'Degraded'; otherwise, the aerosol retrieval quality is not changed.

3.3 Spatial Homogeneity Test (Spatial Filter)

The third test, like the snow adjacency test, is meant to caution users that retrieved ~~AOT~~AOD may be susceptible to sub-pixel snow and snowmelt situations. This alert becomes especially important during spring thaw when snowmelt pixels can spread over large geographic areas. Pixels containing a surface with a mixture of exposed soil, vegetation, old snow and soggy slush introduce a level of spatial inhomogeneity not seen during other seasons. To identify this situation, an internal spatial homogeneity test is introduced in the aerosol algorithm. The spatial filter calculates the standard deviation of the TOA 412 nm reflectance (ρ_{412}, VIIRS band M1) in a grouping of 3×3 pixels to assess the spatial homogeneity. If the assessment shows large spatial heterogeneity of the M1 TOA reflectance within the surrounding 3×3 pixel area, the condition becomes unfavorable for meaningful aerosol retrievals. The 412-nm reflectance is used because of the generally low reflectance of snow-free land surfaces at this wavelength. As shown in Table 1 and Figure 1(c), the spatial filter sets the homogeneity test flag for the center pixel when the following criteria are met:

1 Aerosol retrieval flag of the center pixel is 'Good', and
2 The standard deviation of ρ_{412} of 3×3 surrounding pixels exceeds C2.

C2 has been set to 0.05 in the Mx8.10 and newer versions of the IDPS Aerosol Algorithm. As it has been mentioned above, in the EPS algorithm the NDSI threshold was relaxed from its IDPS value to regain retrievals over heavy smog pixels (see Section 3.1), and consequently the value of C2 had to be adjusted accordingly to ensure a stricter homogeneity requirement to compensate. This is because smog events are usually homogeneous at these spatial scales, and thus an adjustment of the spatial filter threshold does not cause over-screening of smog pixels or other retrieval scenes, yet manages to eliminate the spatially variable sub-pixel snow that appeared once the NDSI threshold was relaxed. The adjustment helps minimize the potential false aerosol retrievals over pixels with sub-pixel snow and NDSI values in the range of 0.01~0.10. However, to verify the new NDSI threshold will not introduce snow and snowmelt contamination, we closely examined 24 granules with smog pixels on smog prevalent days over China from Nov 29, 2015 to Feb 29, 2016, and another 30 granules with snow and snowmelt pixels over Canada on March 27-31 and May 28-29, 2015. With same sets of threshold values of NDSI and spatial filter applied to both heavy smog and snow scenes, a new C2=0.004 was carefully selected to achieve a balance between screening for sub-pixel snow and allowing retrievals of heavy smog. More justification of the threshold changes can be found in Section 4 where the aerosol retrievals from the EPS algorithm are discussed.

Due to the nature of the spatial filter the homogeneity test not only helps detecting sub-pixel snow pixels but also helps screening partial cloudy pixels that contain sub-pixel cloud. The test is particularly effective for those low level 'popcorn' cumulus clouds, which are so small in spatial scale causing higher spatial variability. Since both cloud and snow conditions are unfavorable conditions for meaningful satellite aerosol retrievals, the homogeneity test provides additional quality assurances to the VIIRS aerosol retrievals in terms of both snow and cloud screenings.

Similar to the snow adjacency test, the homogeneity test is designated as one of the 'Degradation' conditions rather than a 'Not Produced' condition. However, for efficient aerosol retrieval the homogeneity test is only conducted when the aerosol retrieval quality of the center pixel is 'Good'. If this flag is 'Good' and the above criteria are met, the homogeneity test quality flag is set and the quality of the aerosol retrieval is degraded from 'Good' to 'Degraded'.

4 Evaluation of the new snow and snowmelt screening scheme

To demonstrate the effectiveness of the new snow and snowmelt screening scheme, we apply old and new schemes to the same granule. In this test the new scheme uses the thresholds in the Mx8.10 IDPS algorithm (C1=0.01 and C2=0.05). As seen in Figure 2(a), an example of "good" quality VIIRS ~~AOT~~AOD retrievals clearly shows anomalously high ~~AOT~~AOD values over areas to the east and south of the Hudson Bay in Canada on May 19, 2015 when the snowpack was melting, as indicated by the snow cover map in Figure 2(c) from the NOAA National Centers for Environmental Information (NCEI) (https://www.ncdc.noaa.gov/snow-and-ice/snow-cover/us/20150519). Comparing the results of the new NDSI-based scheme in Figure 2(b) with the VRA-based snow test of Figure 2(a) clearly shows that the amount of anomalously high ~~AOT~~AOD retrievals are significantly reduced, implying the new scheme has effectively reduced the snow and snowmelt contamination in the ~~high quality~~good quality ~~AOT~~AOD retrievals.

We can better understand the workings of the new scheme by comparing the spectral reflectance of different populations of pixels found in the granules of Figure 2. Five populations of pixels are shown in Figure 3: 1) snow pixels identified by the VRA-based snow test; 2) snow pixels identified by the NDSI-based snow test; 3) snow or snowmelt pixels flagged by the spatial filter; 4) snow adjacent pixels flagged by the snow adjacency test; and 5) pixels with ~~high quality~~good quality aerosol retrievals from both versions of the algorithm, where the retrieval conditions should be less susceptible to snow and snowmelt contamination.

The averages of TOA reflectances at 11 VIIRS spectral bands, the NDSI, and the BT11µm are calculated, respectively, for each population. The TOA reflectance ρ_{865} and ρ_{1240} are connected by a line segment to show the slopes better. Because ice particles have much stronger absorption at 1240 nm than soil and vegetation, the steeper the negative slope from 865 nm to 1240 nm, the higher the NDSI value, the more likely snow exists in those pixels. While this slope is negative for snow and slightly positive for soil, as explained in Section 3.1, the pixels with sub-pixel snow should feature a reduced steepness of the slope depending on the relative coverage of soil and snow within the pixel. Similarly, because the absolute temperature of snow is generally lower than that of vegetation or soil, the more snow exists in the pixels, the lower the radiation emitted by the pixels, thus the lower the brightness temperature at 11µm (i.e. Gutman et al., 1995; Hori et al. 2006; Li et al., 2013).

As shown in Figure 3, the NDSI and BT values for pixels identified as snow by the VRA-based snow test are 0.260 and 265.8K, and those for pixels identified as snow by the NDSI-based snow test are 0.217 and 271.4K. Thus, the NDSI-based snow test has been more aggressive, categorizing pixels as snow despite their spectral signature and temperature being less characteristically snow-like (that is, darker and warmer) than was required by the VRA-based snow test. The snow adjacency and spatial filter tests continue in this vein identifying more pixels with even less snow-like characteristics: NDSI and $BT_{11\mu m}$ values are 0.017 and 283.2K for the spatial filter category and -0.041 and 283.5K for the snow adjacency category. For the category with good quality aerosol retrieval after both schemes were applied, the NDSI is lowest (-0.071) and $BT_{11\mu m}$ is highest (288.4 K), indicating surface conditions with the least snow-like characteristics.

The VRA-based and NDSI-based snow screen schemes were implemented into the aerosol algorithm and applied globally for the testing date of May 18, 2014. Figure 4 shows the ~~high quality~~good quality VIIRS ~~AOT~~AOD retrievals with the old (Figure 4a) and new tests (Figure 4b), and their differences (Figure 4c). Most of the reduced ~~high quality~~good quality ~~AOT~~AOD retrievals were found over high latitude snowmelt prevalent regions. They either became 'Not Produced' because of the stricter new snow test or were degraded from 'Good' to 'Degraded' by the new snow adjacency test and the spatial filter.

To demonstrate the impact of the tests on the number of retrievals statistics of sample size and percentage change in the number of ~~AOT~~AOD retrievals were calculated for 18 10-degree latitude bins, and the results are shown in Figure 5. As expected, the new snow, adjacency and spatial homogeneity tests have largest impact over high latitude regions in the northern hemisphere, where snow is rapidly melting during boreal spring thaw. Overall, global statistics indicate that the new snow test screened out an additional 3.44% VIIRS ~~AOT~~AOD retrievals, and the new snow adjacency test and the homogeneity test degraded another additional 5.57% and 0.26% 'Good' quality ~~AOT~~AOD retrievals, respectively. Although these percentages may change from day to day, they provide rough estimates of the magnitudes of the percentage change in the number of good aerosol retrievals when the VRA-based snow test is replaced by the new snow and snowmelt screening scheme.

The effectiveness of the new snow and snowmelt screening scheme is also verified from the validation of the VIIRS ~~AOT~~AOD products with AERONET ground measurements. Figure 6 compares the VIIRS vs. AERONET matchups over [130ºW-50ºW, 50ºN-90ºN] during boreal spring Feb-May, 2013-2015, during which period the VRA-based snow test was still in operation in the VIIRS aerosol algorithm. A matchup is defined as the mean ~~high quality~~good quality VIIRS ~~AOT~~AOD retrievals within 27.5 km from an AERONET site and the mean AERONET ~~AOT~~AOD observations within ±30 minutes of the VIIRS overpass time.

A significant number of anomalously high VIIRS ~~AOT~~AOD retrievals with positive biases were found in the retrievals plotted in Figure 6(a). Then for each matchup, the corresponding NDSI, BT, snow adjacency and spatial standard deviations were calculated, so that we could apply the various tests of the NDSI-based snow screen using the different threshold values for the various versions of the algorithm. The VIIRS vs. AERONET matchups in Figure 6(a) were removed if the new snow test would have prevented the retrieval or the new snow adjacency test or homogeneity test would have degraded the quality of the retrieval. Figure 6(b) and Figure 6(c) showed two screening conditions, one uses thresholds from the Mx8.10 IDPS algorithm and the other uses thresholds from the EPS algorithm. Out of 260 matchups in Figure 6(a), using the IDPS thresholds, 43 were identified as snow, 94 were found with the adjacency test, and none with the spatial filter test. Because some of the snow pixels were also adjacent to other snow pixels, resulting in redundancy, 97 pixels were screened out, leaving 163 remaining matchups after the screening, with much improved accuracy, much lower uncertainty and much better agreement to AERONET.

Similarly, the same level of improvement was also achieved with the EPS thresholds. 30 matchups were found with snow, 94 with the adjacency test and 81 with the spatial filter test because of the tighter threshold for the standard deviation. Allowing for pixels with multiple conditions, the screening with the EPS thresholds resulted in 158 remaining matchups in Figure 6(c), having better agreement to AERONET. There are two anomalous points in Figure 6 (a)-(c) with higher positive biases in the red circles that were not screened out. With the same snow screening scheme, we ran the EPS algorithm on the same granule and found that the same two matchups with higher positive biases in the red circles were retrieved by the EPS algorithm as ~~high quality~~good quality retrievals but their biases were significantly reduced by ~0.2 from 0.5-0.6 to 0.3-0.4. This means the positive biases of these two anomalies seemed to be related to the ~~AOT~~AOD retrieval itself rather than the under-screening snow.

The new snow and snowmelt scheme was transferred to operation (TTO) in the Mx8.10 IDPS VIIRS aerosol algorithm on Jun 22, 2015 19:43 UTC. No significant snow and snowmelt contamination were found in the operational IDPS aerosol products during the 2016 spring thaw season, demonstrating the new scheme had improved the quality of the products with much better snow and snowmelt screening. The new snow and snowmelt screening scheme is also implemented in the EPS VIIRS aerosol algorithm, but with its own thresholds (Laszlo and Liu, 2016). As previously discussed, the threshold values of the NDSI and spatial filter were adjusted in the EPS VIIRS aerosol algorithm to regain heavy smog retrievals while keeping the same level of snowmelt screening as in the Mx8.10 IDPS algorithm (Huang et al., 2017). Global assessment of the new tests in the EPS algorithm were conducted for the boreal spring season of 2015, which had significant snow and snowmelt contamination over northern hemisphere high latitudinal regions (Figure 7a). The VIIRS aerosol retrieval in the spring thaw season of 2015, produced from the EPS algorithm in Figure 7(b), was compared to the operational IDPS products during the same season in Figure 7(a). Note that May 2015 preceded the implementation of the new snow scheme, which began in June of that year. Thus Figure 7(a) shows high ~~AOT~~AOD along the edge of the northern snow boundary, but Figure 7(b) with the new scheme does not. The new boreal spring seasonal VIIRS ~~AOT~~AOD retrievals are much improved in terms of the significantly reduced amount of anomalously high ~~AOT~~AOD values, particularly over Northern Canada and Northern Russia. At the same time, Figure 7(b) also highlights that the EPS aerosol products regained more ~~AOT~~AOD retrievals of smog events over Eastern China during spring 2015, resulting in higher seasonal mean ~~AOT~~AOD there. This improvement results from the NDSI threshold adjustment. Other advantages to the EPS products, unrelated to the new snow mask, such as retrievals over the bright deserts can also be seen in Figure 7(b).

5 Summary and Discussion

Validation of the S-NPP VIIRS operational aerosol products revealed residual snow and snowmelt contaminations during the boreal spring thaw season over high latitude geographic regions. To reduce such contamination, we proposed a snow and snowmelt screening scheme that combines a new NDSI and BT based snow test, a snow adjacency test and a spatial filter based on the standard deviation of reflectance at 412 nm. The pixels flagged as snow by the snow test will become ‘Not Produced’, while the ‘Good’ ~~AOT~~AOD retrievals adjacent to identified snow pixels or with higher spatial heterogeneity will be ‘Degraded’. It is noteworthy that in the operational environment the cloud test should be conducted before the snow test because the snow detection requires clear sky condition. The snow test should be conducted before the snow adjacency test and the spatial filter because the latter tests need to know whether the central pixel is identified as snow or whether the retrieval is a good quality one. The order of snow adjacency test and spatial filter however does not produce a difference in the aerosol retrieval. Since spatial filter requires standard deviation calculation, which is more computationally expensive than the snow adjacency test, it is usually arranged as the last test of the snow and snowmelt scheme. The testing of the new scheme demonstrated significant improvements in the VIIRS aerosol retrievals with much fewer anomalous high ~~AOT~~AOD retrievals due to snow and snowmelt contamination.

A global testing on May 18, 2014, a typical day in spring thaw season when snow and snowmelt prevail, showed that the new snow test screened out an additional 3.44% ‘Good’ quality VIIRS ~~AOT~~AOD retrievals, which were otherwise contaminated by snow and snowmelt, and the new snow adjacency test and the homogeneity test degraded 5.57% and 0.26% ‘Good’ quality ~~AOT~~AOD retrievals to ‘Degraded’ quality, respectively. Such percentage is expected to be lower in other seasons when ~~AOT~~AOD retrievals are expected to be less susceptible to snow and snowmelt contamination. In future work~~s~~, in order to reach ~~a~~ more quantitative statistics for a better understanding of the relative contributions from each test, more testing dates at different seasons are needed. The additional testing will not only help find seasonal variability of the tests, but also help identify any residual snow and snowmelt contaminations or any over-screened AOD retrievals, both of which are valuable for further algorithm improvement. ~~.~~

The new snow and snowmelt scheme was also able to screen out significant number of the VIIRS vs. AERONET matchups that had anomalous high positive biases in the IDPS VIIRS aerosol products over Canada during the spring thaw season from 2013 to 2015. The new snow and snowmelt screening scheme was transferred to operation (TTO) in the operational IDPS VIIRS aerosol algorithm on Jun 22, 2015 19:43 UTC. No significant snow and snowmelt contamination was found in the operational IDPS aerosol products during the 2016 spring thaw season. The new scheme has also been implemented in the upcoming EPS aerosol algorithm, however with fine-tuned threshold values of NDSI and spatial filter tests, in order to regain some ~~AOT~~AOD retrievals over heavy smog events and to maintain the snow and snowmelt screening at the same strict level as in the IDPS algorithm. The VIIRS ~~AOT~~AOD retrievals during spring 2015 produced by the EPS algorithm were much improved from the IDPS ~~AOT~~AOD product, in terms of the significantly reduced amount of anomalously high ~~AOT~~AOD values, particularly over Northern Canada and Northern Russia. The new EPS VIIRS aerosol algorithm became operational in July, 2017.

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References

Aerosol ATBD: VIIRS ~~Aerosol Optical Thickness~~Aerosol optical depth and Particle Size Parameter Algorithm Theoretical Basis Document (Revision B), Effective Date: May 8, 2014. http://www.star.nesdis.noaa.gov/jpss/documents/ATBD/D0001-M01-S01-020_JPSS_ATBD_VIIRS-~~AOT~~AOD-APSP_B.pdf

Aerosol OAD: VIIRS Aerosol Products (~~AOT~~AOD, APSP & SM) Intermediate Product (IP)/Environmental Data Records (EDR) Software - OAD (Revision F), Effective Date: September 03, 2015. http://npp.gsfc.nasa.gov/sciencedocs/2015-09/474-00073_OAD-VIIRS-Aerosols-IP-EDR_H.pdf

Al-Saadi, J., Szykman, J., Pierce, R. B., Kittaka, C., Neil, D., Chu, D. A.,Remer, L.A., Gumley, L., Prins, E., Weinstock, L., MacDonald, C., Wayland, R., Dimmick, F., and Fishman, J.: Improving national air quality forecasts with satellite aerosol observations, Bull. Am. Meteorol. Soc., 86, 1249-1261, doi:10.1175/BAMS-86-9-1249, 2005.

Doherty, S. J., Warren, S. G., Grenfell, T. C., Clarke, A. D., and Brandt, R. E.: Light-absorbing impurities in Arctic snow, Atmospheric Chemistry and Physics, 10, 11647-11680, doi: 10.5194/acp-10-11647-2010, 2010.

Gao, B. C.: NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space, Remote Sens. Environ., 58, 257-266, doi:10.1016/S0034-4257(96)00067-3, 1996.

Gutman, G., Tarpley, D., Ignatov, A., and Olson, S.: The enhanced NOAA global land data set from the advanced very high resolution radiometer, Bull. Am. Meteorol. Soc., 76, 1141–1156, doi:10.1175/1520-0477(1995)076<1141:TENGLD>2.0.CO;2, 1995.

Hadley, O. L., and Kirchstetter, T. W.: Black-carbon reduction of snow albedo, Nature Climate Change, 2(6), 437-440, doi:10.1038/nclimate1433, 2012.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.J., Nakajima, T., Lavenu, F., Jankowiak, I., Smirnov, A.: AERONET - A federated instrument network and data archive for aerosol characterization, Remote Sensing of Environment, 66(1), 1-16, doi:Doi 10.1016/S0034-4257(98)00031-5, 1998.

Hori, M., Aoki, T., Tanikawa, T., Motoyoshi, H., Hachikubo, A., Sugiura, K., Yasunari, T., Eide, H., Storvold, R., Nakajima, Y., and Fumihiro, T.: In-situ measured spectral directional emissivity of snow and ice in the 8–14 µm atmospheric window. Remote Sensing of Environment, 100(4), 486-502, doi:10.1016/j.rse.2005.11.001, 2006

Huang, J., Kondragunta, S., Laszlo, I., Liu, H., Remer, L.A., Zhang, H., Superczynski, S., Ciren, P., Holben, B. N., and Petrenko, M. : Validation and expected error estimation of Suomi-NPP VIIRS ~~aerosol optical thickness~~aerosol optical depth and Ångström exponent with AERONET, J. Geophys. Res. Atmos., 121, 7139–7160, doi:10.1002/2016JD024834, 2016.

Huang, J., Liu, H., Zhang, H., Kondragunta, S., Laszlo, I., Ciren, P., Remer, L. A., and Superczynski, S.: Detecting Air Pollution Events Over China Using Two Different ~~Aerosol Optical Thickness~~Aerosol optical depth Products Derived from S-NPP VIIRS Observations, Abstract #303078, 13th Annual Symposium on New Generation Operational Environmental Satellite Systems, AMS Annual Meeting 2017, Seattle, 22-26, January 2017

Jackson, J., Liu, H., Laszlo, I., Kondragunta, S., Remer, L.A., Huang, J., Huang, H.: Suomi-NPP VIIRS aerosol algorithms and data products, J. Geophys. Res. Atmos., 118, 12,673–12,689, doi:10.1002/2013JD020449, 2013.

Jethva, H., Torres, O., Remer, L.A., Redemann, J., Livingston, J., Dunagan, S., Shinozuka, Y., Kacenelenbogen, M., Rosenheimer, M. S., and Spurr, R.: Validating MODIS above-cloud aerosol optical depth retrieved from “color ratio” algorithm using direct measurements made by NASA's airborne AATS and 4STAR sensors, Atmos. Meas. Tech., 9, 5053-5062, doi:10.5194/amt-9-5053-2016, 2016.

Kaufman, Y. J., Tanre, D., Remer, L. A., Vermote, E. F., Chu, A., and Holben, B. N.: Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer, Journal of Geophysical Research-Atmospheres, 102(D14), 17051-17067, doi:Doi 10.1029/96jd03988, 1997.

Kaufman, Y. J., Remer, L.A., Tanre, D., Li, R.R., Kleidman, R., Mattoo, S., Levy, R.C., Eck, T.F., Holben, B.N., Ichoku, C., Martins, J.V., and Koren, I.: A critical examination of the residual cloud contamination and diurnal sampling effects on MODIS estimates of aerosol over ocean, IEEE Transactions on Geoscience and Remote Sensing, 43(12), 2886-2897, doi:10.1109/TGRS.2005.858430, 2005.

Key, J. R., Mahoney, R., Liu, Y., Romanov, P., Tschudi, M., Appel, I., Maslanik, J., Baldwin, D., Wang, X., and Meade, P.: Snow and ice products from Suomi NPP VIIRS, J. Geophys. Res. Atmos., 118, doi:10.1002/ 2013JD020459, 2013.

Kloog, I., Koutrakis, P., Coull, B. A., Lee, H.J., and Schwartz, J.: Assessing temporally and spatially resolved PM 2.5 exposures for epidemiological studies using satellite aerosol optical depth measurements, Atmospheric Environment, 45(35), 6267-6275, doi: 10.1016/j.atmosenv.2011.08.066, 2011.

Laszlo, I. and Liu, H.: EPS Aerosol Optical Depth (AOD) Algorithm Theoretical Basis Document, Version 3.0.1, June 28, 2016, https://www.star.nesdis.noaa.gov/jpss/documents/ATBD/ATBD_EPS_Aerosol_AOD_v3.0.1.pdf

Lenoble, J., Remer, L.A., and Tanré, D. (eds.): Aerosol Remote Sensing, Springer Praxis Books, doi:10.1007/978-3-642-17725-5_1, 2013.

Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., and Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, Atmos. Meas. Tech., 6, 2989-3034, doi:10.5194/amtd-6-159-2013, 2013.

Levy, R. C., Remer, L. A., Tanré, D., Mattoo, S., and Kaufman, Y. J.: Algorithm For Remote Sensing of Tropospheric Aerosol Over Dark Targets from MODIS: Collections 005 and 051: Revision 2; Feb 2009, http://modis-atmos.gsfc.nasa.gov/_docs/ATBD_MOD04_C005_rev2.pdf

Li, R.R, Remer, L., Kaufman, Y.J., Mattoo, S., Gao, B.C., and Vermote, E.: Snow and ice mask for the MODIS aerosol products, Geoscience and Remote Sensing Letters, IEEE , 2(3), 306-310, doi: 10.1109/LGRS.2005.847755, 2005

Li, Z.-L., Wu , H., Wang, N., Qiu, S., Sobrino, J. A., Wan, Z., Tang, B., and Yan, G.: Land surface emissivity retrieval from satellite data, International Journal of Remote Sensing, 34(9-10), 3084-3127, doi:10.1080/01431161.2012.716540, 2013.

Liu, H., Remer, L.A., Huang, J., Huang, H., Kondragunta, S., Laszlo, I., Oo, M., and Jackson, J.: Preliminary evaluation of S-NPP VIIRS ~~aerosol optical thickness~~aerosol optical depth, J. Geophys. Res.: Atmos., 119, 3942–3962, doi:10.1002/2013JD020360, 2014.

Lyapustin, A., Wang, Y., Laszlo, I., and Korkin, S.: Improved cloud and snow screening in MAIAC aerosol retrievals using spectral and spatial analysis. Atmos. Meas. Tech., 5, 843-850, doi:10.5194/amt-5-843-2012, 2012.

Meyer, K., Platnick, S., and Zhang, Z.: Simultaneously inferring above-cloud absorbing ~~aerosol optical thickness~~aerosol optical depth and underlying liquid phase cloud optical and microphysical properties using MODIS, J. Geophys. Res. Atmos., 120, 5524–5547, doi: 10.1002/2015JD023128, 2015.

Quaas, J., Boucher, O., Bellouin, N., and Kinne, S.: Satellite-based estimate of the direct and indirect aerosol climate forcing, Journal of Geophysical Research: Atmospheres, 113, D05204, doi:10.1029/2007JD008962, 2008.

Remer, L. A., Kaufman, Y. J., Tanré, D., Mattoo, S., Chu, D. A., Martins, J. V., Li, R. R., Ichoku, C., Levy, R. C., Kleidman, R. G., Eck, T. F., Vermote, E., and Holben, B.N.: The MODIS aerosol algorithm, products, and validation. J. Atmos. Sci., 62, 947–973. doi: http://dx.doi.org/10.1175/JAS3385.1, 2005.

Sayer A. M., Hsu, N. C., Bettenhausen, C., Lee, J., Redemann, J., Schmid, B., and Shinozuka, Y.: Extending "Deep Blue" aerosol retrieval coverage to cases of abC4 AMTD Interactive comment Printer-friendly version Discussion paper sorbing aerosols above clouds: Sensitivity analysis and first case studies, J. Geophys. Res. Atmos., 121, 4830–4854, doi:10.1002/2015JD024729, 2016.

Shi, Y., Zhang, J., Reid, J. S., Liu, B., and Hyer, E. J.: Critical evaluation of cloud contamination in the MISR aerosol products using MODIS cloud mask products, Atmos. Meas. Tech., 7, 1791-1801, doi:10.5194/amt-7-1791-2014, 2014.

VIIRS Cloud Mask ATBD, Effective Date: Aug 5, 2014: http://www.star.nesdis.noaa.gov/jpss/documents/ATBD/D0001-M01-S01-011_JPSS_ATBD_VIIRS-Cloud-Mask_E.pdf

Van Donkelaar, A., Martin, R.V., Brauer, M., Kahn, R., Levy, R.C., Verduzco, C., and Villeneuve, P.J.: Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application, Environmental health perspectives, 118(6), 847, doi:10.1289/ehp.0901623, 2010.

Walter-Shea, E., Privette, J. L., Cornell, D., Mesarch, M. A., and Hays, C.: Relations between Directional Spectral Vegetation Indices and Leaf Area and Absorbed Radiation in Alfalfa, Remote Sensing of Environment, 61(1), 162-177, doi: 10.1016/S0034-4257(96)00250-7, 1997.

Walton, C. C., Pichel, W. G., Sapper, J. F., and May, D. A.: The development and operational application of nonlinear algorithms for the measurement of sea surface temperatures with the NOAA polar-orbiting environmental satellites, J. Geophys. Res., 103(C12),27,999–28,012, doi:10.1029/98JC02370, 1998.

Zhang, H., Kondragunta, S., Laszlo, I., Liu, H., Remer, L. A. , Huang, J., Superczynski, S., and Ciren, P.: An enhanced VIIRS ~~aerosol optical thickness~~aerosol optical depth (~~AOT~~AOD) retrieval algorithm over land using a global surface reflectance ratio database, J. Geophys. Res. Atmos., 121, doi:10.1002/2016JD024859, 2016.

~~Li, Z.-L., Wu , H., Wang, N., Qiu, S., Sobrino, J. A., Wan, Z., Tang, B., and Yan, G.: Land surface emissivity retrieval from satellite data, International Journal of Remote Sensing, 34(9-10), 3084-3127, doi:10.1080/01431161.2012.716540, 2013.~~

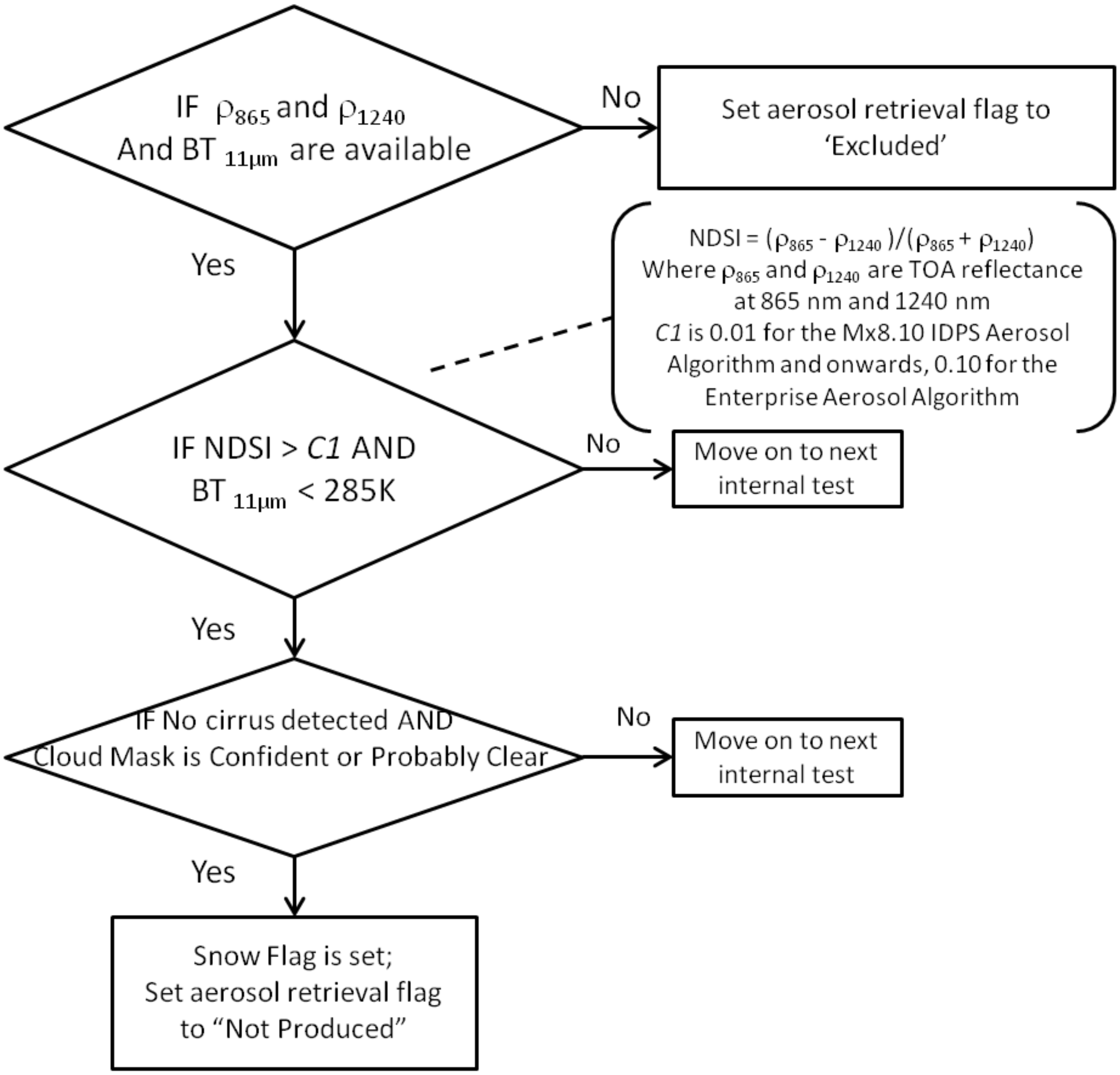
Tables

Table 1. Criteria for the VRA based snow test, NDSI based snow test, snow adjacency test and homogeneity test

Tests	Old VRA Based Test	New NDSI Based Snow Test	Snow Adjacency Test	Spatial Filter
Criteria	1. VRA > 0.02; 2. $\rho_{1240}/\rho_{865} < 0.9$; 3. Surface Temperature < 278 K; 4. No cirrus, and 5. Confidently or probably clear.	1. NDSI > *C1*; 2. $BT_{11\mu m} < 285$ K, 3. No cirrus, and 4. Confidently or probably clear.	For each of the 7×7 pixels except the central pixel, the snow adjacency quality flag is set if: 1. Center pixel is set as 'snow' over land, 2. No cirrus, and 3. Confidently or probably clear.	Sets the homogeneity test flag for the center pixel If: 1. Aerosol retrieval flag of the center pixel is 'Good', and 2. The standard deviation of ρ_{412} 3x3 surrounding pixels exceeds *C2*
~~AOT~~AOD Quality	Not Produced	Not Produced	Degraded to Medium	Degraded to Medium
Notes	1. VRA = $\rho^s_{488} - 0.5\times\rho^s_{672}$, ρ^s_{488} and ρ^s_{672} are 488 nm (VIIRS band M3) and 672 nm (VIIRS band M5) surface reflectance; 2. ST derived from $BT_{11\ \mu m}$ and $BT_{12\mu m}$	1. NDSI = $\frac{(\rho_{865}-\rho_{1240})}{(\rho_{865}+\rho_{1240})}$, ρ_{865} and ρ_{1240} are reflectances at 865 nm (VIIRS M7) and 1240 nm (VIIRS M8) respectively; 2. C1=0.01 for IDPS; C1=0.10 for EPS.	Check ~~high quality~~good quality ~~AOT~~AOD retrievals only	1. Check ~~high quality~~good quality ~~AOT~~AOD retrievals at central pixel only; 2. ρ_{412} is reflectance at 412 nm (VIIRS M1); 3. C2=0.05 for IDPS; C2=0.004 for EPS

Figures

(a) New Internal Snow Test (after 06/22/2015)



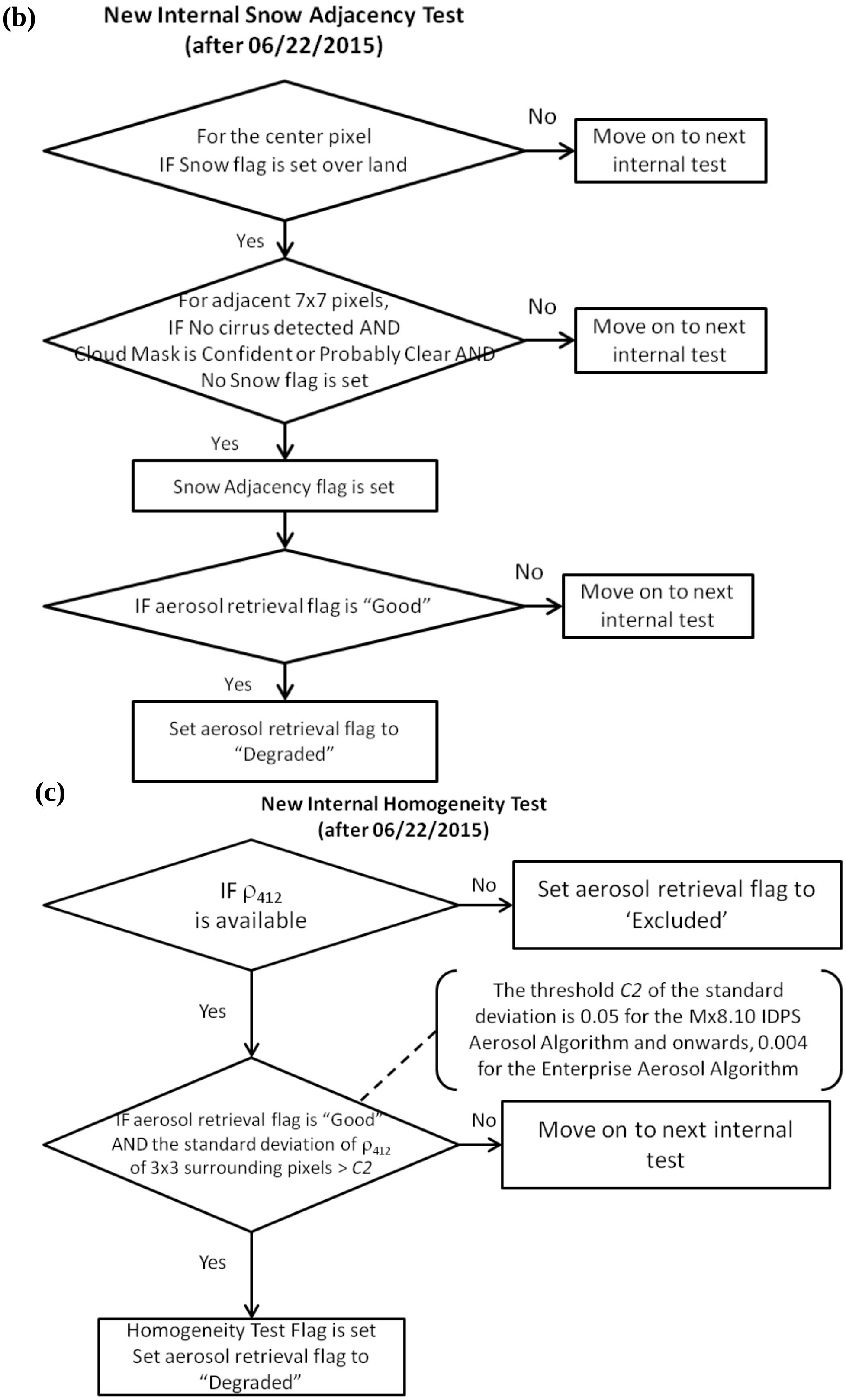


Figure 1. Flow charts of the new snow and snowmelt snow screening scheme in the VIIRS aerosol algorithm: (a) internal snow test; (b) internal snow adjacency test; and (c) internal homogeneity test or spatial filter. The tests were transferred to operation to the Mx8.10 IDPS algorithm on Jun 22, 2015, 19:43 UTC, and they are also used in the new Enterprise VIIRS aerosol algorithm. "Move on to next internal test" means no actions are taken for the current internal test if any of the criteria are not met, and the algorithm continues to the next internal test.

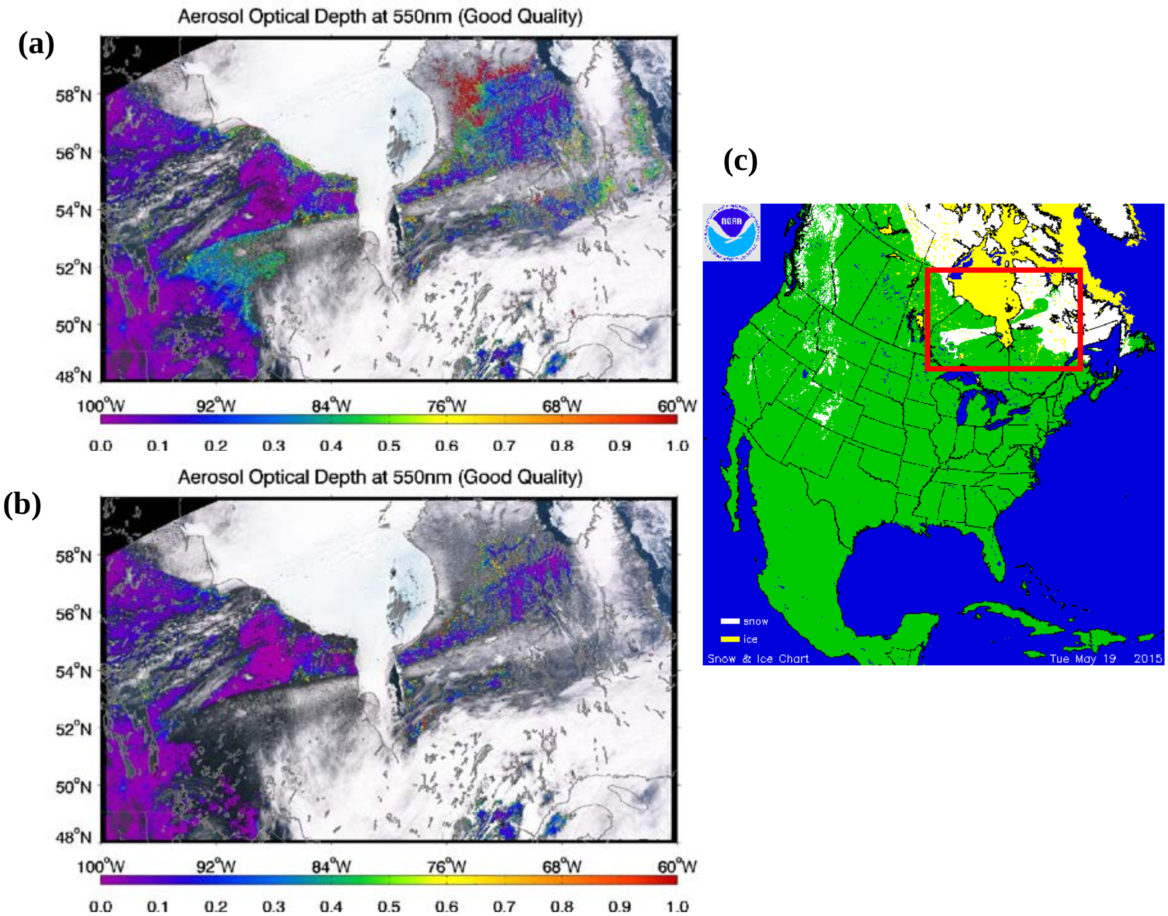
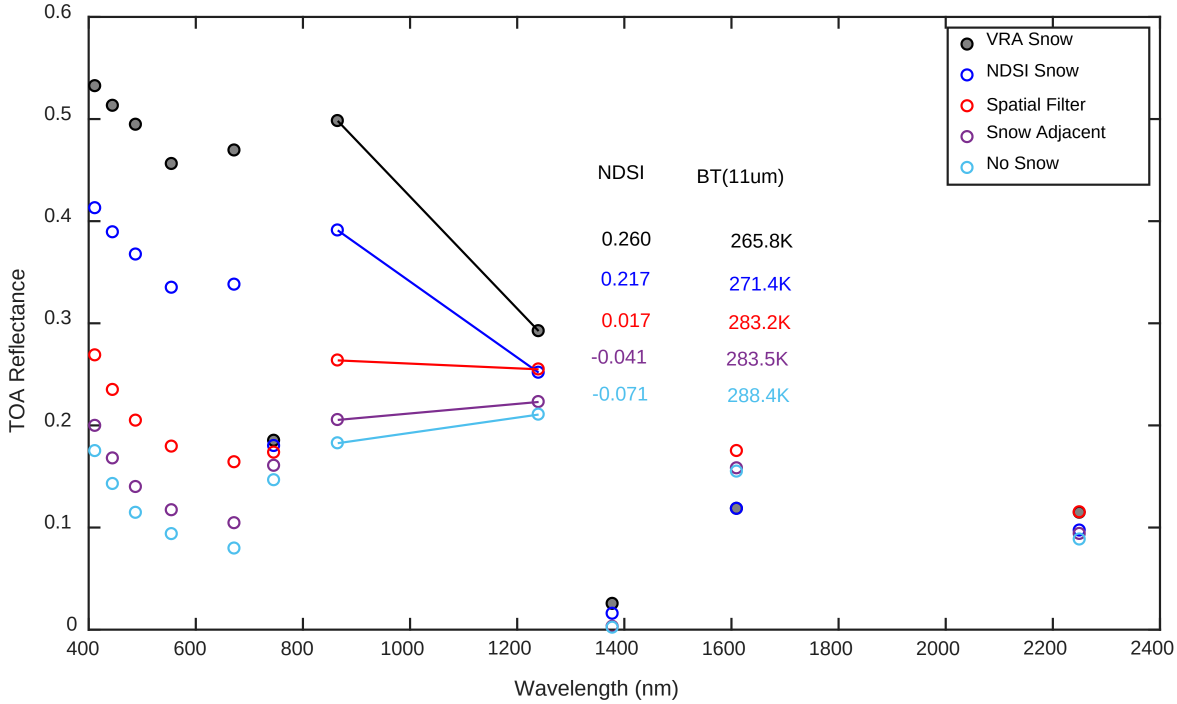


Figure 2. VIIRS 'Good' quality ~~AOT~~AOD retrievals on May 19, 2015: (a) with the old VRA-based internal snow test; (b) with the new snow and snowmelt screening scheme; and (c) the snow cover map produced by the NOAA National Centers for Environmental Information (NCEI) (https://www.ncdc.noaa.gov/snow-and-ice/snow-cover/us/20150519). The red square in (c) shows the areas covered in (a) and (b). Note the snow cover to the east and south of the Hudson Bay in (c) and the associated anomalously high ~~AOT~~AOD values over the same areas in (a) but not in (b).



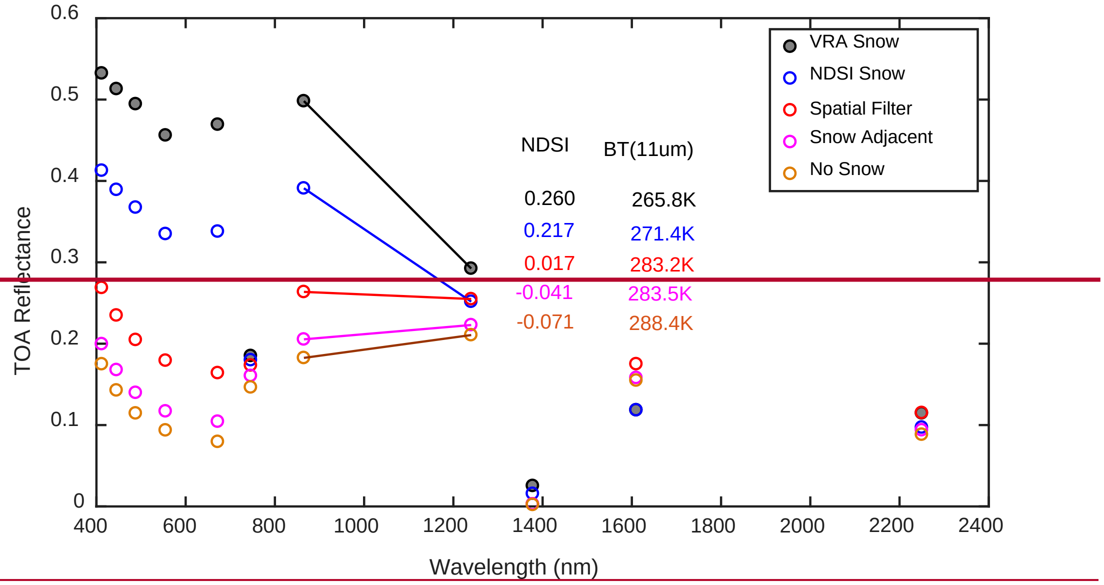
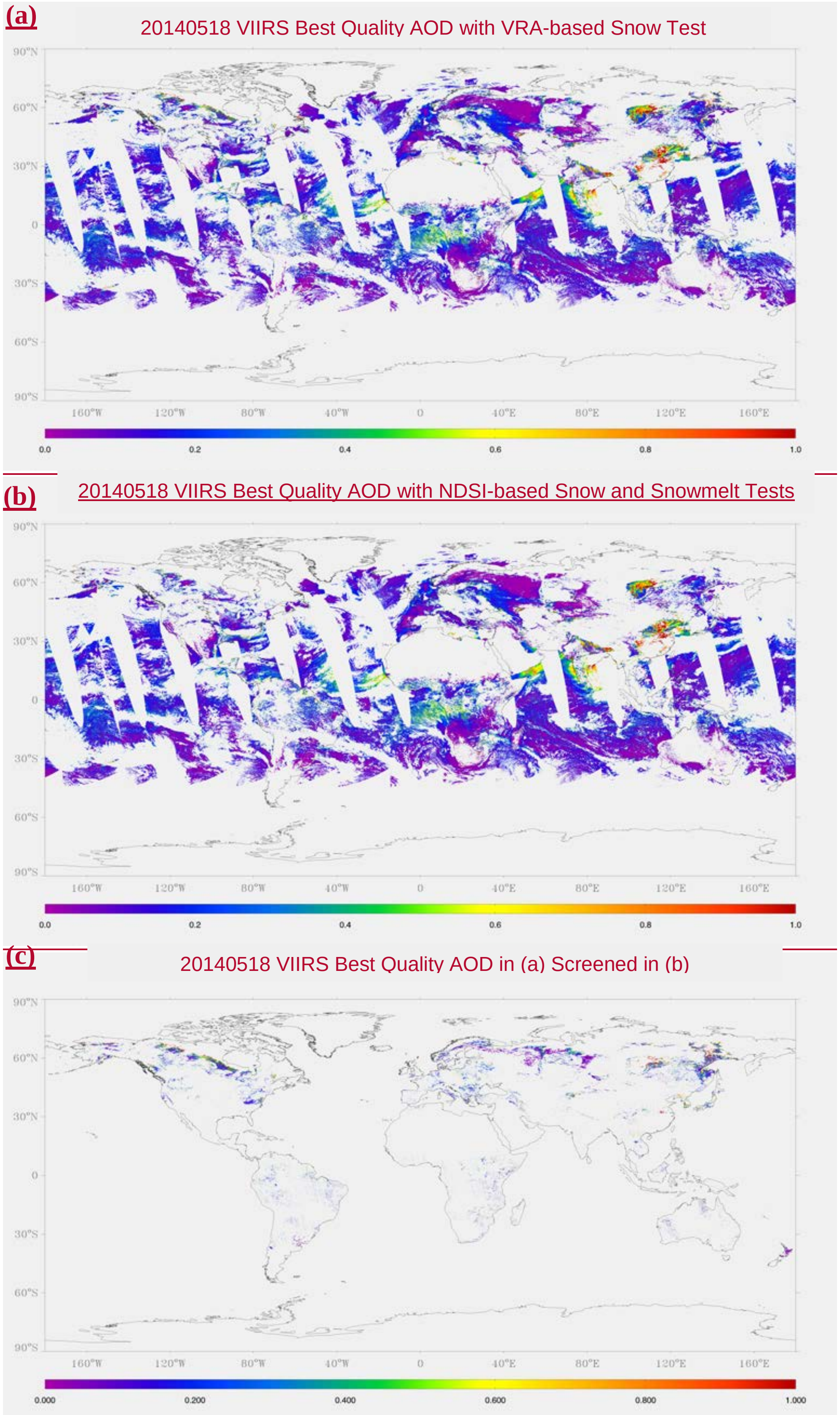
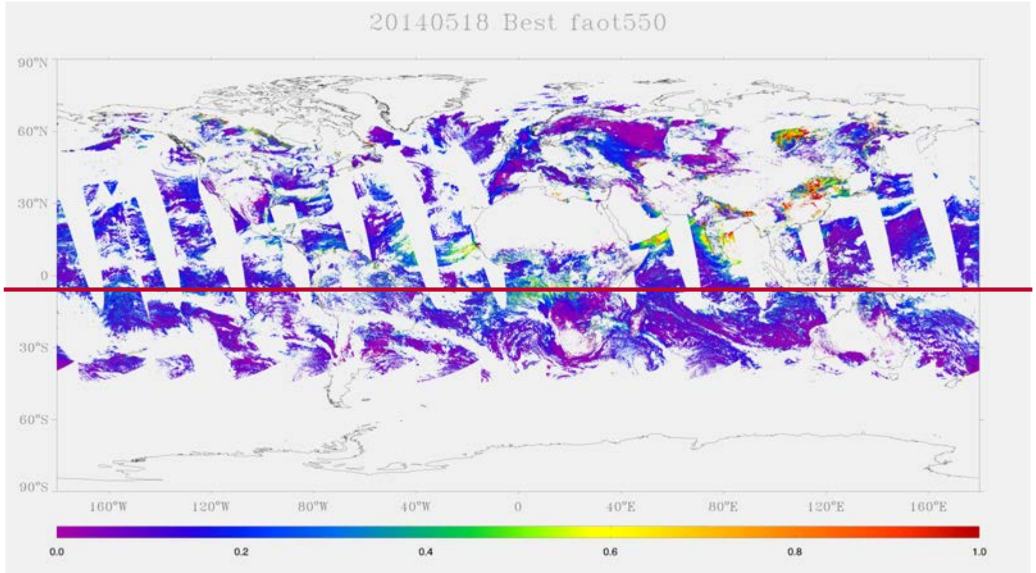


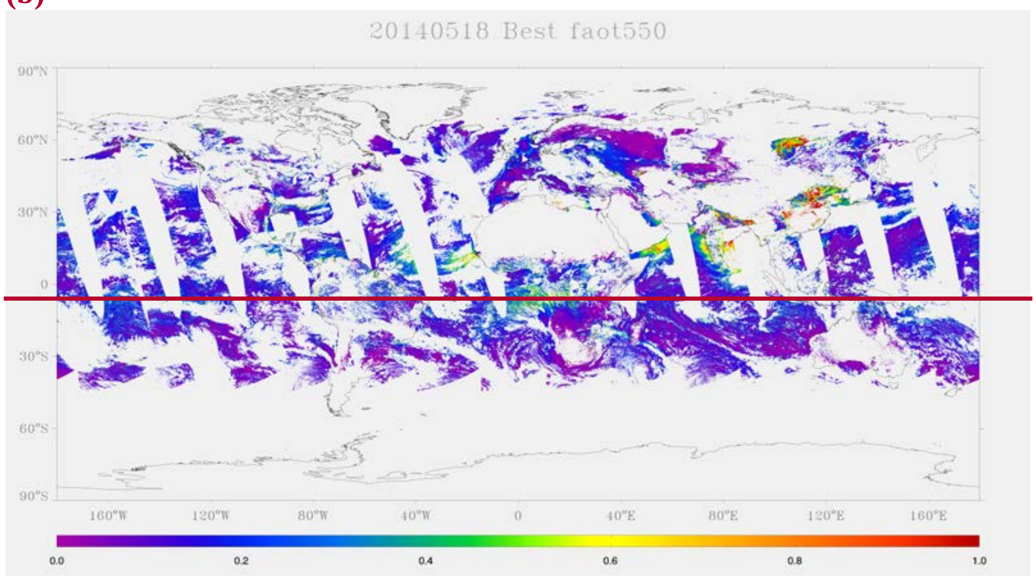
Figure 3. Spectral curve of the TOA reflectance at 11 VIIRS wavelengths in five populations of pixels selected based on internal tests.


(a)
20140518 VIIRS Best Quality AOD with VRA-based Snow Test
(b)
20140518 VIIRS Best Quality AOD with NDSI-based Snow and Snowmelt Tests
(c)
20140518 VIIRS Best Quality AOD in (a) Screened in (b)
90°N
60°N
30°N
0
30°S
60°S
90°S
160°W
120°W
80°W
40°W
40°E
80°E
120°E
160°E
0.0
0.2
0.4
0.6
0.8
1.0
0.000
0.200
0.400
0.600
0.800
1.000

~~(a)~~


20140518 Best faot550
90°N
60°N
30°N
0
30°S
60°S
90°S
160°W
120°W
80°W
40°W
0
40°E
80°E
120°E
160°E
0.0
0.2
0.4
0.6
0.8
1.0

~~(b)~~


20140518 Best faot550
90°N
60°N
30°N
0
30°S
60°S
90°S
160°W
120°W
80°W
40°W
0
40°E
80°E
120°E
160°E
0.0
0.2
0.4
0.6
0.8
1.0

~~(c)~~

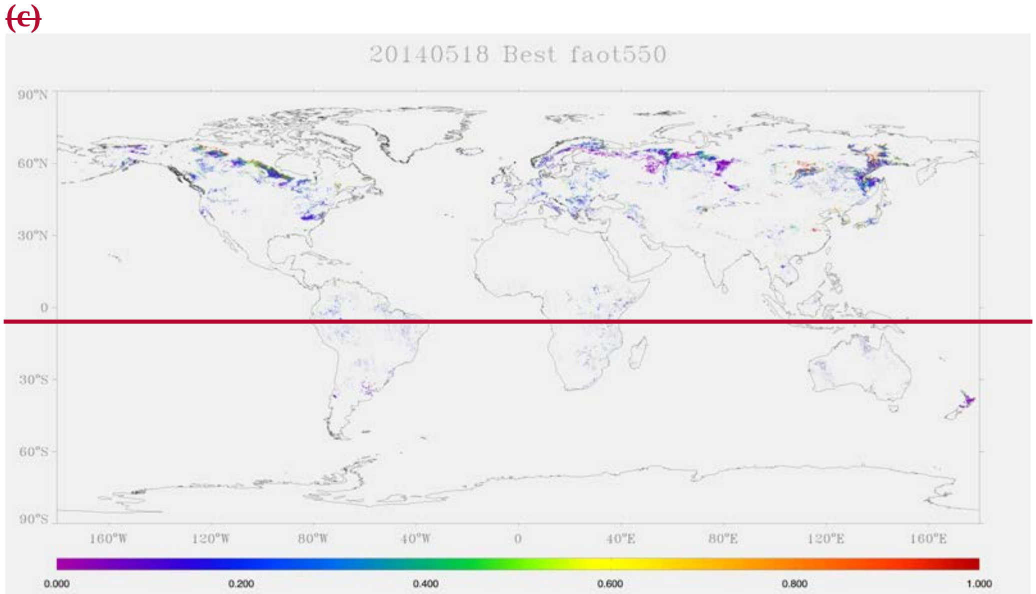

20140518 Best faot550
90°N
60°N
30°N
0
30°S
60°S
90°S
160°W
120°W
80°W
40°W
0
40°E
80°E
120°E
160°E
0.000
0.200
0.400
0.600
0.800
1.000

Figure 4. The best quality VIIRS ~~AOT~~AOD retrievals on May 18, 2014: (a) with the old internal VRA-based snow test; (b) with the new NDSI-based snow and snowmelt screening scheme; and (c) the difference between (b) and (a) that were either removed because of the new snow test or were degraded by the new snow adjacency test and the spatial homogeneity test.

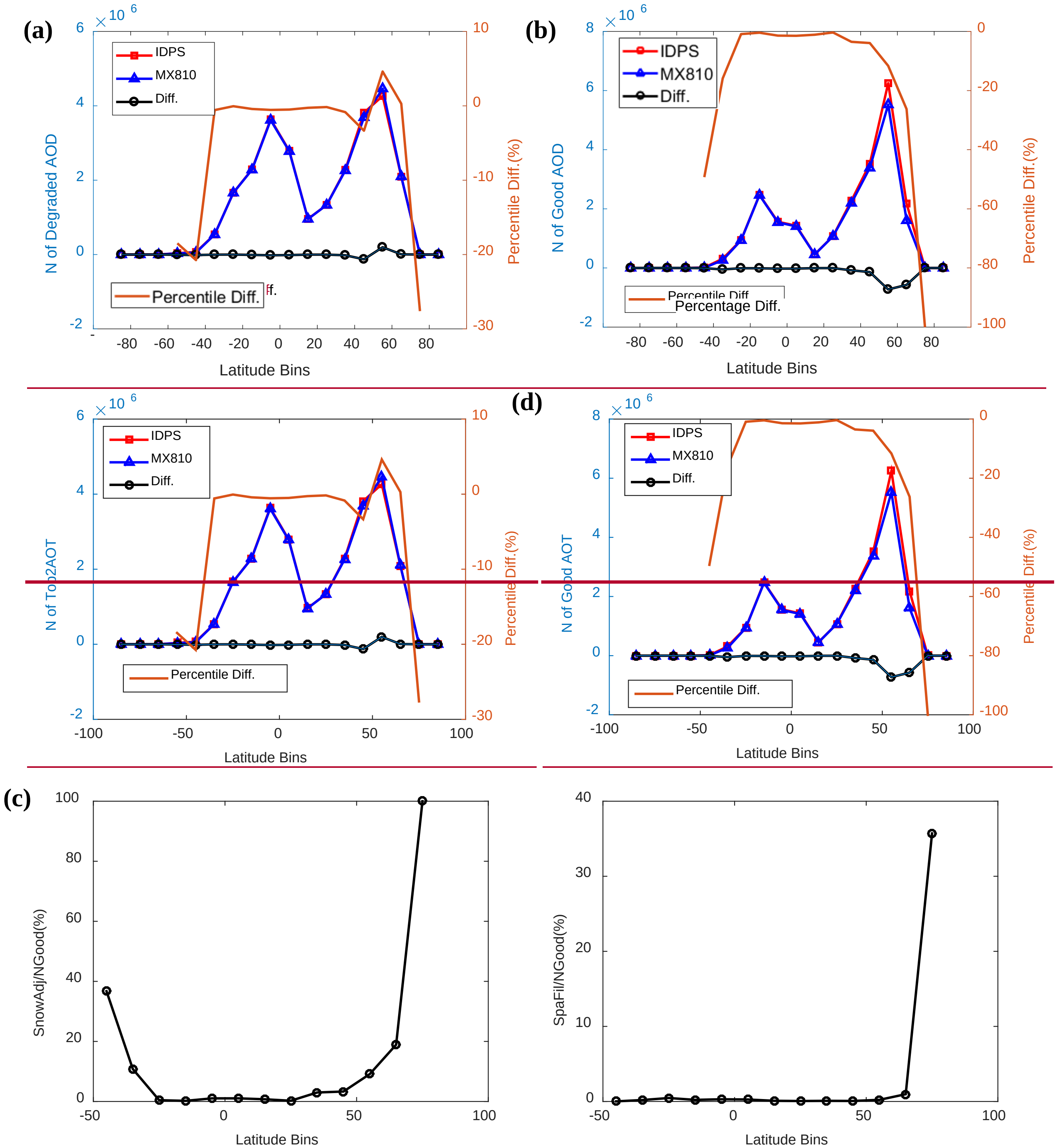


Figure 5. Statistics in the sample size and percentage change in the ~~AOT~~AOD retrievals on May 18, 2014 as a function of 10º latitude bin: (a) Number of ~~'Good and~~ Degraded' quality ~~AOT~~AOD retrievals ~~("Top2AOT")~~, produced by the algorithm running the old VRA-based snow mask (red line with squares) and the new NDSI-based snow mask (blue line with triangles), and the difference between the two (black line with open circles). The brownish red line displays the difference as a percentage that is read along the right-hand axis. (b) Same as (a) but for ~~'good~~ 'Good' quality ~~AOT~~AOD retrievals only; (c) the percentage of the pixels flagged as adjacent to an identified snow pixel over the total number of 'Good' quality ~~AOT~~AOD IP retrievals; and (d) the percentage of the pixels flagged by the homogeneity test (spatial filter) over the total number of 'Good' quality ~~AOT~~AOD retrievals. ~~Top 2 quality in (a) includes both Good and Degraded quality AOT retrievals.~~

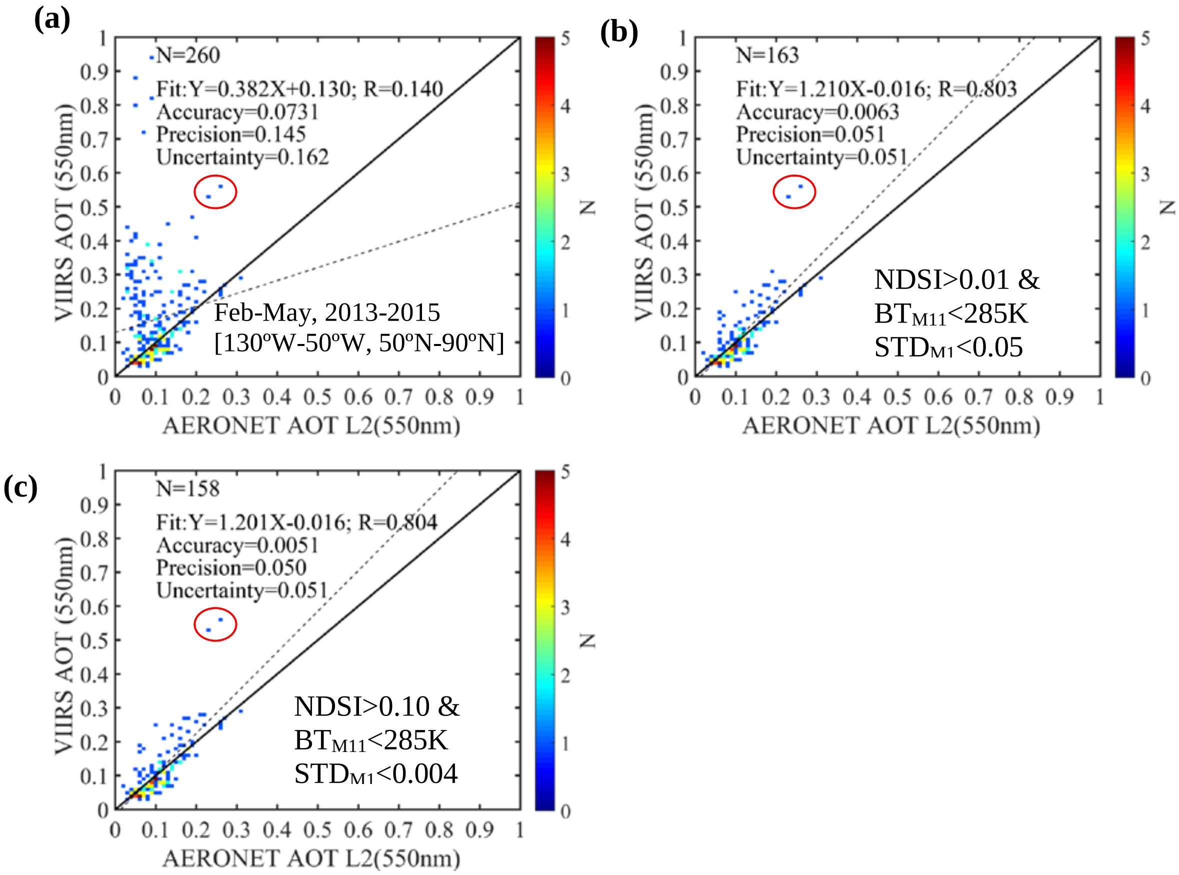


Figure 6. Matchups of the VIIRS ~~High~~ Good Quality ~~AOT~~AOD retrievals with AERONET over [130ºW-50ºW, 50ºN-90ºN] during boreal spring Feb-May, 2013-2015: (a) with the old VRA-based internal snow test; (b) with the new snow and snowmelt screening scheme and the thresholds used in the Mx8.10 IDPS algorithm; and (c) with the new snow and snowmelt screening scheme but the thresholds used in the EPS algorithm. The two anomalous points with higher positive biases in the red circles were found to be more related to the ~~AOT~~AOD retrieval itself rather than snow under-screening.

(a) (b) (c)

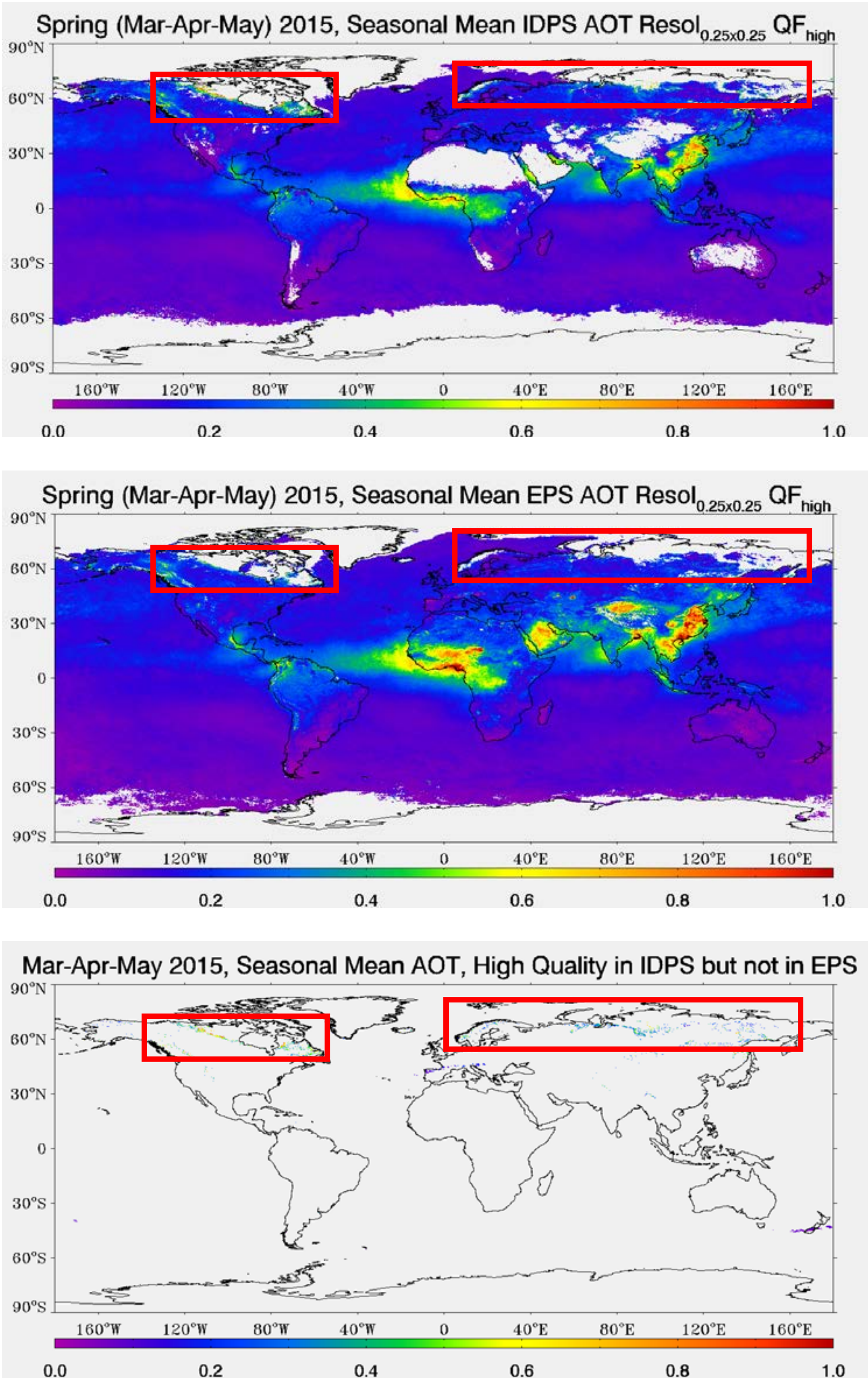


Figure 7. S-NPP VIIRS seasonal mean of ~~high~~ good quality ~~AOT~~AOD during the spring thaw season, March – May 2015: (a) with the old VRA-based snow test in the IDPS Aerosol Algorithm; (b) with the new snow and snowmelt screening scheme in the EPS Aerosol Algorithm; and (c) ~~high~~ good quality ~~AOT~~AOD retrievals in the IDPS product but not in the EPS product, mainly attributable to the improved snow and snowmelt tests. The most outstanding snow and snowmelt under screening regions over northern hemisphere high latitude regions are highlighted in red squares. In the maps shown the original 750-m pixel-level ~~AOT~~AOD retrievals were mapped to 0.25 x 0.25 degree equal-angle latitude and longitude grids.