Using MODIS estimates of fractional snow-covered area to improve streamflow forecasts in Interior Alaska by Bennett et al. examines improvements in model skill when remotely-sensed snow-covered area estimates are used to model streamflow, compared to model runs where model-generated areal depletion curves are used. For this study, two MODIS-derived snow covered area products were used, MOD10A1 and MODSCAG. This study is a nice assessment of the use of remotely-sensed snow cover products with the new CHPS modeling framework for several watersheds in the interior of Alaska. This study demonstrates the improvements as well as pitfalls of using areal depletion curves vs. remotely sensed snow-covered area. The authors find that using remotely sensed snow-covered area yields modest improvements in some basins, especially the sparsely measured ones, but not in others.

These findings agree with previous studies, which the authors cite. Overall, the techniques are well researched and the findings are sound, but I have a few major concerns that I would like to see addressed prior to publication:

Thank you for your review and your positive words about our study.

1) In most of the cited publications, e.g. Painter et al. (2009); Rittger et al. (2013), what is referred to in this manuscript as snow covered extent is called fractional snow-covered area, or fSCA. Since MODSCAG and MOD10A1 are both fractional products, fractional snow-covered area is a more accurate term than snow-covered extent. Thus, I suggest changing snow-covered extent to fractional snow-covered area to align with most other publications.

We agree with this point, and we have changed the referral of fractional snow cover extent (SCE) to fractional snow covered area (fSCA) when we are discussing the remotely sensed products in the paper.

2) What is really needed for model input is the total volume of snow water equivalent (SWE). The fSCA contains no information on depth. Among other problems, as the authors point out, when fSCA reaches 100%, it gives little information about the snow volume. I realize that there is no good direct SWE estimate for model input, however there have been many attempts to create basin-wide SWE estimates, for example by fusing snow telemetry estimates with fSCA (Fassnacht et al., 2003; Dozier et al., 2016; Schneider and Molotch, 2016). It would be worthwhile to at least discuss why fSCA only was chosen to improve the streamflow forecasts.

We agree with your point, and if were we working in the lower 48, our study would have been set up differently. SWE is the more important variable, and the 'grail' for water resources managers and snow scientists. However, in Alaska, there are limitations with regards to the ground-based observations to carry out validation and testing of basin-wide SWE simulations and the remote sensing of snow and topography that can be used for simulations in this environment. Regarding a), ground-based observations such as SNOTEL, as used by Fassnacht et al. (2003) and Schneider and Molotch (2016), are available in Alaska. However, as noted by Fassnacht et al. (2003), to interpolate between the stations there should be a minimum distance between them. In the Upper Colorado River basin (277,000 km^2) there are noted to be 240 SNOTEL sites, operating since 1991. In Alaska, there are 40 SNOTEL sites (1.718 million km^2), and in the basins where we undertook this study (10,160 km^2) there are 7 SNOTEL stations, all of which are located in the Chena River basin. Another issue is the quality of SNOTEL data, including station siting, have been noted by various authors, although the

Alaska SNOTEL station network is not included in these reviews (Dozier et al., 2016; Oyler et al., 2015; Ragwala et al., 2015).
Issues with remote sensing in Alaska are related to availability and quality of polar orbiting remote sensing products, availability of data on snow pack depth and snow density (Muskett 2012), issues related to deep and shallow snow packs, issues related to the mapping forests cover fractions and the density of boreal forest canopies. Unfortunately, many of the remote sensing of snow products that are available are not tested well in the high latitudes and under dense boreal forest cover, which highlights the importance of our work in these regions and also necessitates a simpler initial approach to research in the region.
Additionally, the availability of digital elevation models (DEM) information in Alaska hinders the kind of analysis performed in the aforementioned studies; Alaska's 5-m IFSAR product is nearing completion in 2018, but was not available when this project was carried out. The 30 m National Elevation Model (NED) DEM used in the study likely contains issues (that will be corrected by the updates to the IFSAR Alaskan product), including data voids, data currency, and geodetic datum issues. For example, all datums for Alaska DEMs were previously in NAD27, which caused offsets in the data (Maune, 2008). For these reasons, it has previously been difficult to successfully apply regression or interpolation of fSCA to extract SWE. We are hopeful with the IFSAR DEM for Alaska, these methods may be applied for future work.

3) The interpolation, filtering, and smoothing of both MOD10A1 and MODSCAG is barely mentioned in the text and the supplement. Snow-cloud discrimination and how MODIS data are smoothed is a critical step that the authors have, at the least, not fully addressed. Likewise, viewing geometry also greatly affects the accuracy of MODIS surface reflectance (Tan et al., 2006), which both MOD10A1 and MODSCAG are based on. I recommend the following two studies as examples of different smoothing approaches for snow cover from MODIS, Dozier et al. (2008); Morriss et al. (2016). I would like to know how the authors' approach compares to these two smoothing techniques.

Our interpolation, filtering and smoothing of MODIS data is dealt with through pre-processing, and in the CHPS software. We have added more detail through the paper, and the supplement, to reflect this question. In addition, we have added the suggested references to the paper.

Interpolation: We used the MODIS Re-projection Tool (Dwyer and Schmidt, 2006) to pre-process imagery into an Alaska Equal Area Conic projected GeoTIFF of fractional SCA (USGS, 2011). This preprocessing step assisted us to correct, in part, the viewing geometry and other issues related to projections of the original MODIS data and the influence these projections have on the MODIS data for Alaska. We interpolated the data using Nearest Neighbor interpolation methods available in this tool. We interpreted only cloud-free pixels.

Filtering: We input the MODIS data products, with corrections for viewable area. While we did experiment with a cloud correction, and also with different sized aggregates of MODIS grid cells to determine the influence of spatial aggregation approaches, we only applied the tree correction as detailed in the paper. The reasoning for this is that these methods did not make a difference within the CHPS software, while only considering streamflow responses. We discuss in the paper why we might want to look at different metrics to really evaluate these types of pre-processing methods.

Smoothing: We ingested the MODIS data into CHPS. CHPS provided several different means to filter and smooth the data. First of all, there is the optional element in CHPS, maxGapLength, can be configured to define the maximum length of gaps that should be filled. Gaps equal to or smaller than maxGapLength will be filled with interpolated values, while gaps larger than maxGapLength will not be filled. This ensures that periods with extensive cloud cover obscuring the MODIS fSCA data are interpolated but long periods with no data, such as the summer period, are not interpolated. A maxGapLength of 11 days was selected after testing revealed that longer and shorter interpolation time steps resulted in lower streamflow simulation skill. We describe the use of maxGapLength in the supplemental.

I have included minor comments as an annotated PDF. Several citations in the text were not in the bibliography. Thus, I suggest the authors carefully check that the citations in the text correspond to those in the bibliography. If the authors have any questions about my review, I encourage them to contact me at nbair@eri.ucsb.edu.

Thank you very much. We have gone through and addressed each point you have included as minor comments. They are listed below in incremental order. We have also gone through the paper and addressed all of the comments in the annotated PDF document provided. Please see the attached track-changes version of the manuscript as well.

1. We added to the sentence Two versions of MODIS fSCA are tested “against a base case aerial depletion curve-derived extent of snow cover”.
2. We changed this to “a myriad of impacts”.
3. We added the SWIPA report to the bibliography and also added several more references on snow melt disappearance timing. Although there are challenges, as the reviewer notes, snow covered area estimates and snow melt timing and disappearance timing are considered more robust. On the other hand, SWE estimates, snow depths, and snow density are elusive measurements that have high spatial variability and are not easy to obtain in Alaska, and globally.
4. We deleted the sentence and added Huntington into the bibliography. We moved the Cohen reference to the previous sentence.
5. We deleted the second occurrence of “model output” on page 3 of the manuscript. Thank you for catching this.
6. In the equation, we changed *e* to *elev*.
7. Address the SB constant, look at UADJ. This was a confusing sentence, and we re-wrote it to make it clearer what the assumptions of SNOW17 are. Hopefully this clears up the two issues that you had raised.
8. We deleted gradient from the sentence.
9. We added units to Figure 1.
10. Regarding the low bias in the SWE estimates, we are comparing station locations to the modeled results for the entire Upper Chena River basin (lumped, north and south units are shown separately) unit. Thus, we would expect the average across the lumped basin unit to be lower than the SNOTEL sites. This is accentuated in some sites more than others, for example there is a lot more snow at the Upper Chena SNOTEL gage in water year 2001, as opposed to the Teuchet site where less snow fell. We added some additional clarification where we discuss the results of this figure in section 3.3 of the revised paper.

Sincerely,
Ned Bair

Earth Research Institute
University of California, Santa Barbara

References:

Dozier, J., Bair, E.H. and Davis, R.E., 2016. Estimating the spatial distribution of snow water equivalent in the world's mountains. WIREs Water, 3: 461-474.
Dozier, J., Painter, T.H., Rittger, K. and Frew, J.E., 2008. Time-space continuity of daily maps of fractional snow cover and albedo from MODIS. Advances in Water Resources, 31: 1515-1526.
Fassnacht, S.R., Dressler, K.A. and Bales, R.C., 2003. Snow water equivalent interpolation for the Colorado River Basin from snow telemetry (SNOTEL) data. Water Resources Research, 39(8): 1208.
Morriss, B.F., Ochs, E., Deeb, E.J., Newman, S.D., Daly, S.F. and Gagnon, J.J., 2016. Persistence-based temporal filtering for MODIS snow products. Remote Sensing of Environment, 175: 130-137.
Painter, T.H., Rittger, K., McKenzie, C., Slaughter, P., Davis, R.E. and Dozier, J., 2009. Retrieval of subpixel snow-covered area, grain size, and albedo from MODIS. Remote Sensing of Environment, 113: 868-879.
Rittger, K., Painter, T.H. and Dozier, J., 2013. Assessment of methods for mapping snow cover from MODIS. Advances in Water Resources, 51(1): 367-380.
Schneider, D. and Molotch, N.P., 2016. Real-time estimation of snow water equivalent in the Upper Colorado River Basin using MODIS-based SWE reconstructions and SNOTEL data. Water Resources Research, 52(10): 7892-7910.
Tan, B., Woodcock, C.E., Hu, J., Zhang, P., Ozdogan, M., Huang, D., Yang, W., Knyazikhin, Y. and Myneni, R.B., 2006. The impact of gridding artifacts on the local spatial properties of MODIS data: Implications for validation, compositing, and band-to-band registration across resolutions. Remote Sensing of Environment, 105(2): 98-114.

References:

Dwyer, J. and Schmidt, G.: The MODIS reprojection too, in Earth Science Satellite Remote Sensing, Springer, Berlin, Heidelberg, Germany, 162-177, 2006.
Maune, D.F. 2008. Digital Elevation Model (DEM) Data for the Alaska Statewide Digital Mapping Initiative (SDMI). A report prepared for Alaska Geographic Data Committee. 161 pp.
Maune, D.F. 2009. Alaska Statewide Digitial Mapping Initiative, Mapping Alaska for the First Time.
Muskett, R.R., 2012. Remote sensing, model-derived and ground measurements of snow water equivalent and snow density in Alaska. *International Journal of Geosciences*, *3*(05), p.1127.
Oyler, J.W., Dobrowski, S.Z., Ballantyne, A.P., Klene, A.E. and Running, S.W., 2015. Artificial amplification of warming trends across the mountains of the western United States. Geophysical research letters, 42(1), pp.153-161.
Rangwala, I., Bardsley, T., Pescinski, M., and J. Miller (2015). SNOTEL sensor upgrade has caused temperature record inhomogeneities for the Intermountain West: Implications for climate change impact assessments. Western Water Assessment Climate Research Briefing.
USGS, 2011. MODIS Reprojection Tool User's Manual. Land Processes DAAC USGS Earth Resources Observation and Science (EROS) Center. Accessed August 15, 2018. https://lpdaac.usgs.gov/sites/default/files/public/mrt41_usermanual_032811.pdf. 69 pp.

In their study “Using MODIS estimates of fractional snow cover extent to improve streamflow forecasts in Interior Alaska” Bennett et al. investigate the value of two MODIS-derived snow cover area products (MOD10A1 and MODSCAG) to improve streamflow simulations in the interior of Alaska as compared to simulations where model-generated areal depletion curves are used. The authors conclude that there is only marginal improvement when evaluating the model performance with metrics such as NSE, RMSE etc., but argue that the MODIS derived snow covered area products might be valuable particularly in regions with sparse or poor quality observations. The methods and findings are sound and the article is generally written in a clear, concise and very structured way.

Thank you for your positive words about our study.

Nevertheless, I have some minor comments, which I would like to see addressed prior to publication:

General comments

• The basins with the sparsest streamflow observation had the greatest improvement in streamflow simulations. (P1L13,P14L 25-26) –> could indeed the sparse data be the main reason for the improvement rather than the product? This could be tested with a little model experiment adding some data gaps and see how the performance measure is sensitive to that maybe for the basin with the longest observations.

To test this, we removed May 1st to May 31th from one year (the 2005-2006 water year) of the observed streamflow record from the Upper Chena River basin. We reran the model with and without MODIS inputs, using only the MODSCAG data for this example. We only show the results for the MODIS simulated streamflow data. We reran the statistical analysis to calculate the values for metrics presented in Table 4 and discussed in the text. Note that the SACSMA streamflow simulations do not use the streamflow observations, but they do use the MODIS fSCA estimates. Also, note that this analysis removes missing data, basing the calculations only on complete data.

Statistic	With NA Values	No NA Values
MAE	6.07	6.69
NSE	0.63	0.91
PBias	18.86	41.44
R	1.00	0.99
RMSE	6.92	7.27

The results show that there are minor differences in three of the five metrics (MAE, R, RMSE). For NSE and PBias, we found differences where NSE was higher, and PBias was lower with fewer data points. We assume this is because these metrics are sensitive to the number of data points included in the input observations.

In the paper, we discuss that improvements in streamflow simulations were seen when we included the MODIS fSCA data in the simulations. Some of those streamflow records have gaps, notably the Chatanika. However, the improvement we noted was improvement between simulated streamflow (with and without MODIS) against the observed records. To be clear, we compared simulated streamflow without MODIS (APRFC in Table 4) to observations, and simulated streamflow with MODIS (MOD10A and MODSCAG in Table 4) to observations. Thus, the improvement we refer to is not related to the streamflow observations, because those observations did not change between our different simulations. The only change in the streamflow simulations was the change due to the MODIS data. We have not altered the paper, as we believe that the reason for improvement for basins like the Chatanika is due to the increased observational data (i.e. MODIS) used to simulate streamflow.

• Why do the authors include the Chatanika catchment, when it shows very poor performance both using the model generated and the MODIS product derived snow cover extend? Please clarify.
We were interested to show the results for the Chatanika as we feel that this basin is most representative of the poor-quality streamflow observations in Alaska. We think that even though it didn't perform well, that this is likely the kind of issues that modelers and observationalists will deal with when working with Alaskan hydrology data. This basin is also adjacent to the Caribou-Poker Creek instrumented watershed, and it represents a lowland site in comparison to the Salcha, Chena and Goodpaster systems, which have more upland land cover. For this reason, we would like to keep the basin included in the paper, despite its poor performance.

• Move more detailed description of the derivation and differences between the MODIS products (interpolation, filtering, and smoothing) from the supplements in the main study.
We have now moved more of the details from the MODIS productions to the body of the paper. We originally took it out because we felt that the Methods section was too long, and we didn't want to bog readers down. Based on this comment, and comments from Reviewer 1, we were too gregarious with these edits.

Minor/technical comments
• There are passages in the article where fill words like utmost, great, very are used abundantly. In my opinion, it would help to go through the article and check where these are really needed and where they could be dropped.
We have dropped these words throughout the text. Please see the track changed version of the manuscript.

• There is a mixed use of watershed and basin. Do the authors use it with equivalent meaning? If so, then use only one term throughout the paper, if not please clarify why the two terms are used.
We have removed the use of the word watershed and replaced it with basin throughout the paper. Thank you for noting this.

• Often model runs could be replaced for better clarity with SWE simulations (e.g. P10L30) or streamflow simulations, respectively.
We have replaced run(s) with simulation(s) throughout the paper.

• Please make the units consistent (sometimes there is sec, sometimes there is s, etc.)
We have made the units consistent throughout the text. Please see the track changed version of the manuscript.

P1L29/30 did both extent and duration decrease by the same percentage?
We have adjusted this sentence to read "Snowpack extents in Alaska have decreased over time by 18% (1966-2012) due to an earlier snow melt, while snowpack duration has also decreased (SWIPA, 2012)."

P1L35 Delete this sentence
We changed this sentence to read as follows "Rivers in Alaska have been observed to be changing as a result of an intensified or stronger hydrologic cycle that could lead to an increase

in peak flows in the Northern American high latitudes (Cohen et al. 2012; Huntington, 2006; Rawlins et al., 2010)."

P2L3 Extremes –> Extreme
We corrected this typographic error. Thank you for noting it.

P3L14 in which P3L22/23 what does it mean that they perform better, better than in other regions or these models are better in these regions than the other models. Please clarify.
We meant that temperature index models are presumed to perform better than other models in highly variable landscapes with spare networks. We have added in "…than other models for regions…" to the sentence to clarify.

P3L33 Date missing in reference
We have added the date to the reference. Thank you.

P4L33 delete above the Steese Highway (I do not see the relevance of this information)
We have deleted this part of the sentence.

P5L23 delete at the Steese Highway site
We have deleted this part of the sentence.

P5L35 add eq. 1 in brackets
We have added Equation 1 to the first equation in the paper (SCA_{fadj}), and Equation 2 for this equation.

P6L1 does still really need to be expressed in feet?
Because of the way that the equation was developed, you cannot obtain the same answer by converting 1000 ft to meters. Thus, I believe that you must enter the value of the elevation in feet. It is confusing because I used meters in the example. I have now added the meters to feet conversion to make it clearer, and added the unit value after elevation in brackets.

P6L17 how sensitive are streamflow simulations to this lapse rate? What motivates the assumption that the fixed lapse rate of 0.6_C/100m holds?
This lapse rate is a default in SNOW17 to represent the saturated adiabatic lapse rate, and is used to calculate the percentage of the watershed where precipitation falls as snow. However, the value can be changed for each basin and sub-basin, if warranted by the input temperature data, and also different methods can be applied to separate rain versus snow. The lapse rate is used to find the air temperature threshold value, and this value is used to relate to an elevation, for which the basin area snow fall can be calculated. It is important to note that this is different from other uses of lapse rates in the model.
Although we could not find previous studies that account for the sensitivity of this parameter, there are six main parameters in SNOW17 that have been identified as the most sensitive parameters for SNOW17, SCF, MFMAX, MFMIN, SI and UADJ (Anderson, 2002; Tang et al., 2007). The use of the single lapse rate value for these calculations is widely applied in studies across the globe (e.g. Clark et al., 2011). We have added more detail and these references to this section of the manuscript.

P6L30 delete "and is set to . . . "already mentioned above
We have deleted this part of the sentence.

P6L33 mm/mb/6hr is that the unit for rain on snow, then move to melt from rain of

snow earlier in the sentence
We have moved mm/mb/6hr to come after UADJ events in the revised sentence.

P7L12-15 It might be helpful to see a sketch of how the ADC works.
While we agree it might be useful, we have many figures in this paper already. Thus, we have added a reference to the images that depict the ADC relationships in Anderson 2002's paper (Anderson, 2002; Figure 7.4.3; Figure 7.4.4).

P7L16 add a reference to this look up table
We have added in the reference for the ADC look up table.

P7L29 change "produces streamflow simulates" to "simulates streamflow"
We have changed this sentence as suggested.

P8L12 delete study
We have deleted study.

P8L30 to P910 all of these statistics are well known, I think it would be sufficient to just add some reference for each, else, I would summarize them in a separate table. In case the authors want to keep the equations, check the equations carefully: MAE has to additionally be divided by the number of observations, Spearman correlation coefficient could simply be written in a simpler form.
We agree with this comment and have opted to remove the section and add references for a few of the statistics.

P9L10 make units consistent
We are unsure which units you are referring to here, but we have reviewed all units in the manuscript to ensure they are consistent. Please let us know if we have missed anything.

P10L1 delete "for reasons that are discussed in the following section"
We have deleted this part of the sentence.

P10L5 why it is the maximum recommended value and who recommended it? Maybe refer again to the table with parameter ranges.
Anderson (2002) recommends the ranges for these parameters. We have changed the sentence to include the reference and refer to the table.

P10L14 What does a more rigorous calibration mean here?
We have deleted this sentence.

P11L10 Why for May 15th 2001?
The May 15th date for this region in Alaska represents a time when snow is melting, and we should be partway through the snow recession. For this reason, some snow will be represented at higher elevations and likely less at lower elevations. The year, 2001, was selected somewhat arbitrarily, however it was a moderate snow year, which we thought would show these relationships and differences across MODIS data most clearly.

P12L6 1-R
We have corrected this typographical error. Thank you.

Figures

- Most figures are difficult to read when printed in black and white. This could be improved easily by adapting the color palette.
  We have changed the color palettes in most of the figures.

- Figure1: not all elevation classes are used in the map. Units are missing for the elevation zones. Drop last sentence in caption.
  Although hard to see, the upper two elevation classes (green shades) are found in the Salcha and Goodpaster basins. However, we have revised the color palatte and color ramp on the figure. We also added elevation units and dropped the last sentence as suggested.

- Figure2: what happens to MODIS SASC North between May 10 and 17?
  It looks like the MODIS SASC recorded that snow cover extent increased to 80% of the Upper Chena River basin on May 13th, 2010 at 6:00 am. After this point, at the next recorded interval the snow had all melted. We correlated this with the SNOTEL gauges across the Upper Chena river basin, which are Upper Chena, Teuchet Creek, and Monument Creek. Although it looks like some precipitation fell on the 11th, no snow fell at all around this time. Thus, we believe this is an error in the MODIS data, potentially where clouds were interpreted as snow cover. Also, comparing directly with the SNOTEL gauges indicates that all snow cover extents should also have been at zero at this point, however the model indicates that there were still residual amounts of snow (0.1 fractional SASC) in the catchment. However, the plot is meant to show the differences between the SASC in the SNOW17 when different remote sensing tools are applied. Therefore, to not distract the reader, we opted to remove this outlier data point as quality control. We have not changed the text, as we feel that this level of detail is not warranted, but if you think we should explain the removal of the data point, we will add in a sentence.

- Figure3: It seems there is a difference in the fractional snow cover extend seasonal development for the years that are used for calibration and the years that are used for validation. Is this also the case for each individual catchment, or is one catchment causing this difference? Is it ok to shift the year in validation, calibration period in the Chatanika catchment compared to the other catchments?
  This figure shows the average snow cover extent across all the catchments based on elevation bands, and we tried to capture high and low streamflow years in the calibration and validation periods. Although, the figure shows the variability in snow cover extent across the years, it also shows that there are high and low years where there was variability across elevation zones in the melt trajectories, some years where there was a larger range of snow melt out dates (2000, 2006), while other years there was more consistency in the melt out (2002, 2007). We shifted the calibration and validation period in the Chatanika due to the improvement in quality of the data for the last 5 years of the record, and we think this is fine. To show the variations in the streamflow data, we show all the years for the Upper Chena (Figure 1) and the Chatanika basins (Figure 2) are given below.

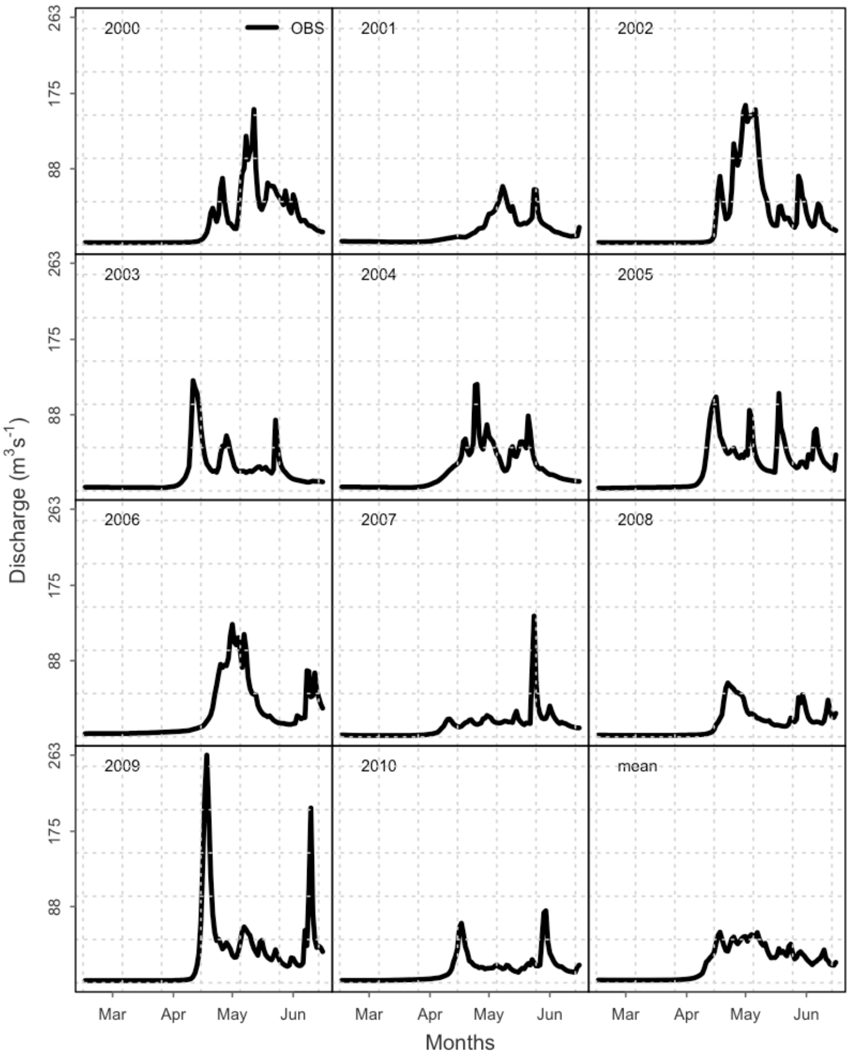

Figure 1. The Upper Chena River basin observed streamflow for the calibration and validation years.

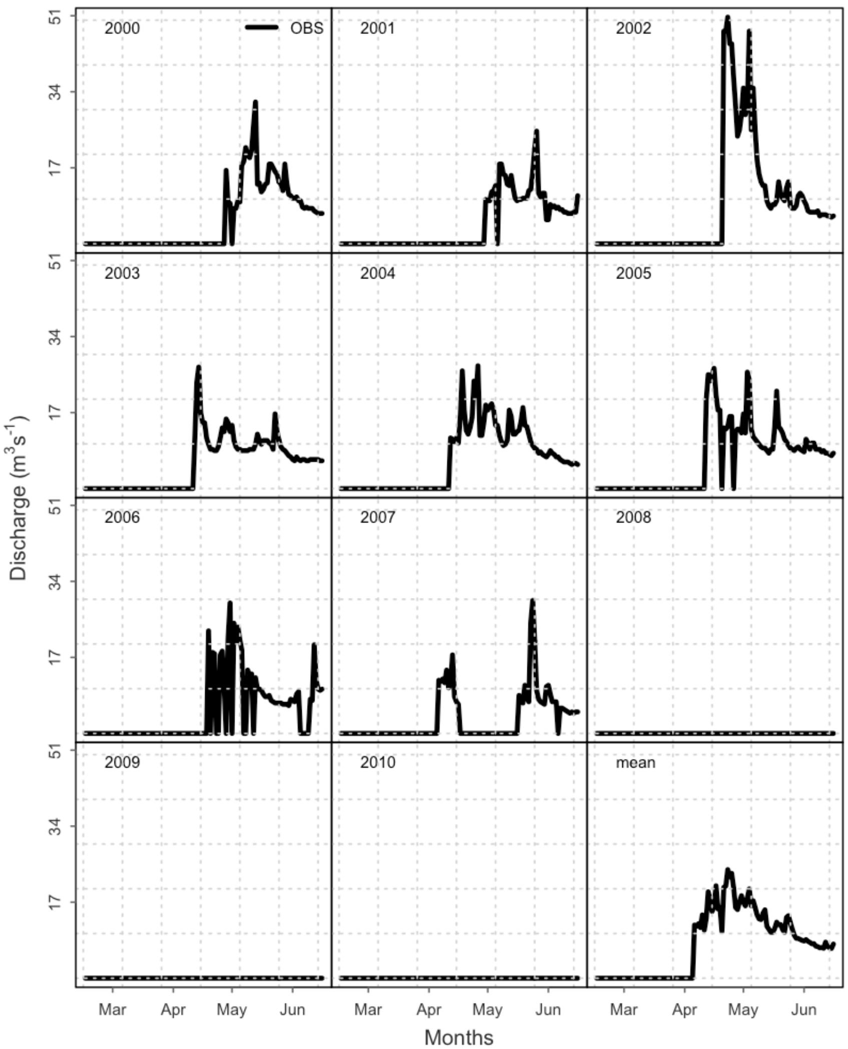

Figure 2 The Chatanika River basin observed streamflow for the calibration and validation years.

To show the variations in the catchments we generated the year 2000 based on the upper basin areas (Figure 3). We do not think there is a lot of variation across the basins, and hence we feel that the variability observed in each panel in Figure 3 is due to the elevation differences, and the year-to-year variations in climate, which occur across all basins.

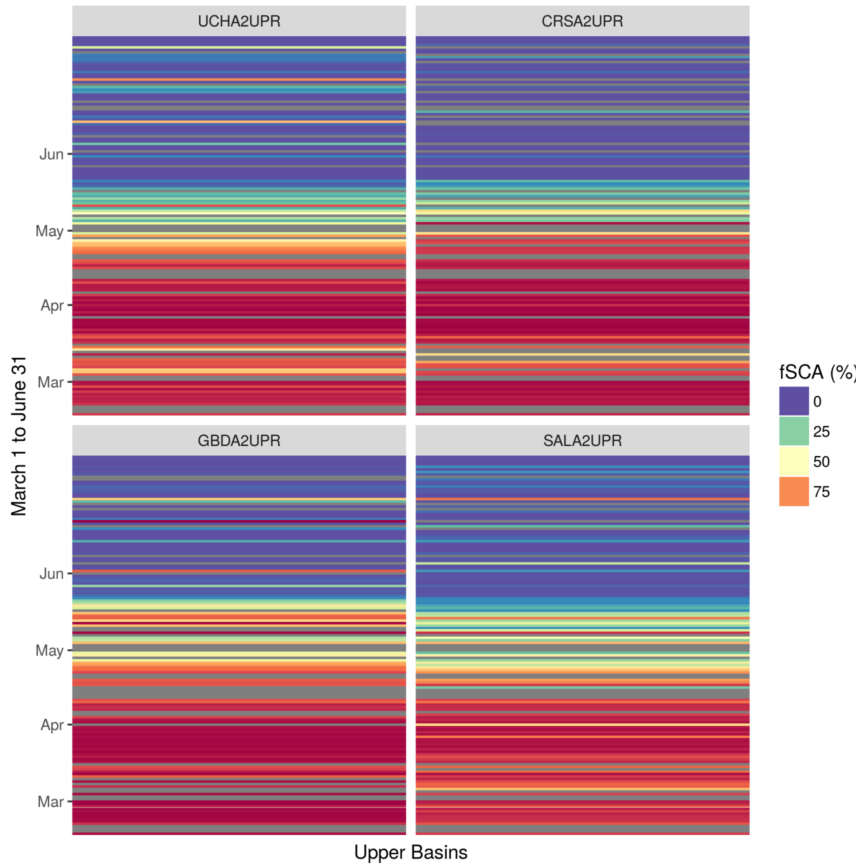

Figure 3. Four upper basins and their SCA (%) values.

- Figure9: could the time be extended spanning April to September as also used in Table 1? Would it be possible to add quantiles of the streamflow to get an idea about the range per season? Unit should be m3/s, I do not understand what the average of all basins can tell me.
  We decided to change the table to align with Figure 9. So, the table now shows precipitation values for Nov-Dec-Jan-Feb (winter), and Mar-Apr-May-June (spring). Because we calibrated the models only for the snow melt season, the rainy season is not illustrated in the plots. Also, we corrected the units in the plots. The average of all basins was included to show the regional streamflow magnitude and hydrograph shape for the average of all basins. We have opted to retain it in the plots but if you feel strongly about this we can remove it.

Tables

- Table1: units: elevation m a.s.l.; Q m3/s?
  We have corrected the Table, and changed the period of P to align with Figure 9.

- Table2: maybe replace current with the last year included.
  We have replaced current with last year of the study (2010), as suggested.

- Table3: SCF Max values seem messed up

We are unsure what you mean by this comment. The SCF values ranges from 0.65 to 0.95 across the catchments.

- Table4: mention that period of record is not the same for each catchment!
  We have added this to the table caption as suggested.

References:

Anderson, E.A., 2002. Calibration of conceptual hydrologic models for use in river forecasting. Office of Hydrologic Development, US National Weather Service, Silver Spring, MD. http://140.90.113.200/oh/hrl/modelcalibration/1.%20Calibration%20Process/1_Anderson_CalbManual.pdf Accessed August 17th, 2018. pp 372.

Clark, M.P., Hendrikx, J., Slater, A.G., Kavetski, D., Anderson, B., Cullen, N.J., Kerr, T., Hreinsson, E.Ö. and Woods, R.A., 2011. Representing spatial variability of snow water equivalent in hydrologic and land-surface models: A review. *Water Resources Research*, *47*(7).

Tang, T., P. Reed, T. Wagener, K. Van Werkhoven. Comparing sensitivity analysis methods to advance lumped watershed model identification and evaluation. Hydrology and Earth System Sciences Discussions, European Geosciences Union, 2007, 11 (2), pp.793-817.

In this paper, the authors employ daily Moderate Resolution Spectroradiometer (MODIS) fractional snow cover extent (SCE) data to improve streamflow simulations in several Alaskan sub-watersheds of the Tanana River. The study period covers 2000-2010 with simulations with the SAC-SMA conceptual rainfall-runoff model that also incorporates the one-layer SNOW17 model for the representation of snowpack conditions. Runoff simulations that include MODIS-derived snow areal depletion curves (ADCs) in SNOW17 are compared with baseline simulations with the standard model formulation for ADCs in the five sub-basins of the Tanana River. The authors conclude that the assimilation of the MODIS SCE data leads to better representation of snow conditions and runoff simulations in Interior Alaska.

This paper presents interesting results on the potential application of MODIS SCE data in operational models for improved runoff simulations in Interior Alaskan watersheds where in situ data remain sparse. The paper is generally well-written and illustrated, but the paper requires some revisions prior to publication.

Thank you for your positive words and your detailed review. We feel that your suggestions, along with other reviewers, have vastly improved the paper.

The following provides a list of suggestions that may be helpful to the authors in revising their paper:

General Comments:

1) The paper includes non-metric units including feet for elevations and inches for snow water equivalent (SWE). Please convert all non-metric units to metric and adjust Equation (1) accordingly.We added units to the elevation map (m). We have changed the inches to mm as referred to in the text and shown in Figure 6.

2) A considerable amount of effort has been placed into ingesting the MODIS SCE data into SAC-SMA model simulations of runoff in five sub-watersheds of the Tanana River. The authors should be commended for this effort. Nonetheless, the results shown in Figure 9 show little differences between the simulations that incorporate the MODIS data versus those with the standard model formulation. Table 4 confirms there are only very modest gains to be made by ingesting the MODIS data into the runoff simulations. As stated by the authors, more significant gains would be obtained by having more accurate forcing data (air temperature and precipitation) in the remote and complex terrain of these Alaskan watersheds. Further to this, SNOW17 incorporates only one snow layer which may miss some of the snow dynamics at play within the thin snowpack layer than interacts with the atmosphere. As such, why spend so much effort in trying to improve the runoff simulations with the data assimilation strategy when more significant gains may be obtained by improving other aspects of the modeling framework? This is an interesting comment, and it highlights a point regarding the work that isn't necessarily raised in the paper. We went to considerable effort to ingest MODIS data into the modeling framework that is being used operationally in Alaska by the Alaska Pacific River Forecast Center (APRFC). We wanted very much to work closely with the APRFC on the effort, so that our work could feedback to their operational workflow. There was a lot of interest within the APRFC in ingesting remote sensing tools, and this study pointed out that there are some gains to be made, but other efforts (e.g. improved climate station data, and model ensembles, including physical models) should be pursued as well. And, it also points to the need for a more flexible calibration scheme that considers all available ground based and remotely sensed observations, including SWE, fSCA, in addition to streamflow observations. Considering that we have received support to implement the operational stages of this work, and also test a

physically based model in the state, we feel that this effort was an important step and was valued by the stakeholders involved in the project.

3) Why does the study period cover only 2000-2010 when MODIS data are available up to present? Further to this, how are gaps in the MODIS data in-filled? For instance, persistent cloud cover can lead to a significant reduction in the available snowcover data from optical remote sensing. Is any gap-filling procedure used to address this issue (see for example Hall et al., 2010 and Tong et al., 2009). The study period reflects the time when the work was undertaken. Although there is more recent information, we feel that the 2000-2010 time period is sufficient to illustrate our points, and we do not think the message of the paper would change by adding more data to the study. Regarding the infilling of gaps, we have now added more details regarding how we pre-processed the MODIS data outside of CHPS, and within CHPS, in section 2.2 of the paper.

4) Hydrological simulations such as those presented in Figure 9 are averaged over 10 water years. Results for each individual year should also be presented to illustrate the model's ability to represent interannual variability in the discharge patterns. We have generated the figures for each year, and we have included these in the Supplemental. We refer to them in the text ~page 15.

5) The references need to be fully revised and presented in the journal's standard format. We have revised the references to follow the format presented in https://www.hydrology-and-earth-system-sciences.net/for_authors/manuscript_preparation.html.

6) Note that Déry et al. (2005) used MODIS ADCs to improve their simulations of runoff on the Alaskan North Slope and may be a relevant reference to this study. We have included a reference to Déry et al. (2005) in the paper. This was an oversight on our part, thank you for pointing this out.

Specific Comments:
1) P. 2, Abstract: Include the study period within the abstract. We have included the study period in the abstract.
2) P. 2, lines 5 and 25: Define "US". We now define US in the Abstract and Introduction.
3) P. 2, lines 29/30: Have both snow cover extent and duration in Alaska indeed declined by 18% from 1966 to 2012? We have corrected this line per Reviewer #2 comments to read "Snowpack extents in Alaska have decreased over time by 18% (1966-2012) due to an earlier snow melt, while snowpack duration has also decreased (SWIPA, 2012)."
4) P. 2, line 31: What aspect of permafrost has declined in response to warmer air temperatures in Alaska? Its depth, extent, or other characteristic? We have added thaw to this sentence.
5) P. 2, line 34: Change to "North American". We have made this change. Thank you for pointing this out.
6) P. 3, line 3: "Extremes" should be singular. We have made this change.
7) P. 3, line 16: Delete the extra "model output". We have deleted these words.
8) P. 3, line 20: Define "NOAA". We have added the definition.
9) P. 3, line 30: Change to "these data have". We have changed this to these and has to have.
10) P. 5, line 15: Why does the study period end in 2010 although MODIS data are available up to present? See answer to this question above in general comments.
11) P. 5, line 27: Define "SWE" upon first usage rather than in the following line. We have added the definition. Thank you for pointing this out.
12) P. 5, line 35: Perhaps number the equations, depending on the journal's formatting guidelines. Convert the equation to metric units and ensure the elevation *e* is in meters, not feet.

We have added numbers for the equations. See response to Reviewer #2 comments regarding this equation.

13) P. 6, line 3: Define "SAC-SMA". SAC-SMA is defined on page 4 of the revised manuscript, in the Introduction.

14) P. 6, line 17: Should the air temperature lapse rate be 0.6°C/100 m? Insert a space in "100 m". This was an error, we have now corrected it to read 6ºC/1000 m.

15) P. 6, line 23: The journal may prefer dates in a format such as "21 December". We have changed all dates to adhere to the suggested format.

16) P. 6, line 29: Insert a space in "100 m". We have made the correction here and elsewhere in the paper.

17) P. 6, line 31: What atmospheric temperature is used to compute incoming longwave radiation with the Stefan-Boltzmann Law?

This part of the text describes the calculation for rain-on-snow in SNOW17. From Anderson (2006, pg A-5, A-6) "T is the air temperature at ground level. Such a relationship typically assumes that the temperature of the cloud base is the same as the surface air temperature during overcast conditions and that there is fairly constant relationship between surface and upper air temperatures when the sky is clear."

18) P. 6, line 32: Why assume a constant relative humidity (RH) at 90%? Is this relative to a water (and not an ice) surface even when air temperatures are subfreezing? How does RH enter the calculation of the simplified energy balance, through the latent heat flux?

This part of the text describes the calculation for rain-on-snow in SNOW17. "When it is raining, relative humidity can be assumed to be high. With a 90% relative humidity the wet bulb temperature, the assumed temperature of the rain drops, is essentially equal to the air temperature. By making these assumptions, the energy budget equation for melt can be used to compute snowmelt during periods when it is raining" (Anderson, 2006, pg 13).

19) P. 6, line 33: How can wind have units of "mm/mb/6 hr"?

UADJ is the average wind function and has units of mm/mb/6 hr (Anderson, 2006, pg 13). We are not describing wind here. We have moved the units to fall after UADJ so it is clearer.

20) P. 6, lines 34/35: Write "snowpack" as one word. We have corrected this through the paper.

21) P. 8, line 30: Revise to: "Three additional objectives" We have corrected this sentence as suggested.

22) P. 9, lines 1 through 9: Equations numbers run on two lines and are missing for the last three equations. We have removed these equations as suggested by Reviewer #2.

23) P. 9, line 10: The units should be "m3/s". We have removed the sentence to respond to a suggestion by Reviewer #2.

24) P. 9, line 17: Provide probability values for all correlation coefficients reported in the study. We feel that the correlation coefficients and other statistics provided are sufficient. If the reviewer feels that this is a sticking point, we will calculate it.

25) P. 10, line 18: What are the units for snow density, listed here only as 0.2? The values we are reporting here is not snow density, but negative melt factor, NMF, a coefficient used to represent the snow heat deficit. "Snow heat deficit is either negative or positive; the rate of heat loss or gain is based on the amount of energy exchange that occurs when melt is not taking place at the snow surface." It is defined on page 9. The units for NMF mm/ºC/6 hr). See Table 3 and Anderson, 2006.

26) P. 10, line 19: Insert a space in "6 hr". We have corrected this through the paper.

27) P. 10, line 35: Insert a space in "850 m". We have corrected this through the paper.

28) P. 10, line 36: Should this be "SNOW17's"? We have corrected this error. Thank you for pointing this out.

29) P. 11, lines 1 and 11: Write "snowpack" as one word. We have corrected this through the paper.

30) P. 11, line 10: Date format may need to be revised to “15 May 2001”. Please also change to “is shown in Figure 5b”. We have changed all dates to adhere to the suggested format.
31) P. 11, line 13: Change to “watershed’s”. We have adjusted this sentence. Thank you for pointing this out.
32) P. 11, lines 20 to 22: Convert SWE from inches to mm. We have changed these figures and numbers in the text to mm.
33) P. 11, line 33: Change to “improve”. We have changed this as suggested.
34) P. 12, lines 4/5 and 13/15: Avoid sentences that just describe the figures – this is what figure captions are for. We have adjusted the sentences as follows: “The calibration, validation and whole period of record results shown in Figure 3, illustrates that the poorly performing basins,” and we removed the sentence starting with “Here the percent…” and the sentence starting with “Plots illustrate…”. We also adjusted the sentence starting with “Statistics show…”.
35) P. 12, line 35: Delete “Because this.” We have deleted these words.
36) P. 13, line 14: Change to “SNOW17’s”. We have changed this as suggested.
37) P. 13, line 17: Revise to “data are temporally”. We have changed this as suggested.
38) P. 14, line 11: Write “snowpack” as one word. We have changed this as suggested through the paper.
39) P. 14, line 19: Change to “are adding”. We have changed this as suggested. Thank you for pointing this out.
40) P. 14, line 20: Change to “data appear”. We have changed this as suggested.
41) P. 15, line 22: Change to “have improved”. We have changed this as suggested.
42) P. 16, line 11: For consistent language, change to “floods and droughts”. We have changed this as suggested.
43) P. 16, line 27: Delete “to” before “during”. We have changed this as suggested.
44) P. 16, lines 32 to 34: This sentence is long and confusing. Consider revising it and perhaps dividing it into two sentences. We have changed the sentences to read “The observations of rapid change in the Arctic highlight important alterations to hydrological regimes in the subarctic Interior boreal forest of Alaska. These observed, rapid changes and future anticipated alterations introduce a pressing need in Alaska to further understand the anticipated changes through modeling of major climate drivers of streamflow.”
45) P. 17, line 1: Delete the space after the hyphen in “high-quality”. We have corrected this.
46) P. 17, line 8: Change to “Natural Sciences”. We have corrected this.
47) P. 18, line 1: Note that the references do not generally follow the format used by HESS; for instance, journal names should be abbreviated, not listed in full. The year of publication should be listed at the end of the reference, not after the list of authors. We have adjusted the references accordingly.
48) P. 18, line 4: Is this a journal article, technical report or book? Please provide full details of the Anderson (1976) reference. We have corrected this reference.
49) P. 18, line 14: Provide the full range of pages for this article. We have corrected this reference.
50) P. 18, line 16: Add the article # for this reference. We have corrected this reference.
51) P. 18, line 26: Provide the full range of pages for this article. We have corrected this reference.
52) P. 20, lines 8/9: Why is the journal name in italics? We have corrected this reference.
53) P. 20, line 11: Is the French name of the journal needed here? We have corrected this reference.
54) P. 21, line 6: Provide the full range of pages for this article. We have corrected this reference.
55) P. 21, line 8: There is a period missing after “design”. We have corrected this reference.
56) P. 21, line 13: Provide the full range of pages for this article. We have corrected this reference.

57) P. 21, line 31: Is there an appropriate issue number (other than zero) for this article?
58) P. 22, line 9: Provide the range of pages for this article. We have corrected this reference.
59) P. 22, line 19: Use upper case "H" in "Journal of Hydrology". We have corrected this reference.
60) P. 23, line 16: Why is this "Woo et al. (2008a)" when there is no corresponding "Woo et al. (2008b)"? We have corrected this reference. Thank you for pointing this out.
61) P. 24, Figure 1: I presume the upper and lower divisions shown in each catchment are delineated by the black contours? If so, the figure caption should clearly state this. The range of colors is misleading since there does not appear to be elevations above 1000 m. As such, consider using a shorter range of elevations for the map with more distinctive colors.
We have changed the figure's color ramp and included Elevation (m) in the legend title for the elevation zones. We have added the basin divisions to the legend.
62) P. 25, Figure 2: For which year(s) are these results valid for? Is this for a given year or a climatology over the study period? We have added the year to the figure and figure caption.
63) P. 26, Figure 3: Here snow cover extent is expressed as a percentage in the color legend but in Figure 2 it was shown as a fraction from 0 to 1. Use a consistent parameter for the presentation of the results. The range of elevations for each zone should be provided in a table.
We have corrected Figure 2 to be consistent with Figure 3. The range of elevations are provided now in the Figure 3 caption.
64) P. 27, line 27: The date format may need revisions. We have changed all dates to adhere to the suggested format.
65) P. 28, line 34: Same comment. We have changed all dates to adhere to the suggested format.
66) P. 29, Figure 6: Convert the SWE data from inches to mm and redraft the figures accordingly. We have adjusted the units on these figures from inches to mm.
67) P. 30, Figure 7: Provide units for RMSE on the y-axis. Would it be possible to have ovals around the different clusters to identify specific basins on the plot? We have provided units and ovals on the figure.
68) P. 31, line 51: Change to "on the plots". We have changed this as suggested.
69) P. 32, Figure 9: Discharge should be in units of m3/s on the y-axis. Rather than presenting the average results over 10 water years, why not depict results for each ablation season? We have changed the units. We now include the 10 water years in the Supplemental.
70) P. 33, Table 1: For the upper Little Chena, provide the air temperature with one decimal, i.e. "-21.0" for consistency with values reported elsewhere. We have changed this as suggested.
71) P. 34, Table 2: Is the average SWE reported here the annual average, or the average annual peak value? We have changed the caption and the table accordingly.
72) P. 35, Table 3: There are a couple extraneous numbers in the table just under "Max" ("13" and "14", which appear to be line numbers. The maximum MBASE temperature should read "0.00". These line numbers appear in the PDF only. I will make sure they are corrected in the next stage of reviews. The MBASE temperature has been corrected.
73) P. 36, Table 4: Probability values should be reported for the correlation statistics. See response to this comment above.

New References:

Déry, S. J., Salomonson, V. V., Stieglitz, M., Hall, D. K., and Appel, I. 2005: An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modelling in Alaska, Hydrol. Proc, 19, 2755-2774, doi: 10.1002/hyp.5784.
Hall, D. K., Riggs, G. A., Foster, J. L., Kumar, S. V. 2010: Development and evaluation of a cloud-gap-filled MODIS daily snow-cover product, Remote Sens. Env., 114(3), 496-503.

Tong, J., Déry, S. J., and Jackson, P. L., 2009: Topographic control of snow distribution in an alpine watershed of western Canada inferred from spatially-filtered MODIS snow products, Hydrol. Earth Syst. Sci., 13, 319-326.

Thank you for these suggestions. We have added these references to the paper.

References:

Anderson, E., 2006. Snow Accumulation and Ablation Model - SNOW-17. http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/part2/_pdf/22snow17.pdf, NWS NOAA, pp. 44.

Anderson, E. A.: Snow Accumulation and Ablation Model - SNOW-17. http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/part2/_pdf/22snow17.pdf, Nat. Weather Serv. NOAA, last access: 17 Aug 2018, pp., 44, 2006.

Using MODIS estimates of fractional snow cover area to improve streamflow forecasts in Interior Alaska

Katrina E. Bennett[1,2,3], Jessica E. Cherry[1,2,4], Ben Balk[5], Scott Lindsey[4]

[1]International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, 99775 U.S.A.
[2]Water and Environmental Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, 99775 U.S.A.
[3]Current affiliation, Earth and Environmental Sciences, Los Alamos National Lab, Los Alamos, NM, 87545, U.S.A
[4]Alaska Pacific River Forecast Center, Anchorage, Alaska, 99502 U.S.A.
[5]Deltares USA, Silver Spring, Maryland, 20910 U.S.A.

Deleted: AMEC Environment and Infrastructure, Boulder, Colorado, 80302 …

Formatted: Affiliation

Correspondence to: Katrina E. Bennett, kbennett@lanl.gov, 505-664-0698, Earth and Environmental Sciences, Los Alamos National Lab, Los Alamos, NM, 87545, U.S.A

Abstract Remotely sensed snow cover observations provide an opportunity to improve operational snowmelt and streamflow forecasting in remote regions. This is particularly true in Alaska, where remote basins and a spatially and temporally sparse gaging network plague efforts to understand and forecast the hydrology of subarctic boreal basins and where climate change is leading to rapid shifts in basin function. In this study, the operational framework employed by the United States (US) National Weather Service, including the Alaska Pacific River Forecast Center, is adapted to integrate Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed observations of fractional snow cover area (fSCA) to determine if these data improve streamflow forecasts in Interior Alaskan river basins. Two versions of MODIS fSCA are tested against a base case aerial depletion curve-derived extent of snow cover: the MODIS 10A1 (MOD10A1), and the MODIS Snow Cover Area and Grain size (MODSCAG) product over the period 2000-2010. Observed runoff is compared to simulated runoff to calibrate both iterations of the model. MODIS-forced simulations have improved snow depletion timing compared with snow telemetry sites in the basins, with discernable increases in skill for the streamflow simulations. The MODSCAG fSCA version provides moderate increases in skill but is similar to the MOD10A1 results. The basins with the largest improvement in streamflow simulations have the sparsest streamflow observations. Considering the numerous low-quality gages (discontinuous, short, or unreliable) and ungaged systems throughout the high latitude regions of the globe, this result is of value and indicates the utility of the MODIS fSCA data in these regions. Additionally, while improvements in predicted discharge values are subtle, the snow model better represents the physical conditions of the snowpack and therefore provides more robust simulations, which are consistent with the US National Weather Service's move toward a physically-based National Water Model. Physically-based models may also be more capable of adapting to changing climates than statistical models tuned to past regimes. This work provides direction for both the Alaska Pacific River Forecast Center and other forecast centers across the US to implement remote sensing observations within their operational framework, to refine the representation of snow, and to improve streamflow forecasting skill in basins with few or poor-quality observations.

1 Introduction

Arctic climate change is rapidly transforming the North with a myriad of impacts on the hydrologic realm, which has important implications for the largest biome on earth, the boreal forest. For the northernmost United States (US) state, Alaska, climate change has affected the hydrology, ecology, and society in significant ways (Euskirchen et al., 2009, Hinzman et al., 2005, Hinzman et al., 2013, Wrona et al., 2016). Alaska has warmed more than two times the rate of the rest of the US since the 1950s (Karl et al., 2009). Interior boreal Alaska has warmed the most of all regions in the state, increasing by 4 ºC in winter and 1.9ºC annually from 1949-2011 (Stewart et al., 2013). Snowpack extents in Alaska have decreased over time by 18% (1966-2012) due to an earlier snow melt, while snowpack duration has also decreased (SWIPA, 2012). Changes in temperature and snow are also affecting frozen ground and leading to permafrost thaw—the temperature of the permafrost near Fairbanks Alaska has risen by 2-4ºC from 1930-2003 (Slater and Lawrence, 2013; Koven et al., 2013). Rivers in Alaska have been observed to be changing as a result of an intensified or stronger hydrologic cycle that could lead to an increase in peak flows in the North American high latitudes (Cohen et al., 2012; Huntington, 2006; Rawlins et al., 2010). Riverine breakup dates have been noted to be occurring earlier (Cooley and Pavelsky, 2016; Lesack et al., 2014; Muhammed et al., 2016). Extreme events are also changing; annual maximum streamflow trends indicate that Alaskan riverine systems are experiencing streamflow declines, while minimum flow trends are largely increasing (Bennett et al., 2015). All of these shifts are leading to increased streamflow variability (Stuefer et al., 2017), which has strong impacts on the infrastructure and economy of Alaska, and the Arctic as a whole (Instanes et al., 2016), leading to a substantial task in terms of observing, understanding, mitigating, and adapting to these effects. The Far North (Arctic and Subarctic) is also rapidly developing its hydroelectric water resources, unlike the contiguous US, and needs accurate decision support for managing this infrastructure (Cherry et al., 2017; Sturm et al., 2017).

A challenge for scientists attempting to accurately represent the impacts of climate change on the Alaskan hydrosphere is the vast territory, complex landscape, and sparse observational network. Alaskan hydrologic systems suffer from large uncertainties in various data inputs, and thus require care when attempting to simulate hydrologic water balance components with skill. For example, precipitation measurements are of very poor quality in winter (Cherry et al., 2005; 2007; Groisman et al., 2014) and river stage and discharge measurements by automated gages do not read accurately when ice is present in the river. Reducing these uncertainties is important, as they will reduce the value of model output (Magnusson et al., 2015; Slater et al., 2013; Clark et al., 2017) and the results cannot provide actionable guidance on water resource management (Stocker et al., 2013). In addition, the variability in landscape (i.e. forest cover, topography, discontinuous permafrost) and climate across Alaska require robust modeling techniques to account for potential climate-driven shifts. This adaptable approach is increasingly important as the National Oceanic and Atmospheric Administration (NOAA)'s National Weather Service (NWS) develops the National Water Model (NWM) framework, a multi-scale water prediction model in operations over the contiguous US (NOAA, 2017). Temperature index models, based on the most reliable climate forcing, are often presumed to perform better than other models for regions with highly variable landscapes and a sparse network (Hock, 2003; Stahl et al., 2006). Alternatively, a skillfully calibrated conceptual model may provide a better representation of hydrologic responses because the underlying model is reliant upon parameterizations rather than observations that lack spatial and temporal consistency (Franz et al., 2008; Reed et al., 2004).

Deleted: decreases in the

Deleted: 5

Deleted: ern

Deleted: The intensification is owing to the Clausius–Clapeyron relation that dictates an exponential increase in specific humidity with increased temperature (Huntington, 2006; Cohen et al. 2012).

Deleted: s

Deleted: massive

Deleted: challenge

Deleted:

Deleted: n

Deleted: enormous

Deleted: great

Deleted: of utmost

Deleted: importance

Deleted: model output

Deleted: in

To deal with the inoperability of stream gages during breakup and *in situ* snow observations, one technique is to use remotely sensed snow cover areal extent (fSCA) to supplement point observations such as temperature, precipitation, and streamflow commonly used both as model inputs and for model calibration and validation (Parajka and Blöschl, 2008). There are two main ways that these data have been used to date: either to directly insert a time series of fSCA data into the model (McGuire et al., 2006; Rodell et al., 2004), or to use complex assimilation procedures to filter the snow series and merge it with observational data (Andreadis and Lettenmaier, 2006; Sun et al., 2004; Zaitchik and Rodell, 2009). There is a concern that direct insertion methods are ineffective at improving streamflow models and do not perform better than uninformed models because melt can occur before snow cover drops below 100% (Clark et al., 2006). In addition, the melt season duration is often short, transitioning rapidly from snow-covered to snow-free, although this is largely basin-dependent (Clark et al., 2006). Assimilation approaches have yet to be integrated into operational models, in part because of the limited research showing the impacts of assimilation on the hydrologic forecast. Other studies have found calibrating models based solely on fSCA values may not improve skill in estimating discharge, and the improvements for in-catchment distributed fSCA estimates do not always result in improved discharge simulation (Franz and Karsten, 2013; Duethmann et al., 2014). However, Liu et al., (2013), Thirel et al., (2013), and Déry et al. (2005) found marked improvements in land surface model output for basins in Alaska when MODIS data were applied.

One approach to improve streamflow forecasts under climate change is to utilize newly developed frameworks to ingest remotely sensed data on snow cover area into streamflow models. These newer tools have been adopted by the NWS's River Forecast Centers (RFCs) and offer an opportunity for more advanced streamflow forecasting techniques, including ensemble prediction using variable input and/or forcing data. The Community Hydrologic Prediction System (CHPS), brought online in 2012 by the Alaska Pacific River Forecast Center (APRFC), is a test case for this approach. The modeling framework, developed on the Delft-FEWS software platform, can run many different types of models, but in its current state implements the conceptual Sacramento Soil Moisture Accounting System (SAC-SMA) rainfall-runoff model (Burnash et al., 1973), with snowpack input from the SNOW17 snow model (Anderson, 2006).

The objective of this paper is to adapt the CHPS operational forecasting modeling framework to ingest Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed fSCA data for improved streamflow modeling of the Interior boreal forest region of Alaska within sparsely and poorly-observed river basins that are experiencing shifts associated with a changing climate. We replace the standard areal depletion curve used in SNOW17 with pre-processed MODIS fSCA grids for snow depletion. Two different versions of MODIS are applied: the MOD10A1 fractional fSCA product, which is the standard MODIS global snow cover product (Hall et al., 2002), and the MOD-Snow Covered Area and Grain size (MODSCAG) fractional fSCA product, which is a regional product (Painter et al., 2009). The SNOW17 manual calibration using all model parameters is evaluated, including a tolerance parameter controlling

Deleted: this
Deleted: has
Deleted: and
Deleted: where data assimilation processes were applied
Deleted: ¶

snow cover updates (snow cover tolerance, SCTOL), to simulate a mixed method between direct insertion and more complex data assimilation. Pre-processing, model frameworks, and use of existing parameterizations are thus offered as a means of incorporating remotely sensed information into operational models that can be utilized out-of-the box by the NWS RFCs. The paper also examines issues around the use of MODIS fSCA in high latitude boreal forest basins, the interpolation of missing data, and the improvement of streamflow estimates by calibrating model parameters used in streamflow forecasting systems across the US.

2 Methods

Formatted: Heading 1

2.1 Study area

This study was carried out in five adjoining headwater sub-basins of the Tanana River, which is a sub-basin of the Yukon River basin (Figure 1). The sub-basins include the Chatanika, Upper Chena, Little Chena, Salcha, and Goodpaster basins. The Chatanika River basin (64°50′37″ N, 147°43′23″ W; Figure 1) is approximately 950 km^2 in size and is oriented predominantly east to west. Only the area upstream of the Caribou-Poker Creek confluence is considered in this study. The Chatanika was gaged from 1987 to 2007 but the records are highly discontinuous. The Upper Chena River basin is approximately 2440 km^2 and has gage records from 1967 to present. This portion of the basin contains high elevation peaks and rocky outcrops where snow can persist late into the melt season. The Little Chena is 1030 km^2 and contains the highest proportion of lowlands relative to the other basins; it has been gaged since 1966 to present. The Salcha River basin is a large, 5740 km^2 basin with its gage at the Salchaket Bridge and has the longest historical record of all rivers in this region (1948 to present). The Goodpaster basin is located east of the Salcha and is 1770 km^2 in size. It has the highest proportion of its basin above 600 m elevation and has been gaged since 1997 to present. Upper basins are split into sub-basin units with north and south facing aspects, with the exception of the Little Chena. There are minor urban and agriculture developments throughout the region, including the town of Fairbanks, which is located downstream of the Little Chena gage on the main stem of the Chena River. These minor developments have little or no bearing on the hydrologic response of the headwater systems of Chena basins we examine here. More information on the basins is provided in Table 1.

Deleted: above the Steese Highway

Deleted: watershed

Deleted: watersheds

Deleted: watersheds

2.2 Data

The MODIS satellite product (Terra MOD10A1, version 5) provides daily, 500 m resolution fractional snow cover area (fSCA) data. It was downloaded from the National Snow and Ice Data Center (Hall and Riggs, 2007; Hall et al., 2006; Riggs et al. 2006) for 2000-2010, and we used the MODIS Re-projection Tool (MRT, USGS, 2011) to pre-process imagery into an Alaska Equal Area Conic projected GeoTIFF of fractional fSCA for each sub-basin, which assisted us to correct, in part, the viewing geometry and other issues related to projections of the original MODIS data, and the influence these projections have on the MODIS data for Alaska. (Dwyer and Schmidt, 2006; Tan et al., 2006). MODSCAG data products were obtained from the NASA Jet Propulsion Laboratory's Snow Data System Portal (http://snow.jpl.nasa.gov/) for the area of interest and pre-processed into projected GeoTIFFs to match the spatial properties of the MOD10A1 data. We interpolated cloud- and error-free pixels using a Nearest Neighbor approach; only fSCA data from 0-100% for 1 October to 30 June are ingested into CHPS. Further information on the MODIS data products applied in this study are provided in the supplemental materials (Supplemental, section 1.1).

Both MOD10A1 and MODSCAG fractional products require correction to adjust the values of fSCA estimates (Raleigh et al., 2013; Rittger et al., 2013), which do not account for the snow that is blocked from the sensor view. For the MOD10A1 fSCA product, this calculation is based on the viewable gap fraction, or the amount of snow covered ground between trees that the sensor can see (Liu et al., 2004). This technique, while widely applied, assumes that the viewable gap fraction remains constant through the snowmelt season, which is incorrect as the viewable gap fraction can vary based on a complex number of factors, including forest canopy density, age and class, zenith angle of the sensor, solar zenith angles, topography, and snow loading (Kane et al., 2008; Liu et al., 2008; Molotch and Margulis, 2008; Raleigh et al., 2013; Rittger et al., 2013). To account for some of these issues, rather than applying a forest cover product to correct the product itself, the MOD10A1 data are used (Durand et al., 2008). All 2000-2013 1 March to 15 March MOD10A1 pixels across Interior Alaska are differenced from 100, and then a composite average of all days (n=207) is calculated. While in southeast Alaska some melt may have occurred during this time, the Interior fSCA should still be at 100% snow convered across most of the region. To account for bare ground regions such as open, wind-blown rocky faces, values less than 20% fSCA are removed from the correction. The standard division by viewable gap fraction,

$$SCA_{fadj} = \frac{SCA_f}{1-F_{veg}} \quad \text{(Equation 2)}$$

where F_{veg} is the tree cover percentage, SCA_{fadj} (henceforth referred to simply as fSCA) is the fSCA adjusted for canopy cover, and SCA_f is the unadjusted SCA data. This formulation is applied as a static adjustment to each SCA pixel in all days and years. For MODSCAG, the daily vegetation fractional product provided with the data product is utilized, resulting in a dynamic adjustment for each SCA pixel in all days and years. In both cases, the results are constrained to 100% fSCA when exceeded. We did not include any cloud-corrections or additional interpolation methods (Dozier et al., 2008; Morriss et al., 2016).

Deleted: pre-processed into projected GeoTIFFs (North Pole Stereographic)

Deleted: ,

Deleted: pre-processing requirements and adjustments for both

Deleted: Sect.

Deleted:

Formatted: Centered

Deleted: ,

Mean areal values of temperature and precipitation at 6-hr increments are obtained for each sub-basin from the APRFC for the time period 1969 to 2012; only the 1999-2010 data are utilized in this study. River discharge at each gage is based on the US Geological Survey (USGS) gaging record database. The exception to this is the Chatanika River basin, where observed discharge is generated based on once-a-day stage readings from a Cooperative Network observer. These daily stage readings are converted to mean daily discharge using the APRFC's rating curve for the river. Aspect and elevation were calculated using the 30 m US Geological Survey's National Elevation Dataset (NED), updated for the region in 2012 (Gesch et al., 2002). Seven snow telemetry (SNOTEL) sites are utilized to compare simulated snow water equivalent (SWE) with observed data (Table 2, NRCS 2013). SNOTEL SWE is downloaded from the National Resource Conservation Service (NRCS) snow pillow data repository (http://www.wcc.nrcs.usda.gov/ftpref/data/snow/snotel/cards/alaska/).

Potential evapotranspiration (PET) estimates are provided by the APRFC based on an assessment of historical potential evapotranspiration from pan evaporation data and Thornthwaite estimates (Anderson, 2006). These data are used to develop a general linear relationship between PET and elevation to estimate average monthly PET values for a generic low elevation site. The APRFC uses the low elevation PET values to derive monthly estimates for the mean elevation of each sub-basin as a coefficient. The coefficient, C, is derived using the equation,

$$C = 0.9 - [(elev - 1000) \cdot 0.00011] \quad \text{(Equation 2)}$$

where *elev* represents elevation (ft). For example, if the catchment mean elevation is 716 m (2349 ft), the coefficient is 0.75. Finally, a monthly PET adjustment factor is applied to account for vegetation changes during the year. The result is an evapotranspiration demand estimate that is used in the SAC-SMA model, described in the next section.

2.3 Models

The SNOW17 and the SAC-SMA models are run by the APRFC in an operational framework referred to as CHPS. CHPS is built upon the Delft Flood Early Warning System (FEWS), developed by Deltares. The CHPS system is briefly described in the Supplemental, section 1.2.

2.3.1 SNOW17

The SNOW17 snow model is a single layer snow model that calculates snow accumulation and ablation using empirical formulae to estimate heat and liquid water storage, liquid water throughflow and snowmelt (Anderson, 1976). The model is designed for river forecasting and has been used operationally by the NWS RFCs since the mid-1970s. The only input requirements for SNOW17 are temperature and precipitation

Deleted: our
Deleted: watershed
Deleted:
Deleted: at the Steese Highway site
Deleted:
Deleted: snow water equivalent (
Deleted: , mm)
Deleted: e
Deleted: 1000
Deleted: Equation
Formatted: Paragraph Text
Deleted: e
Formatted: Not Highlight
Deleted: in feet
Deleted: 716
Deleted: m
Deleted: materials
Deleted: (Supplement, Sect.
Deleted:)

(winds are accounted for but not input as observations), at the model time step (6 hr). There are 12 parameters in the SNOW17 model, including the areal snow depletion curve; sensitive or 'major' parameters control the model outputs while less sensitive or 'minor' parameters have little impact on the model output (Table 3; He et al., 2011).

SNOW17 determines the division between rain and snow using the rain-snow elevation (RSNWELEV) module. RNSWELEV uses a defined lapse rate (6ºC/1000 m) to represent the saturated adiabatic lapse rate, which is commonly applied to determine the air temperature threshold that results in rain turning to snow (PXTEMP; Table 3; Anderson, 2002; Clark et al., 2011). This temperature threshold is related to an elevation and is passed to SNOW17, the percent area above and below that elevation is determined from a defined area elevation curve. Multiplying these percentages by the precipitation thus defines the proportion of precipitation falling as snow or rain in the basin. Non-rain snowmelt (mm) is determined from air temperature minus the baseline temperature at which melt occurs (MBASE; set to 0ºC), weighted by a seasonably variable melt factor that is calculated using an oscillating sine curve that varies between the minimum (MFMIN) and maximum (MFMAX) melt factors for 21 December and 21 Jun (mm/ºC/6 hrs). These values are adjusted for latitudes above 54ºN to account for low radiation input, a paucity of days when temperatures rise above freezing, and rapid changes in melt rates during spring and fall (Anderson, 2006). A fixed lapse rate is applied to mean air temperature within the lumped basins for the elevation at which the air temperature time series is collected (TAELEV), in the case when TAELEV differs from basin mean elevation. This fixed lapse rate can be configured in the SNOW17 model using parameters that define the lapse rate at time of maximum/minimum temperature.

A simplified energy balance method is used to calculate melt from rain-on-snow using the following assumptions; the Stefan-Boltzmann constant is used to estimate incoming longwave radiation, negligible shortwave radiation, 90% relative humidity, and wind speed is accounted for by adjusting for the average value of the wind during rain-on-snow events using the parameter UADJ (mm/mb/6 hr). Heat content within the snowpack is calculated based on a gradient between air temperature and the near-surface snowpack temperature index to determine the heat flow direction when melt is not occurring. Depending on the near-surface snowpack temperature index, more or less weight is assigned to temperatures from previous time intervals to represent deeper or shallower snowpack temperatures.

The snow heat deficit is either negative or positive; the rate of heat loss or gain is based on the amount of energy exchange that occurs when melt is not taking place at the snow surface (negative melt factor; NMF; mm/ºC/6 hr), which is weighted by MFMAX to account for seasonal variations in pack heat translation. Heat can also be translated from the ground to the snow using a parameter that controls the daily melt volume at the interface between snow and soil, and is assumed to occur continuously through the snow season (DAYGM). When the snowpack is at peak water-holding capacity (PLWHC) and is isothermal at 0ºC, the snow is ripe and any excess water entering the snow will flow through it as outflow. Water

Deleted: s
Deleted: ,
Deleted: uses a defined lapse rate (6ºC/100m) to
Formatted: Highlight
Formatted: Not Highlight
Formatted: Not Highlight
Deleted: ,
Deleted: ,
Deleted: ,
Deleted: 21st
Formatted: Not Superscript/ Subscript
Deleted: n 21st
Deleted:
Deleted: ,
Deleted: and is set to 0.6ºC/100m in this study
Deleted: ,
Deleted: based on the following assumptions: (1)
Deleted: e of
Deleted: for
Deleted: ; (2)
Formatted: Not Highlight
Deleted: ; (3)
Deleted: ;
Deleted: (4)
Deleted: accounting for
Deleted: (mm/mb/6hr)
Deleted:
Deleted: (
Deleted:)
Deleted: difference
Deleted:
Deleted:
Deleted:
Deleted: defined as the
Deleted: ,
Deleted: ,

movement through a ripe pack is attenuated or lagged based on empirical formula derived from lysimeter studies (Anderson, 2006).

2.3.2 fSCA in SNOW17

SNOW17 uses an areal depletion curve (ADC) to represent the snow cover area; the ADC is used to calculate the area of the basin over which surface melt, changes in heat storage, ground melt, and rainfall on bare ground occurs (Anderson, 2002; Fig. 7.4.3). The ADC not only represents areal extent of snow cover, but also accounts for slope, aspect, and differences in vegetative cover (i.e. open versus closed sites, Anderson, 2002; Fig. 7.4.3). In the baseline model simulation, the areal extent of snow cover was calculated from a lookup table (Anderson, 2002; Fig. 8) that defines the ADC and relates it to the ratio of SWE to either a) the maximum value of SWE that occurred during snow accumulation or b) a parameter (SI) that represents the areal SWE at which 100% snow cover exists (referred to as the areal index). The ADC in the baseline model simulation is applied as follows: when snow accumulates, the snow cover is set to 100%, and it stays at this value until it falls below SI or the maximum SWE value, whichever is smaller. If new snow totaling greater than 0.2 mm/hr falls onto bare ground, 100% snow cover is assumed until 25% of the new snow has melted. For Alaska, several different ADC configurations are used depending on whether slopes are south versus north facing, or in upper versus lower elevation basins. The basins in this study used the same ADC for upper south, upper north, and lower sub-basin units since they have similar orientations within a similar geographic region. Only the Little Chena uses a different ADC for its upper basin, as no north/south aspect split is used in this basin. For all other model simulations, the ADC was replaced by areal extent of snow cover derived from the two MODIS fSCA datasets (Figure 2). Other parameter settings used to alter the impact of the MODIS fSCA data in SNOW17 are described in the Supplemental, section 1.3.

2.3.3 SAC-SMA

The SAC-SMA model is a conceptual rainfall-runoff model that simulates streamflow from observed input precipitation and PET (Burnash et al., 1973). SAC-SMA has been widely applied by the NWS to estimate streamflow runoff in basins across the US. The model moves water into either an upper or lower storage zone that conceptually represent soil interception or deep groundwater storage. Interception water in the upper zone flows to the lower zones via downward percolation, or can run off directly or via interflow when the upper zone layers become saturated and the precipitation rate exceeds downward percolation. Lower zone water can be held in tension storage and contribute to baseflow runoff slowly over time, or can run off more quickly over shorter durations. Drainage from the upper and lower zones follows gravity drainage and is governed in part by both water delivery from the upper zone and soil moisture in the lower

Formatted: Heading 3

Deleted: ,

Deleted: ,

Deleted: run

Deleted: (reference)

Formatted: Highlight

Deleted: run

Deleted: watersheds

Deleted: in

Deleted: watershed

Deleted: runs

Deleted: Section

Deleted: produces

Deleted: simulations

zone. Tension water is driven by potential evapotranspiration and diffusion, with a fraction of the lower zone unavailable for potential evapotranspiration as it is considered below the rooting zone.

A unit hydrograph model is used to adjust runoff timing for each lumped basin in the SAC-SMA model. Each sub-basin has its own unit hydrograph to translate the runoff through the channel system to the gage location. Simple routines sum the unit hydrograph outputs to calculate simulated streamflow at the basin outlet. While downstream basins incorporate routing models to move water from upstream to downstream basins, this study focuses on headwater basins so no routing models are needed.

2.4 Calibration

Several calibration procedures were undertaken for this project; the baseline calibration, and the two MODIS data set calibrations. The baseline calibration effort updated the SAC-SMA/SNOW17 model parameters to the 2000-2010 years used in this study, as they had previously been adjusted by APRFC to 1970-2003 historical data. The two MODIS manual calibrations used the updated baseline to adjust parameters and generate statistics. Calibration entailed using both visualizations of streamflow hydrographs from 2006-2010 and statistics from the entire period of record for ultimate parameter selection.

To calibrate the MODIS model output, a simple approach is taken to minimize the terms required for calibration. This ensures that it was a) easy to replicate the model adjustments to the MODIS fSCA data and b) solely focused on the snow parameterization, as adjustments to the SAC-SMA parameters resulted in only minor improvements to model calibration statistics during the spring ice breakup period. Also, priority was placed on adjusting the empirical parameters towards a physically-based realization using basin and sub-basin unit properties, including the topographic aspects and the observed melt trajectory impacted by the MODIS fSCA data. To complete this simple, physically realistic calibration approach only the parameters MFMAX and TAELEV were adjusted. Further details of the calibration efforts are described in the Supplemental, section 1.4.

2.5 Validation

For validation purposes, statistics from 2000-2005 are provided for all basins except the Chatanika. The Chatanika basin was calibrated using 2000-2004 data and validated from 2005-2010 to make use of the better data quality and availability during the first five years of the study. Statistics used to evaluate model success are based on five main objective functions. The first two of these criteria are standard in NWS RFC calibration approaches and are provided in the CHPS statistical output. These statistics were used for evaluation during the calibration; total volume bias as a percent (PBIAS, %) and the correlation coefficient (R, unitless). Three additional objectives were added for further validation of the results, Nash Sutcliffe efficiency (NSE, unitless, reference), the mean absolute error (MAE, m^3/s), and the root mean squared error (RMSE, m^3/s). Statistics were run only for April, May, and June to focus on the changes to the snowmelt season; March is not included because generally, river ice melts and breaks up in Interior Alaska in March, thus any differences in statistics would be indicative of changing winter conditions rather than changes in spring snowmelt timing or volume.

3 Results

3.1 Baseline Model Results

The APRFC SAC-SMA/SNOW17 baseline model estimates of streamflow in Interior Alaskan river basins for the 11-year period of record indicate that these basins are captured with skill (Table 4). The Chatanika basin is problematic given the limited quality and quantity of the observed streamflow data, as noted in the statistics below for each objective function. For all of the five basins analyzed, the daily average bias for the period of record is ±3% or less. Daily correlation coefficients (R, unitless) are equal to or greater than 0.84 and higher for the four basins with quality observed data, while the Chatanika basin is 0.70. NSE (unitless) daily values are also above 0.60 for all basins except the Chatanika, which is 0.18 due to the noise in the observed data values. Daily mean absolute error statistics are below 10 m^3/s for all basins except the Salcha, which is 15.89 m^3/s owing to its long discharge record. RMSE ranges from 3.5 m^3/s (Chatanika) to 33 m^3/s (Salcha). Across all basins, fSCA is variable by elevation zones and years (Figure 3). Upper elevation areas tend to have 100% fSCA, while mid-to-lower areas often begin the year with 75% fSCA or less. The very lowest elevation zone appears to have a slightly higher fSCA values than two adjacent higher elevation zones (Figure 3). Some years have a markedly late melt out, with high variability across all elevation bins. Lower elevation zones tend to melt out in early April, while the upper regions of the basins hold snowpack weeks or months into the subarctic spring (Figure 3).

3.2 SAC-SMA Model MODIS Calibrations

Calibrated SNOW17 parameters for the APRFC and MOD10A1 simulations resulted in increased MFMAX for north facing aspect in two sub-basin units and increased TAELEV for the northern slopes (Table 5) compared to the baseline APRFC SAC-SMA/SNOW17 simulation. In some sub-basin units, TAELEV was set to be equal for the north and south slopes. MFMAX for the Chatanika's lowland sub-basin increased and TAELEV at the north sub-basin was increased, while TAELEV was decreased for the south sub-basin unit. MFMAX in the Upper Chena north was unchanged and TAELEV was equalized for both south and north sub-basin units. The Little Chena sub-basin parameters were altered by setting MFMAX equal to its maximum recommended value for forested regions (1.4; Anderson, 2002; Table 7-4-1) for the upper and lower sub-basins, and by increasing TAELEV 100 m greater than the elevation for both sub-basins. TAELEV for Salcha and Goodpaster were differenced by 100 m for the north and south sub-basin units, and the northern sub-basin MFMAX for Goodpaster was increased slightly. Goodpaster's lower basin

Deleted: . The equations are calculated as follows:

$$PBIAS=\left[\frac{\sum_{i=1}^{N}(S_i-Q_i)}{\sum_{i=1}^{N}Q_i}\right]*100 \quad (2\text{-}1)$$

$$R=\frac{N\cdot\sum_{i=1}^{N}S_iQ_i-\sum_{i=1}^{N}S_i\cdot\sum_{i=1}^{N}Q_i}{\left[\left(N\cdot\sum_{i=1}^{N}S_i^2-\left(\sum_{i=1}^{N}S_i\right)^2\right)\left(N\cdot\sum_{i=1}^{N}Q_i^2-\left(\sum_{i=1}^{N}Q_i\right)^2\right)\right]^{0.5}} \quad (2\text{-}2)$$

$$NSE=1-\left(\frac{\sum_{i=1}^{N}(S_i-Q_i)^2}{\sum_{i=1}^{N}(Q-Q_i)^2}\right)$$

$$MAE=\sum_{i=1}^{N}|S_i-Q_i|$$

$$RMSE=\left[\frac{\sum_{i=1}^{N}(S_i-Q_i)^2}{N}\right]^{0.5}$$

where N is equal to the number of data points (i.e. sub-daily streamflow realizations), i is the time step (days), S is the simulated streamflow (m^3/s), and Q is the observed streamflow (m^2/sec)

Deleted:

Formatted: Heading 2

Deleted: watersheds

Deleted: watersheds

Deleted: ec

Deleted: watersheds

Deleted: runs

Deleted: run

Deleted: , for reasons that are discussed in the following section

Formatted: Not Highlight

Formatted: Not Highlight

Deleted: ,

Deleted: ,

Deleted: 5

MFMAX was reduced by a small amount. Although these changes may appear minor, MFMAX is highly sensitive during the melt season and therefore these changes have a substantial effect on the MODIS fSCA forced snowmelt trajectory at these sites (Anderson, 2006).

In the MODSCAG simulations, values for MFMAX were increased slightly for the north sub-basin units for all basins. TAELEV values were adjusted slightly in Upper Chena, Salcha, and Little Chena bains (Table 6), but were not altered from the baseline run in Chatanika. In the Goodpaster basin, the TAELEV value for the south sub-basin unit was decreased. NMF was altered slightly for both MODIS simulations to account for different snow densities and thermal conductivities of snow on south and lowland sites versus north aspects. Snow density is generally low in Interior Alaskan basins; based on analysis of field data from the Caribou Poker Creek basin, snow density on the sites is approximately 0.20 and is slightly higher on the southern sites compared to the north site. The northern facing slopes were therefore given the NMF value of 0.15 mm/°C/6 hr, which Anderson (2002) indicates is a 'reasonable' value of NMF. The south and lowland sites, which have generally warmer temperatures and more dense snow, were assigned the NMF value of 0.2. For these simulations, SCTOL is set to 0 for all basins to ensure that the MODIS data are utilized 100% of the time.

3.3 fSCA and SWE

Compared to the APRFC simulations, the MODIS simulations have less snow cover on the north facing slopes and more on the south facing slopes (Figure 4; the average Upper Chena River basin unit results for 2001 plotted against the SNOTEL stations are shown as an example). Differences between the two simulations become discernable in late January as a result of the different calibrations of the SNOW17 model in the basins (Figure 4), with larger differences at the north sub-basin units compared to the south sub-basin unit. As soon as the MOD10A1 fSCA begins to alter the weighting factors for outflow from the snow, differences between the SWE generated by APRFC and MODIS simulations are observed. The greatest differences between the model simulations occur during the melt season. All model simulations peak in early April and start a downward melt trajectory, reflecting melt patterns at the upper elevation SNOTEL sites: Mt. Ryan, Munson, and Upper Chena. The APRFC and MOD10A1 run melt out later than the MODSCAG fSCA north unit and the MODSCAG estimates are closer to the APRFC simulations in volume, although all simulations terminate on the same approximate day for the northern sub-basins. The SNOTEL sites are mostly located at upper elevations (Mt. Ryan 850 m; Munson 940 m) compared to the SNOW17's ~800 m elevation parameter and thus illustrate conditions exhibited at high elevation northern sites in the basin. Mt. Ryan, in particular, does not build a snowpack early in the season, perhaps owing to its open, mountainous, and presumably windy environment. The SNOW17 model is run over a lumped area so there is mix of site conditions that act to smooth and reduce the volume of SWE; hence the comparison between SNOTEL SWE and SNOW17 modeled SWE are inherently qualitative as opposed to

Deleted: runs
Deleted: For this version of MODIS, it appears that a slightly more rigorous calibration was required.
Deleted: runs
Deleted: watersheds
Deleted: watershed
Deleted: runs
Formatted: Heading 2
Deleted: runs
Deleted: runs
Deleted: ,
Deleted:
Deleted: runs
Deleted: watersheds
Deleted: runs
Deleted: runs
Deleted: runs
Deleted: runs
Deleted: runs
Deleted: ,
Deleted: and
Deleted: ,
Deleted: watershed
Deleted:
Deleted: the model responses

quantitative (Molotch and Bales, 2005). The lower elevation SNOTEL sites, Teuchet and Little Chena, show earlier melt out than is seen in either the model output or the MODIS datasets. There is stronger coherence in the response of the northern sites as opposed to the southern sites. In the south sub-basin units, the MODIS simulations melt out later, with MODSCAG again having the latest melt, similar in timing to the high elevation stations.

The areal extent of snow cover varies across the basins in both simulations. The preprocessed gridded MOD10A1 fSCA illustrated for 15 May, 2001 is shown in Figure 5a and the MODSCAG fSCA is shown in Figure 5b for the basins. The high elevation snowpack (blue) is present within the upper basin regions but the pack is largely gone in the valleys and lower basin reaches. This translates into the lumped average fSCA estimates shown in Figures 5c and 5d, which illustrate how CHPS ingests and converts the gridded MODIS fSCA for the sub-basin units. North and south sub-basin units are differentiated in the upper sub-basin units (see Table 1) but not at other locations because both aspects have begun to melt by this date (as opposed to early in the melt period when the south slopes would have comparatively less fSCA than the north slopes). MODSCAG has less cloud cover interaction in this scene (Figure 5b) and this results in slightly higher values of fSCA (Figure 5d).

SWE estimates for MOD10A1 (Figure 6a), MODSCAG (Figure 6b), and the difference between the MODIS (both versions) and APRFC run (Figure 6c and 6d) is shown for 15 May, 2001. Sub-basin units can be clearly differentiated in these plots, which illustrate the range of SWE values from 0-25 mm in the lowland regions to 125 mm in the upper headwaters. The MODSCAG data has an average fSCA value of 0.51 (51%), and SWE is 45 inches, whereas the MOD10A1 has an average of 0.45 (45%) fSCA, and an average of 54 inches SWE, very small differences overall although sub-basin-to-sub-basin the variation between the products is notable. The difference plots highlight the fact that MODIS tends to have lower SWE values compared to the APRFC SNOW17 model simulations on the north facing slopes and higher values on the south facing slopes. The APRFC tends to be have lower SWE estimates for the lowland regions, although this is more true for MOD10A1 than MODSCAG (Figure 5c, d).

3.4 Streamflow Estimates

Calibration and validation results are provided for April-May-June (Table 4) for the MODIS and APRFC simulations. For MODIS data, many statistics are similar or nearly identical to the APRFC run with slight declines in model performance and some gains (Chatanika; Little Chena), particularly for the analysis focused on the whole period of record (Table 4). NSE statistics are particularly poor for all simulations in the Chatanika basin, where the lack of continuous and high-quality observations hamper calibration efforts. The MOD10A1 data improves streamflow simulations in the Chatanika and Goodpaster systems during the calibration period, while it performs similarly or slightly worse during the validation and period of record in most of the basins except the Chatanika. The MODSCAG run exhibits better performance compared to

Deleted: runs
Deleted: watersheds
Deleted: runs
Deleted: 15th
Deleted: for the watersheds
Deleted: is
Deleted:
Deleted: watershed
Deleted: watershed
Deleted: watersheds
Deleted: 15th
Formatted: Not Highlight
Deleted: 0.5
Deleted: inches
Formatted: Not Highlight
Deleted: 5
Formatted: Not Highlight
Deleted: inches
Formatted: Not Highlight
Deleted: remaining
Formatted: Not Highlight
Deleted: f
Deleted: f
Formatted: Not Highlight
Deleted: 0.5
Formatted: Not Highlight
Deleted: 1.7
Formatted: Not Highlight
Formatted: Not Highlight
Deleted: 0.45
Formatted: Not Highlight
Formatted: Not Highlight
Formatted: Not Highlight
Deleted: 2.1
Formatted: Not Highlight
Deleted: watershed-to-watershed and
Deleted: runs
Formatted: Heading 2
Deleted: runs
Deleted: ,
Deleted: runs
Deleted: watersheds

the APRFC run during the calibration periods in the Chatanika, Salcha, and Goodpaster basins, while the validation period statistics showed improvement for the Chatanika, Little Chena, and Upper Chena basins. Overall, improvements in skill are observed for the MODIS simulations in the Chatanika and Goodpaster basins, the validation period for Upper Chena and the calibration period for Goodpaster (Table 4). The calibration, validation, and whole period of record results shown in Figure 3 illustrates that the poorly performing basins, MODSCAG (and MODSCAG with SCTOL=0.25) tends to do slightly better versus APRFC in the calibration/validation time where improvements are also made for MOD10A1, while both MODIS versions perform nearly identically over the 11-year period. This can also be observed from the analysis presented in Figure 8 for all five basins. Figure 8 illustrates that the MODSCAG results tend to follow more closely (and are hence more constrained) with the APRFC results, while the MOD10A1 product has more scatter. However, the differences from observed are similar between the two products. Average (2000-2011) streamflow for each basin shown in Figure 9 highlights variations between simulated discharges plotted against observed discharge at the streamflow gages; results for each year and basin are provided in the Supplemental. Only March to June results are shown in Figure 9; in March the basins have not begun to melt and the hydrograph depicts baseflow contributions in the systems. The active period begins in late March to early April and the differences between the two estimates of streamflow persist until June, after which point streamflow responses to rainfall input are essentially the same. Statistics for the April-May-June calibration, validation, and the period of record in Table 4 illustrate that the Upper Chena River basin shows improvement compared to the APRFC run during the early melt period, while the later period is over predicted by the MODSCAG. For Chatanika, the simulated MODIS simulations are of greater magnitude (Figure 9) and have earlier timing compared to the APRFC simulated flows. In the Little Chena river basin, MODIS simulated discharge overall fits better than the APRFC, which over simulates streamflow on average, and both products perform similarly well. Streamflow simulations for the Upper Chena, Salcha, and Goodpaster systems on average match observed more closely by the MODSCAG simulations. This also is clear from the averages across basins and years; the MODSCAG simulations match observed streamflow, while the MOD10A1 product underestimates runoff during the mid-May to early June period (Figure 9, last panel). The year-to-year variability illustrates similar results to the long-term averages for each basin (Supplemental).

3.5 Other Integration Methods

Two methods were applied to integrate the MODIS data into CHPS. One method involved interpolating between missing data values, changing the number of interpolated days from 1 to 11 to investigate how changing the value impacted model results. Generally, the number of days of interpolation had little impact, but the longer interpolation period results produced slightly higher correlations and improved streamflow estimation. We also investigated the response to altering model parameter SCTOL, which can be used by

Deleted: the greatest
Deleted: runs
Deleted: Figure 7 shows the
Deleted: are provided for all watersheds for
Deleted: ,
Deleted: R-1 plotted against RMSE. In the
Deleted: watersheds
Deleted: watersheds
Deleted: Here the percent differences from the observed are plotted as the APRFC differences against the MOD10A1 and MODSCAG products for comparison between the three estimates. The plots…
Deleted: Plots illustrate the average of all years in each panel, with average of the five watersheds provided in the last panel.
Deleted: watersheds
Deleted: Statistics for the April-May-June calibration, validation and the period of record are also provided in Table 4
Deleted: . T
Deleted: runs
Deleted: ;
Deleted: runs
Deleted: watersheds
Formatted: Heading 2

forecasters to combine the strength of the ADC and the MODIS data and is similar to partial rule-based direct insertion approach, however the parameter can be altered without any additional changes to the CHPS model framework. Table 7 illustrates the results of setting the SCTOL parameter to 0.25, 0.50, and 0.75 for the MODSCAG run only, while holding the rest of the parameters constant. No recalibration is performed. NSE and R statistics increase during the calibration period, MAE and RMSE remain similar on average but the range of responses across the basins decreases for SCTOL=0.50. Interestingly, Chatanika, which has the largest improvement based on the differences between APRFC and MODIS simulations does not benefit from model integration, owing to the low skill within the APRFC model version (Table 7). However, for the remaining basins strong improvements are apparent for higher values of SCTOL during the calibration period (Upper Chena, Little Chena, and Salcha), validation, and period of record (Upper Chena, Little Chena). Diminishing returns occur at a threshold between 0.25 and 0.50 SCTOL for most basins; however, Goodpaster improves at 0.50 but not 0.75. This suggests that the SCTOL parameter should be uniquely applied dependent upon the basin.

Deleted: Because this.

Deleted: greatest

Deleted: runs

Deleted: (Chatanika)

4 Discussion

Results illustrate that streamflow in interior Alaska can be simulated with skill using conceptual, semi-lumped hydrologic models, even without the use of gridded observations of MODIS fSCA. However, if the initial streamflow observations are of poor-quality (i.e. Chatanika River basin), applying gridded observations of MODIS fSCA in the models will generate streamflow estimates as good as or better than estimates based on SNOW17's areal depletion curve. However, as the climate shifts, conceptual, semi-lumped models may not be representative of process changes that will likely occur as the Arctic warms (Clark et al., 2017). As fully process-based models are challenging to run in Arctic environments, where high quality data are temporally and spatially sparse, using conceptual models parameterized with as many observations as possible represents a bridge between the fully processed based models and conceptual approaches to hydrologic modeling.

Deleted: is

However, we found there to be major challenges in obtaining improvements in simulated streamflow discharge values when introducing additional observed data sets and their associated uncertainties into models. This result was also found in work performed in the American River basin where the California Nevada RFC lumped model provided the most accurate representation of snow cover area (Franz and Karsten, 2013). As indicated by Franz and Karsten (2013), although the gridded representation of fSCA is improved in their distributed version of SNOW17, the streamflow simulations and associated statistics did not reflect this improvement. In addition, they found that discharge values had lower skill when estimates of snow cover are included in the calibration even though it is hypothesized that the process representation is improved, which is a finding of a number of other research studies focusing on this topic (Parajka and

Blöschl, 2008; Udnæs et al., 2007). These findings are also true for Alaskan interior boreal basins, highlighting the importance of performing this work in remote and under monitored systems that are changing quickly due to climate shifts and increased occurrences of extreme events (Bennett and Walsh, 2015; Bennett et al., 2015).

The goal of this work was, in part, to undertake a simple application of inserting preprocessed MODIS fSCA into the CHPS operational framework to simulate streamflow across basins in Interior Alaska. The preprocessing of MODIS data for insertion into the model, which included the MOD10A1 and MODSCAG data products, along with the CHPS areal averaging eliminated some of the issues related to cloud cover and missing data, as noted results provided in Liu et al. (2013), who assimilated Air Force Weather Agency–National Aeronautics and Space Administration Snow Algorithm or (ANSA) fSCA data for similar stations in the region. For example, the findings in Liu et al. (2013) for the best case indicate NSE improvement for Salcha, Little Chena, and Chena at Fairbanks of 0.30, 0.31, and 0.06. Our study reports comparable NSE improvement values for some stations (Chatanika and Goodpaster) for the months impacted by the adjustments, although the Salcha and Little Chena system differences are closer to those values reported for the raw MODIS data in Liu et al.'s (2013) study. The averaging approach and use of newly developed tools (ANSA, MODSCAG) applied in both studies appear to produce slightly superior results from that of MOD10A1. Further analysis is required to determine if cloud correction processes, such as those applied in the ANSA study, would act to reduce the impact of pixel shifting that is likely a major problem in Alaska (Arsenault et al., 2014) and improve streamflow estimates further. Both studies indicate improved representation of internal snowpack and improvements in streamflow estimates for some basins, but not all, for these new iterations of the MODIS data.

Differences in the streamflow improvements provided by Liu et al. (2013) for the Salcha and Little Chena highlight some important variations between the two studies that should be considered. The first is that, as noted by the authors, the model simulated streamflow estimates are biased and thus the improvements reported in the paper are still poor representations of the streamflow (Liu et al., 2013). The question then remains that if a model result without updated observations is already skillful, how much better or improved can the model be by added information (which carries its own uncertainty with it)? Perhaps the differences between the distributed model in Liu et al. (2013) versus the lumped models used in this study are adding a buffer to the data improvements in the case of this study, and limiting the amount of difference or improvement that MODIS fSCA insertion can provide. Snow cover data appear to be improved at Interior locations within the model when compared to five different SNOTEL stations (Figure 5), particularly for the melt timing. However, the discharge values improved moderately given either MODIS input over the different periods analyzed, and in particular smaller changes are noted over the entire period of record (Table 4, Figure 8, 9). For the Chatanika basin, with limited observed data and poorer streamflow simulations however, the improvements are closer to the values shown in the Liu study. These results

Deleted: watersheds

Deleted: snow pac

Deleted: k

Deleted: is

Deleted: also

Deleted: s

suggest that skill can be added by introducing new observations when the models are performing poorly due to inadequate or low-quality records. Considering that there are numerous incomplete and low-quality gages throughout the high latitude regions of the globe, this result is of value and indicates the utility of the MODIS fSCA data in this regard.

Calibrations performed on the SACSMA model were limited in nature and targeted specifically at two parameters exhibiting the most influence on improving discharge estimates during the melt season: MFMAX and TAELEV. These parameters control the air temperature and impact snow cover depletion by either increasing or retaining melt. Previously, the APRFC parameters were set to lower MFMAX values. The TAELEV parameter was not equal to the true elevation (ELEV) and set to different values for north and south aspects. For north-facing upper elevations, TAELEV was less than ELEV so temperatures were lapsed upward to simulate the slower melt rates and cooler conditions. For south-facing aspects, TAELEV was set to greater than ELEV, so temperatures were lapsed downward to simulate increased melt from solar influence. Our updated parameterization using the MODIS data required an upward adjustment of these values because the areal depletion curve is no longer controlling the melt rate. Thus, fSCA present on northern, upper elevation slopes in the late spring must have higher melt rates applied to melt the snow with the correct timing. The primary reason that the areal depletion curves in SNOW17 differs from one that would be derived from actual measurements of fSCA is that melt rates decline as fSCA declines because the remaining snow is usually found in locations where snow melts at a slower rate, such as under canopies or on north facing slopes (Anderson, 2006).

Adjustments to MFMAX across the north sub-basin units suggest that the modified areal depletion curves within SNOW17 underestimate snow covered area. At many of the sites, particularly when using the MODSCAG product, MFMAX for the northern sites had to be increased. This suggests that the APRFC run uses a lower value that attempts to account for cooler temperatures on the northern slopes by retaining the snow on these slopes for longer, thus slowing runoff (Franz and Karsten, 2013). By more accurately representing conditions in the north sub-basin units, the MODIS simulations required an increase in the snowmelt factor to allow for initiation of the melt on these slopes. MFMAX represents the dependency between the melt factor to account for a constant fSCA curve used in the model, and the ability of the 'standard' fSCA curves used in the APRFC SNOW17 to replicate the conditions of the melt properties within the basins (Shamir and Georgakakos, 2007). As noted in Shamir and Georgakakos (2007), there is considerable inter-annual variability in snow cover depletion and this variability is not represented when the standard APRFC model is applied. Therefore, by improving the internal physical processes in the model, the snowmelt timing should improve. However, this might not translate into improved discharge estimates because precipitation and temperature inputs could still be incorrect, and errors in forcing data that generate incorrect water equivalents for snow carry larger uncertainty bounds than that which can be

Deleted: great

Deleted: SCE

Deleted: SCE

Deleted: SCE

Deleted: of the watersheds

Deleted: runs

Deleted: SCE

Deleted: ;

Deleted: SCE

addressed by changing the weighting factors and timing of snowmelt by adjusting fSCA, as undertaken in this study.

For the MOD10A1 calibration, fewer parameters were adjusted compared to the MODSCAG simulations. The end result is that the MODSCAG data have improved streamflow simulations compared to the MOD10A1 result. The model parameters require greater adjustment for MODSCAG simulations as a result of the variability between the two data sets compared to the APRFC baseline simulations. As shown in Figure 4, the MODSCAG data have a different melt trajectory for northern slopes and hold snow for longer on the south facing slopes of the Upper Chena River basin, while the MOD10A1 acts similarly to the APRFC melt trajectory for SWE data. This region is known to have variable melt timing based on south-facing slopes therefore the north and south slopes should be differentiated to reflect the physical processes occurring on the warmer south facing slopes compared to the cold, and often permafrost-dominated north facing slopes (Jones and Rinehart, 2010). Although MODSCAG improvement is noted for the Chatanika and Goodpaster basins in the streamflow statistics, the results for both MODIS versions are overall very similar in this region (Figure 8). This may be due to the different canopy adjustments applied to the data sets, or because of the lack of a spectral end member for the boreal forest in MODSCAG (Painter et al. 2009). Regardless, it is not clear that one of these data sets is markedly improving streamflow estimates and it is possible that both approaches could be considerably useful as additional observations of fSCA estimates for the region.

Two other means by which the CHPS framework can be altered to improve streamflow estimates are explored in this work. The interpolation over MODIS missing days can be altered easily in CHPS, however this had only a small effect on the streamflow results. The SCTOL, which allows for interaction between the model and the observed MODIS fSCA data, had an effect on streamflow and therefore may be a useful technique for the RFCs to apply during recalibration efforts to observed snow cover data. An advantage was noted between the MODSCAG with an SCTOL setting greater than to 0.25. However, the basins with the strongest improvement (Chatanika) over the APRFC simulation did not improve using an SCTOL greater than zero, which was because the baseline model performed so poorly given the weakness of the underlying observed discharge data. Therefore, the RFCs may wish to selectively apply this parameter when basins have reliable observed information and the MODIS data can be utilized partially in conjunction with the model ADC and partially on the MODIS fSCA observations.

5 Conclusions

Although complex tools and distributed models are available from the research community and in the CHPS system to integrate observed snow cover area data, the RFCs across the US are not, as of writing this paper, using these features in their operational river forecasting to estimate floods and droughts. This study focuses on developing tools that can, with a minor amount of testing, be brought into the RFC's CHPS modeling framework and used to improve physical estimates of fSCA across basins of interest. The method integrates information such as MODIS remotely sensed snow cover into the model framework using a simple calibration approach for the SNOW17 model, and also provides some input regarding expected improvements and other possible parameters that may be introduced to enrich forecasting and simulation of streamflow. Our recommendation it to incorporate MODIS data as an interim step, however, in the long run the RFCs should begin to use more complex models and data assimilation tools as the move towards the National Water Model proceeds.

In this work, we answer several outstanding questions regarding the application of MODIS data in the RFC models. Basins with poor-quality streamflow observations benefited from the use of the MODIS fSCA but improvements are also made to the internal snow timing estimates, observed in both the validation against SNOTEL data and also through the calibration that corrected the model parameters to better reflect the physical differences altering processes occurring on north and south facing slopes. Overall, minor differences were observed between MOD10A1 and MODSCAG data, however the MODSCAG data provided improvement over MOD10A1 when considering average changes to streamflow simulations were observed in all basins. We observed limited impact of changing the interpolation length between missing days, although adjustments based on altering the interaction between the model and the observed MODIS fSCA data did alter streamflow and therefore are useful during recalibration efforts.

The utility of the MODIS data in CHPS goes beyond improvements to the streamflow; these tools can be used for a number of internal checks for SWE and fSCA that are currently under way, such as the ingestion of data for ensemble forecasts (NWS, 2012). This study opens the door for insertion of parameters via assimilation alongside developments such as physically-based model usage.

The observations of rapid change in the Arctic highlight important alterations to hydrological regimes in the subarctic Interior boreal forest of Alaska. These observed, rapid changes, and future anticipated alterations introduce a pressing need in Alaska to further understand the anticipated changes through modeling of major climate drivers of streamflow. The sparse observational network in Alaska, along with the magnitude and rate of change necessitates the use of robust modeling tools to examine these changes and their impacts on hydrology. However, due to the limited high-quality observations, and our lack of understanding of Arctic hydrologic processes (Woo et al., 2008; Prowse et al., 2016), process-based modeling approaches are limited in this environment. Therefore, we must apply available conceptual models with calibrations informed by observations, including remote sensing tools of SWE and fSCA to examine these effects. In this way, we will be able to define and quantify increasing impacts associated with these changes that lead to multi-scale risk to hydro-ecological systems, not only to the local and state resources, but also regionally and globally.

6 Acknowledgements

Bennett acknowledges support for this work from the Alaska Climate Science Center, the Natural Science and Engineering Research Council of Canada, and the DOE Office of Science, Biological and Environmental Research program, Next Generation Ecosystem Experiment, NGEE-Arctic, project. Bennett, Balk, and Cherry acknowledge support from the GOES-R High Latitude Proving Ground award NA08OAR432075. The authors thank the Alaska Pacific River Forecast Center staff for their collaborative efforts and the Arctic Region Supercomputer Center for the use of their supercomputer.

Formatted: Heading 1

Deleted: and

Deleted: National

Deleted: .

Deleted:

7 References

Anderson, E. A.: Calibration of conceptual hydrologic models for use in river forecasting. Office of Hydrologic Development, US National Weather Service, Silver Spring, MD. http://140.90.113.200/oh/hrl/modelcalibration/1.%20Calibration%20Process/1_Anderson_CalbManual.pdf, last access: 17 Aug 2018, pp 372, 2002.

Anderson, E. A.: Snow Accumulation and Ablation Model - SNOW-17. http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/part2/_pdf/22snow17.pdf, Nat. Weather Serv. NOAA, last access: 17 Aug 2018, pp. 44, 2006.

Anderson, E. A., 1976. A point energy and mass balance model of a snow cover. NOAA Tech. Rep. NWS 19, Office of Hydrology, National Weather Service, Silver Spring, MD, 150 pp.

Andreadis, K. M., and Lettenmaier, D. P.: Assimilating remotely sensed snow observations into a macroscale hydrology model, Adv. in Water Res., 29, 872-886, https://doi.org/10.1016/j.advwatres.2005.08.004, 2006.

Bennett, K. E., and Walsh, J.: Spatial and temporal changes in indices of extreme precipitation and temperature for Alaska. Int. J. Climatol., 35, 1434–1452, https://doi.org/10.1002/joc.4067, 2015.

Bennett, K. E., Cannon, A. J., and Hinzman, L.: Historical trends and extremes in boreal Alaska river basins, J. Hydrol., 527, 590-607, https://doi.org/10.1016/j.jhydrol.2015.04.065, 2015.

Burnash, R. J. E., Ferral, R. L., and McGuire, R. A.: A generalized streamflow simulation system, Joint Federal-State River Forecast Center, Sacramento, CA, pp. 204, 1973.

Clark, M. P., Hendrikx, J., Slater, A. G., Kavetski, D., Anderson, B., Cullen, N. J., Kerr, T., Hreinsson, E. Ö. and Woods, R.A: Representing spatial variability of snow water equivalent in hydrologic and land-surface models: A review. Water Resour. Res., 47, 1-23, https://doi.org/10.1029/2011WR010745, 2011.

Cherry, J. E., Knapp, C., Trainor, S., Ray, A. J., Tedesche, M., and Walker, S.: Planning for climate change impacts on hydropower in the Far North, Hydrol. Earth Syst. Sci., 21, 133-151, doi:10.5194/hess-21-133-2017, 2017.

Deleted: ,…2002. ... [1]

Formatted: Font: Not Italic

Deleted: … last access: 17 Aug 2018, Accessed August 17th, 2018. …p 372, 2002.. ... [2]

Deleted: , 2006. …now Accumulation and Ablation Model - SNOW-17. http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/part2/_pdf/22snow17.pdf, Nat. Weather Serv. S ... [3]

Moved down [1]: pp. 44.

Moved (insertion) [1]

Deleted: .

Formatted: Not Highlight

Deleted: ,…2006. …ssimilating remotely sensed snow observations into a macroscale hydrology model,….Adv.vances…in Waterer…Res.sources… 299 (6)… ... [4]

Deleted: .

Deleted: ,…2015. …patial and temporal changes in indices of extreme precipitation and temperature for Alaska. Int. J. Climatol.International Journal of Climatology… 35,:…1434–1452,….DOI…https://doi.org/10.1002/joc.4067, 2015.: 10.1002/joc.4067. ... [5]

Deleted: ,…2015. …istorical trends and extremes in boreal Alaska river basins,….J. Hydrol., Journal of Hydrology, 527,:…590-607,….https://doi.org/10.1016/j.jhydrol.2015.04.065DOI:10.1016/j.jhydrol.2015.04.065…. ... [6]

Deleted: ,…1973. … generalized streamflow simulation system, Joint Federal-State River Forecast Center, Sacramento, CA, pp. 204, 1973.. ... [7]

Deleted: ., 2011.…Representing spatial variability of snow water equivalent in hydrologic and land-surface models: A review. Water Resour. Res.Water Resources Research ... [8]

Deleted: (7)… 1-23, ... [10]

Formatted ... [9]

Formatted: Not Highlight

Deleted: , 2017.…Planning for climate change impacts on hydropower in the Far North, Hydrol. Earth Syst. Sci.Hydrology and Earth System Sciences ... [11]

Formatted: Not Highlight

Deleted: .

Cherry, J. E., Tremblay, L. B., Déry, S. J., and Stieglitz, M.: Reconstructing solid precipitation from snow depth measurements and a land surface model, Water Resour. Res., 41, 1-15, https://doi.org/10.1029/2005WR003965, 2005.

Cherry, J. E., Tremblay, L. B., Stieglitz, M., Gong, G., and Déry, S. J.: Development of the pan-arctic snowfall reconstruction: new land-based solid precipitation estimates for 1940-99, J. Hydrometeorol., 8, 1243-1263, https://doi.org/10.1175/2007JHM765.1, 2007.

Clark, M. P., Slater, A. G., Barrett, A. P., Hay, L. E., McCabe, G. J., Rajagopalan, B., and Leavesley, G. H.: Assimilation of snow covered area information into hydrologic and land-surface models. Adv. in Water Res., 29, 1209-1221, https://doi.org/10.1016/j.advwatres.2005.10.001, 2006.

Clark, M. P., Bierkens, M. F., Samaniego, L., Woods, R. A., Uijlenhoet, R., Bennett, K. E., Pauwels, V. R., Cai, X., Wood, A. W., and Peters-Lidard, C. D.: The evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism, Hydrology and Earth System Sciences, 21, 3427-3440, https://doi.org/10.5194/hess-21-3427-2017, 2017.

Cooley, S. W., and Pavelsky, T. M.: Spatial and temporal patterns in Arctic river ice breakup revealed by automated ice detection from MODIS imagery, Remote Sens. Environ., 175, 310-322, https://doi.org/10.1016/j.rse.2016.01.004, 2016.

Cohen, J. L., Furtado, J. C., Barlow, M. A., Alexeev, V. A., and Cherry, J. E.: Arctic warming, increasing snow cover and widespread boreal winter cooling, Environ. Res. Lett., 7, 014007, 1-8, https://doi.org/10.1088/1748-9326/7/1/0140072012, 2012.

Déry, S. J., Salomonson, V. V., Stieglitz, M., Hall, D. K., and Appel, I.: An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modelling in Alaska, Hydrol. Proc., 19, 2755-2774, https://doi.org/10.1002/hyp.5784, 2005.

Dozier, J., Painter, T. H., Rittger, K. and Frew, J. E.: Time-space continuity of daily maps of fractional snow cover and albedo from MODIS, Adv. in Water Res., 31, 1515-1526, https://doi.org/10.1016/j.advwatres.2008.08.011, 2008.

Durand, M., Molotch, N. P., Margulis, S. A.: Merging complementary remote sensing datasets in the context of snow water equivalent reconstruction, Remote Sens. Environ., 112, 1212-1225, https://doi.org/10.1016/j.rse.2007.08.010, 2008.

Deleted: ., 2005
Formatted: Not Highlight
Formatted: Not Highlight
Deleted: Water Resources Research
Formatted: Not Highlight
Field Code Changed
Deleted: .
Formatted: Highlight
Deleted: Dery… S. J.:,…2007. …evelopment of the pan-arctic snowfall reconstruction: new land-based solid precipitation estimates for 1940-99, Journal …. Hydrometeorol.of Hydrometeorology… 8, 1243-1263, https://doi.org/10.1175/2007JHM765.1Doi 10.1175/2007jhm765.1… 2007..… ... [12]
Deleted: ,…2006. …ssimilation of snow covered area information into hydrologic and land-surface models. Adv. in Water Res.Advances in Water Resources… 29,9 (8):…1209-1221, https://doi.org/10.1016/j.advwatres.2005.10.001, 2006. ... [13]
Moved down [8]: M. F.
Moved (insertion) [8]
Deleted: L.
Moved down [9]: R. A.
Deleted: R.
Moved down [10]: K. E.
Moved (insertion) [10]
Moved down [11]: V. R.
Moved (insertion) [9]
Moved (insertion) [11]
Deleted: X. …ai, A. W…X., ... [14]
Formatted: Not Highlight
Deleted: and C. D.
Formatted: Not Highlight
Deleted: ,…2017. …he evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism, Hydrology and Earth System Sciences, 21(7)… 3427-3440, https://doi.org/10.5194/hess-21-3427-2017, 2017.3427 ... [15]
Deleted: ,…2016. …patial and temporal patterns in Arctic river ice breakup revealed by automated ice detection from MODIS imagery, Remote Sens. Environ.Remote Sensing of Environment… 175, 310-322, https://doi.org/10.1016/j.rse.2016.01.004,. ... [16]
Deleted: ,…2012. …rctic warming, increasing snow cover and widespread boreal winter cooling, Environ. Res. Lett.Environmental Research Letters… 7, 014007, 1-8, https://doi.org/10.1088/1748-9326/7/1/0140072012, 2012.. ... [17]
Deleted: ,…2008. …ime-space continuity of daily maps of ... [18]
Deleted: ,…2008. …erging complementary remote sensing ... [19]

Duethmann, D., Peters, J., Blume, T., Vorogushyn, S., and Güntner, A.: The value of satellite-derived snow cover images for calibrating a hydrological model in snow-dominated catchments in Central Asia, Water Resour. Res., 50, 2002-2021. doi:10.1002/2013WR014382, 2014.

Dwyer, J. and Schmidt, G.: The MODIS reprojection too, in Earth Science Satellite Remote Sensing, Springer, Berlin, Heidelberg, Germany, 162-177, 2006.

Euskirchen, E., McGuire, A., Chapin III, F., Yi, S., and Thompson, C.: Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks, Ecol. Appl., 19, 1022-1043, https://doi.org/10.1890/08-0806.1, 2009.

Franz, K. J., Hogue, T. S., and Sorooshian, S.: Operational snow modeling: Addressing the challenges of an energy balance model for National Weather Service forecasts, J. Hydrol., 360 (1–4), 48-66, https://doi.org/10.1016/j.jhydrol.2008.07.013, 2008.

Franz, K. J. and Karsten, L. R.: Calibration of a distributed snow model using MODIS snow covered area data. J. Hydrol., 494, 160-175, https://doi.org/10.1016/j.jhydrol.2013.04.026, 2013.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D.: The National Elevation Dataset, Photogramm. Eng. Remote Sens., 68, 5–11, 2002.

Groisman, P. Y., Bogdanova, E., Alexeev, V., Cherry, J., and Bulygina, O.: Impact of snowfall measurement deficiencies on quantification of precipitation and its trends over northern Eurasia, Ice Snow, 54, 29-43, https://doi.org/10.15356/2076-6734-2014-2-29-43, 2014.

Hall, D. K., and Riggs, G. A.: Accuracy assessment of the MODIS snow product, Hydrol. Process., 21, 1534-1547, https://doi.org/10.1002/hyp.6715, 2007.

Hall, D. K., Riggs, G. A., and Salomonson, V. V.: MODIS/Terra Snow Cover Daily L3 Global 500m Grid V005, 2000-Daily Updates, National Snow and Ice Data Center, Boulder, Colorado USA, 2006.

Hall, D. K., Riggs, G. A., Salomonson, V. V., DiGirolamo, N. E., and Bayr, K. J.: MODIS snow-cover products. Remote Sens. Environ., 83, 181-194, https://doi.org/10.1016/S0034-4257(02)00095-0, 2002.

He, M., Hogue, T. S., Franz, K. J., Margulis, S. A., and Vrugt, J. A.: Characterizing parameter sensitivity and uncertainty for a snow model across hydroclimatic regimes, Adv. in Water Res., 34 (1): 114-127, https://doi.org/10.1016/j.advwatres.2010.10.002, 2011.

Deleted: &…Güntner, A.: 2014. …he value of satellite-derived snow cover images for calibrating a hydrological model in snow-dominated catchments in Central Asia, . …ater Resour. Res.Water Resources Research… 50(3) ... [20]

Deleted: ,…2006. …he MODIS reprojection too, il. I ... [21]

Deleted: .…Springer, Berlin, Heidelberg, Germany,.… pp. 162-177,.… ... [22]

Formatted: Font: Not Italic

Deleted: ¶ Euskirchen, E., McGuire, A., Chapin III, F., Yi, S., and Thompson, C.:,…2009. …hanges in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks, . …col. Appl., 19, (4):…1022-1043,.… ... [23]

Deleted: ,…2008. …perational snow modeling: Addressing the challenges of an energy balance model for National Weather Service forecasts,.…J. Hydrol.Journal of Hydrology… 360 (1–4),:…48-66,.… ... [24]

Moved down [2]: 2013.

Deleted: L. R. …arsten, L. R.:. ... [25]

Deleted: Journal of Hydrology. …94, :…60-175,. ... [26]

Moved (insertion) [2]

Deleted: M. …imoen, M., S. …reenlee, S., C. …elson, C., M. Steuck, M., and D. …yler, D. (2002),… …he National Elevation Elevation Dataset, Photogramm. Eng. Remote Sens., 68, 5–11 ... [27]

Deleted: ,…2014. …mpact of snowfall measurement deficiencies on quantification of precipitation and its trends over northern Eurasia, Lëd i Sneg…ce Snow, 5454… 29-43, https://doi.org/10.15356/2076-6734-2014-2-29-43, 2014.3… ... [28]

Deleted: ,…2007. …ccuracy assessment of the MODIS snow product, s… Hydrol. Process., 21, (12):…1534-1547, https://doi.org/10.1002/hyp.6715, ... [29]

Deleted: ,…2006. …ODIS/Terra Snow Cover Daily L3 Global 500m Grid V005, 2000-Daily Updates,.…National Snow and Ice Data Center, Boulder, Colorado USA, 2006.. ... [30]

Deleted: ,…2002. …ODIS snow-cover products. Remote Sens. Environ., 83, (1):…181-194, https://doi.org/10.1016/S0034-4257(02)00095-0, 2002.. ... [31]

Deleted: ,…2011. …haracterizing parameter sensitivity and uncertainty for a snow model across hydroclimatic regimes,.…Adv. in Water Res.Advances in Water Resources… 34 (1): 114-127, https://doi.org/10.1016/j.advwatres.2010.10.002, 2011.. ... [32]

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntinton, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F. E., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K. S., and Yoshikawa, K.: Evidence and implications of recent climate change in northern Alaska and other Arctic regions, Clim. Change, 72, 251-298, DOI: 10.1007/s10584-005-5352-2, 2005.

Hinzman, L. D., Deal, C. J., McGuire, A. D., Mernild, S. H., Polyakov, I. V., and Walsh, J. E.: Trajectory of the Arctic as an integrated system, Ecol. Appl., 23, 1837-1868, doi:10.1890/11-1498.1, 2013.

Hock, R.: Temperature index melt modelling in mountain areas. J. Hydrol., 282: 104-115, https://doi.org/10.1016/S0022-1694(03)00257-9, 2003.

Huntington, T. G.: Evidence for intensification of the global water cycle: review and synthesis. J. Hydrol., 319, 83-95, https://doi.org/10.1016/j.jhydrol.2005.07.003, 2006.

Instanes, A., Kokorev, V., Janowicz, R., Bruland, O., Sand, K. and Prowse, T.: Changes to freshwater systems affecting Arctic infrastructure and natural resources, J. Geophys. Res. Biogeosci., 121, 567-585, https://doi.org/10.1002/2015JG003125, 2016.

Jones, J. B., and Rinehart, A. J.: The long-term response of stream flow to climatic warming in headwater streams of interior Alaska, Can. J. Forest Res., 40, 1210-1218, 2010.

Kane, V. R., Gillespie, A. R., McGaughey, R., Lutz, J. A., Ceder, K., and Franklin, J. F.: Interpretation and topographic compensation of conifer canopy self-shadowing, Remote Sens. Environ., 112, 3820-3832, https://doi.org/10.1016/j.rse.2008.06.001, 2008.

Koven C. D., Riley W. J., and Stern, A.: Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth system models, J. Clim., 26, 1877–900, https://doi.org/10.1175/JCLI-D-12-00228.1, 2013.

Lesack, L. F. W., Marsh, P., Hicks, F. E., and Forbes, D. L.: Local spring warming drives earlier river-ice breakup in a large Arctic delta, Geophys. Res. Lett., 41, 1560-1567, 10.1002/2013GL058761, 2014.

Deleted: ,…2005. …vidence and implications of recent climate change in northern Alaska and other Arctic regions,…Clim. Change, 72,:…251-298, DOI: 10.1007/s10584-005-5352-2, 2005.… ... [33]
Moved down [3]: C. J.
Moved down [4]: S. H.
Moved down [5]: I. V.
Moved (insertion) [5]
Deleted:
Moved down [6]: J. E.
Moved (insertion) [3]
Moved (insertion) [4]
Deleted: A. D.
Moved (insertion) [6]
Deleted:
Deleted: ….2013. …rajectory of the Arctic as an integrated system, Ecol. Appl., 23(8)… 1837-1868, doi:10.1890/11-1498 ... [34]
Deleted: ,…2003. …emperature index melt modelling in mountain areas. J. Hydrol.Journal of Hydrology… 282: 104-115 ... [35]
Deleted: ,…2006. …vidence for intensification of the global ... [36]
Formatted ... [37]
Deleted: (1)… pp.…3-95, ... [38]
Deleted: V. …okorev, V., R. …anowicz, R., O. …ruland, O ... [39]
Moved down [7]: 2016.
Deleted: Journal of Geophysical Research: Biogeosciences
Formatted ... [40]
Deleted: (3)
Moved (insertion) [7]
Deleted: doi:10.1002/2015JG003125.
Deleted: ,…2010. …he long-term response of stream flow to ... [41]
Deleted: -Revue Canadienne De Recherche Forestiere
Deleted: (7): …210-1218, 2010.. ... [42]
Deleted: ,…2008. …nterpretation and topographic ... [43]
Deleted: Koven, C. D., Schuur, E., Schädel, C., Bohn, T. ... [44]
Formatted ... [45]
Deleted: 2013a
Formatted ... [46]
Formatted: Font: Not Bold, Not Italic
Formatted: Font: Not Italic
Deleted: .
Formatted: Font: Not Italic
Deleted: Geophysical Research Letters,

Liu, J., Melloh, R.A., Woodcock, C.E., Davis, R.E., and Ochs, E.S.: The effect of viewing geometry and topography on viewable gap fractions through forest canopies. Hydrol. Process., 18, 3595-3607, https://doi.org/10.1002/hyp.5802, 2004.

Liu, Y., Peters-Lidard, C. D., Kumar, S., Foster, J. L., Shaw, M., Tian, Y., and Fall, G. M., Assimilating satellite-based snow depth and snow cover products for improving snow predictions in Alaska, Adv. in Water Res., 54, 208-227, doi:http://dx.doi.org/10.1016/j.advwatres.2013.02.005, 2013.

Liu, J., Woodcock, C.E., Melloh, R.A., Davis, R.E., McKenzie, C., and Painter, T.H.: Modeling the view angle dependence of gap fractions in forest canopies: Implications for mapping fractional snow cover using optical remote sensing. J. Hydrometeorol., 9, 1005-1019, https://doi.org/10.1175/2008JHM866.1, 2008.

Magnusson, J., Wever, N., Essery, R., Helbig, N., Winstral, A., and Jonas, T.: Evaluating snow models with varying process representations for hydrological applications, Water Resour. Res., 51, 2707-2723, https://doi.org/10.1002/2014WR016498, 2015.

McGuire, M., Wood, A. W., Hamlet, A. F., and Lettenmaier, D. P.: Use of satellite data for streamflow and reservoir storage forecasts in the Snake River Basin. Journal of Water Resources Planning and Management, 132, 97-1109, https://doi.org/10.1061/(ASCE)0733-9496(2006)132:2(97), 2006.

Molotch, N. P., and Bales, R. C.: Scaling snow observation from the point to the grid element: Implications for observation network design. Water Resour. Res., 41: 1-16, https://doi.org/10.1029/2005WR004229, 2005.

Molotch, N. P., and Margulis, S. A.: Estimating the distribution of snow water equivalent using remotely sensed snow cover data and a spatially distributed snowmelt model: A multi-resolution, multi-sensor comparison. Adv. in Water Res., 31, 1503-1514, https://doi.org/10.1016/j.advwatres.2008.07.0172008.

Morriss, B. F., Ochs, E., Deeb, E. J., Newman, S. D., Daly, S. F. and Gagnon, J. J.: Persistence-based temporal filtering for MODIS snow products, Remote Sens. Environ., 175: 130-137, https://doi.org/10.1016/j.rse.2015.12.030, 2016.

Muhammad, P., Duguay, C., and Kang, K.-K.: Monitoring ice break-up on the Mackenzie River using MODIS data, The Cryosphere, 10, 569-584, https://doi.org/10.5194/tc-10-569-2016, 2016.

NOAA. 2017. NOAA National Water Model: Improving NOAA's Water Prediction Services. http://water.noaa.gov/documents/wrn-national-water-model.pdf. 2 pp., last access: 1 December 2018.

NWS. 2012. Overview of the Hydrologic Ensemble Forecast Service (HEFS). http://www.nws.noaa.gov/os/water/RFC_support/HEFS_doc/HEFS_Overview_0.1.2.pdf. Office of Hydrologic Development. 34 pp, last access: 1 December, 2018.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., and Jennings, A.: Arctic environmental change of the last four centuries. Science, 278 1251-1256, DOI: 10.1126/science.278.5341.1251, 1997.

Painter, T.H., Rittger, K., McKenzie, C., Slaughter, P., Davis, R.E., and Dozier, J.: Retrieval of subpixel snow covered area, grain size, and albedo from MODIS. Remote Sens. Environ., 113, 868-879, https://doi.org/10.1016/j.rse.2009.01.001, 2009.

Parajka, J., and Blöschl, G.: The value of MODIS snow cover data in validating and calibrating conceptual hydrologic models. J. Hydrol., 358, 240-258, https://doi.org/10.1016/j.jhydrol.2008.06.006, 2008.

Prowse, T., Bring, A., Mård, J., Carmack, E., Holland, M., Instanes, A., Vihma, T., and Wrona, F.: Arctic Freshwater Synthesis: Summary of key emerging issues, J. Geophys. Res. Biogeosci., 120, 1887-1893, https://doi.org/10.1002/2015JG003128 2015.

Raleigh, M. S., Rittger, K., Moore, C. E., Henn, B., Lutz, J. A., and Lundquist, J. D.: Ground-based testing of MODIS fractional snow cover in subalpine meadows and forests of the Sierra Nevada. Remote Sens. Environ., 128, 44-57, https://doi.org/10.1016/j.rse.2012.09.016, 2013.

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., and Seo, D.-J.: Overall distributed model intercomparison project results. J. Hydrol., 298, 27-60, https://doi.org/10.1016/j.jhydrol.2004.03.031, 2004.

Riggs, G. A., Hall, D. K., and Salomonson., V.V.: MODIS Snow Products User Guide to Collection 5 http://modis-snow-ice.gsfc.nasa.gov/?c=userguides, 80pp, last access: 1 December 2018, 2006.

Rittger, K., Painter, T. H., and Dozier, J.: Assessment of methods for mapping snow cover from MODIS. Adv. in Water Res., 51, 367-380, https://doi.org/10.1016/j.advwatres.2012.03.002, 2013.

Rodell, M., Houser, P., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., and Toll, D.: The global land data assimilation system. B. Am. Meteorol. Soc., 85, 381-394, https://doi.org/10.1175/BAMS-85-3-381, 2004.

Salomonson, V., and Appel, I.: Estimating fractional snow cover from MODIS using the normalized difference snow index. Remote Sens. Environ., 89, 351-360, https://doi.org/10.1016/j.rse.2003.10.016, 2004.

Serreze, M. C., and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis. Global Planet. Change, 77, 85-96, https://doi.org/10.1016/j.gloplacha.2011.03.004, 2011.

Serreze, M. C., and Francis, J. A.: The Arctic amplification debate. Clim. Change, 76, 241-264, DOI: 10.1007/s10584-005-9017-y, 2006.

Serreze, M. C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison, J., Zhang, T., and Barry, R. G.: Observational evidence of recent change in the northern high-latitude environment. Clim. Change, 46, 159-207, https://doi.org/10.1023/A:1005504031923, 2000.

Shamir, E., and Georgakakos, K. P.: Estimating snow depletion curves for American River basins using distributed snow modeling, J. Hydrol., 334, 162-173, 10.1016/j.jhydrol.2006.10.007, 2007.

Slater, A. G., and Lawrence, D. M., Diagnosing present and future permafrost from climate models, J. Clim., 26, 5608-5623, https://doi.org/10.1175/JCLI-D-12-00341.1, 2013.

Stahl, K., Moore, R. D., Floyer, J. A., Asplin, M. G., and McKendry, I. G.: Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density. Agr. and For. Met., 139: 224-236, https://doi.org/10.1016/j.agrformet.2006.07.004, 2006.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Climate Change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5), Cambridge Univ Press, New York, https://www.ipcc.ch/report/ar5/wg1/, last access: 1 December 2018, 2013.

Deleted: e.a.
Deleted: , 2004.
Deleted: (3).
Field Code Changed
Deleted: , 2004.
Deleted: (3):
Deleted: .
Deleted: , 2011.
Deleted: (1–2)
Deleted: :
Deleted: .
Deleted: ,
Deleted: 2006.
Deleted: (3-4):
Deleted: .
Deleted: ,
Deleted: 2000.
Deleted: (1-2):
Deleted: .
Deleted: ,
Deleted: 2007.
Deleted: Journal of Hhydrology,
Deleted: .
Deleted: 2013.
Deleted: Journal of Climate
Deleted: .
Deleted: ,
Deleted: 2006.
Deleted: ricultural
Deleted: est
Deleted: eorology
Deleted: .
Deleted: 2013.
Deleted: c
Deleted: (
Deleted:)
Deleted: .

Stuefer, S. L., Arp, C. D., Kane, D. L., and Liljedahl, A. K.: Recent extreme runoff observations from Coastal Arctic watersheds in Alaska, Water Resour. Res., 53, 9145-9163, https://doi.org/10.1002/2017WR020567, 2017.

Sturm, M., Goldstein, M. A., and Parr, C.: Water and life from snow: A trillion dollar science question, Water Resour. Res., 53, 3534-3544, https://doi.org/10.1002/2017WR020840, 2017.

Sun, C., Walker, J. P., and Houser, P. R.: A methodology for snow data assimilation in a land surface model. J. Geophys. Res.: Atmos., 109, D08108, 1-12, https://doi.org/10.1029/2003JD003765 2004.

Tan, B., Woodcock, C. E., Hu, J., Zhang, P., Ozdogan, M., Huang, D., Yang, W., Knyazikhin, Y. and Myneni, R. B.: The impact of gridding artifacts on the local spatial properties of MODIS data: Implications for validation, compositing, and band-to-band registration across resolutions. Remote Sens. Environ., 105, 98-114, https://doi.org/10.1016/j.rse.2006.06.008, 2006.

Thirel, G., Salamon, P., Burek, P., and Kalas, M.: Assimilation of MODIS Snow Cover Area Data in a Distributed Hydrological Model Using the Particle Filter. Remote Sens., 5, 5825-5850, DOI: 10.3390/rs5115825, 2013.

Udnæs, H., Alfnes, E., and Andreassen, L. M.: Improving runoff modelling using satellite-derived snow covered area? Hydrol. Res., 38, 21-32, https://doi.org/10.2166/nh.2007.032, 2007.

Werner, M., Schellekens, J., Gijsbers, P., Van Dijk, M., Van den Akker, O., and Heynert, K.: The Delft-FEWS flow forecasting system. Environ. Model. Software, 40, 65-77, https://doi.org/10.1016/j.envsoft.2012.07.010 2013.

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mård, J., Myers-Smith, I. H., Prowse, T. D., Vincent, W. F., and Wookey, P. A.: Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime, J. Geophys. Res. Biogeosci., 121, 650-674, 10.1002/2015JG003133, 2016.

Woo, M. K., Thorne, R., Szeto, K., and Yang, D.: Streamflow hydrology in the boreal region under the influences of climate and human interference. Philos. Trans. R. Soc. Lond. B. Biol. Sci., 363, 2249-2258, doi: 10.1098/rstb.2007.2197, 2008.

Deleted: E
Deleted: R
Deleted: O
Deleted: F
Deleted: W
Deleted: Water Resources Research
Deleted: 10.1002/2017WR020567
Deleted: Water Resources Research
Deleted: , 2004.
Deleted: (D8)
Deleted: :
Deleted: .
Deleted: ,
Deleted: 2006.
Deleted: Remote Sensing of Environment
Deleted: (2):
Deleted: .
Deleted: &
Moved down [13]: 2013.
Deleted: sing
Deleted: (11):
Deleted: . Retrieved from http://www.mdpi.com/2072-4292/5/11/5825…
Moved (insertion) [13]
Deleted: ,
Deleted: 2007.
Deleted: Nordic Hydrology
Deleted: (1):
Field Code Changed
Deleted: .
Deleted: ,
Deleted: 2013.
Deleted: :
Deleted: .
Deleted: Journal of Geophysical Research: Biogeosciences
Deleted: ,
Deleted: 2008a.
Deleted: Philosophical Transactions of the Royal Society B: Biological Sciences
Deleted: (1501):
Deleted: .

Zaitchik, B., and Rodell, M.: Forward-looking assimilation of MODIS-derived snow-covered area into a land surface model. J. Hydrometeorol., 10, 130–148, https://doi.org/10.1175/2008JHM1042.1, 2009.

Deleted: ;

Deleted: 2009.

Deleted: :

Deleted: .

Page 21: [1] Deleted	Microsoft Office User	11/26/18 11:09:00 AM

Page 21: [1] Deleted	Microsoft Office User	11/26/18 11:09:00 AM

Page 21: [2] Deleted	Microsoft Office User	11/26/18 11:11:00 AM

Page 21: [2] Deleted	Microsoft Office User	11/26/18 11:11:00 AM

Page 21: [2] Deleted	Microsoft Office User	11/26/18 11:11:00 AM

Page 21: [3] Deleted	Microsoft Office User	11/26/18 11:11:00 AM

Page 21: [3] Deleted	Microsoft Office User	11/26/18 11:11:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [4] Deleted	Microsoft Office User	11/26/18 11:20:00 AM

Page 21: [5] Deleted	Microsoft Office User	11/26/18 11:41:00 AM

Page 21: [5] Deleted	**Microsoft Office User**	**11/26/18 11:41:00 AM**

Page 21: [5] Deleted	**Microsoft Office User**	**11/26/18 11:41:00 AM**

Page 21: [5] Deleted	**Microsoft Office User**	**11/26/18 11:41:00 AM**

Page 21: [5] Deleted	**Microsoft Office User**	**11/26/18 11:41:00 AM**

Page 21: [5] Deleted	**Microsoft Office User**	**11/26/18 11:41:00 AM**

Page 21: [5] Deleted	**Microsoft Office User**	**11/26/18 11:41:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [6] Deleted	**Microsoft Office User**	**11/26/18 11:37:00 AM**

Page 21: [7] Deleted	**Microsoft Office User**	**11/26/18 11:42:00 AM**

Page 21: [7] Deleted	**Microsoft Office User**	**11/26/18 11:42:00 AM**

Page 21: [7] Deleted	**Microsoft Office User**	**11/26/18 11:42:00 AM**

Page 21: [8] Deleted	**K.E. Bennett**	**11/26/18 11:49:00 AM**

Page 21: [8] Deleted	**K.E. Bennett**	**11/26/18 11:49:00 AM**

Page 21: [9] Formatted	**K.E. Bennett**	**11/26/18 11:46:00 AM**

Font: Not Italic

Page 21: [9] Formatted	**K.E. Bennett**	**11/26/18 11:46:00 AM**

Font: Not Italic

Page 21: [10] Deleted	**K.E. Bennett**	**11/26/18 11:47:00 AM**

Page 21: [10] Deleted	**K.E. Bennett**	**11/26/18 11:47:00 AM**

Page 21: [11] Deleted	**K.E. Bennett**	**11/26/18 11:49:00 AM**

Page 21: [11] Deleted	**K.E. Bennett**	**11/26/18 11:49:00 AM**

Page 22: [12] Deleted	**K.E. Bennett**	**12/1/18 5:25:00 PM**

Page 22: [12] Deleted	**K.E. Bennett**	**12/1/18 5:25:00 PM**

Page 22: [12] Deleted	**K.E. Bennett**	**12/1/18 5:25:00 PM**

Page 22: [12] Deleted	**K.E. Bennett**	**12/1/18 5:25:00 PM**

Page 22: [12] Deleted	**K.E. Bennett**	**12/1/18 5:25:00 PM**

Page 22: [12] Deleted	K.E. Bennett	12/1/18 5:25:00 PM

Page 22: [12] Deleted	K.E. Bennett	12/1/18 5:25:00 PM

Page 22: [13] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [13] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [13] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [13] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [13] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [14] Deleted	K.E. Bennett	12/1/18 5:54:00 PM

Page 22: [14] Deleted	K.E. Bennett	12/1/18 5:54:00 PM

Page 22: [14] Deleted	K.E. Bennett	12/1/18 5:54:00 PM

Page 22: [15] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [15] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [15] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [15] Deleted	K.E. Bennett	11/26/18 12:17:00 PM

Page 22: [16] Deleted	K.E. Bennett	11/26/18 12:23:00 PM

Page 22: [16] Deleted	K.E. Bennett	11/26/18 12:23:00 PM

Page 22: [16] Deleted	K.E. Bennett	11/26/18 12:23:00 PM

Page 22: [16] Deleted	K.E. Bennett	11/26/18 12:23:00 PM

Page 22: [17] Deleted	K.E. Bennett	11/26/18 12:29:00 PM

Page 22: [17] Deleted	K.E. Bennett	11/26/18 12:29:00 PM

Page 22: [17] Deleted	K.E. Bennett	11/26/18 12:29:00 PM

Page 22: [17] Deleted	K.E. Bennett	11/26/18 12:29:00 PM

Page 22: [18] Deleted	K.E. Bennett	11/26/18 1:04:00 PM

Page 22: [18] Deleted	K.E. Bennett	11/26/18 1:04:00 PM

Page 22: [18] Deleted	K.E. Bennett	11/26/18 1:04:00 PM

Page 22: [18] Deleted	K.E. Bennett	11/26/18 1:04:00 PM

Page 22: [18] Deleted	K.E. Bennett	11/26/18 1:04:00 PM

Page 22: [18] Deleted	K.E. Bennett	11/26/18 1:04:00 PM

Page 22: [19] Deleted	K.E. Bennett	11/26/18 1:12:00 PM

Page 22: [19] Deleted	K.E. Bennett	11/26/18 1:12:00 PM

Page 22: [19] Deleted	K.E. Bennett	11/26/18 1:12:00 PM

Page 22: [19] Deleted	K.E. Bennett	11/26/18 1:12:00 PM
Page 22: [19] Deleted	K.E. Bennett	11/26/18 1:12:00 PM
Page 23: [20] Deleted	K.E. Bennett	11/26/18 1:15:00 PM
Page 23: [20] Deleted	K.E. Bennett	11/26/18 1:15:00 PM
Page 23: [20] Deleted	K.E. Bennett	11/26/18 1:15:00 PM
Page 23: [20] Deleted	K.E. Bennett	11/26/18 1:15:00 PM
Page 23: [20] Deleted	K.E. Bennett	11/26/18 1:15:00 PM
Page 23: [21] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [21] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [21] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [22] Deleted	K.E. Bennett	11/26/18 2:07:00 PM
Page 23: [22] Deleted	K.E. Bennett	11/26/18 2:07:00 PM
Page 23: [22] Deleted	K.E. Bennett	11/26/18 2:07:00 PM
Page 23: [22] Deleted	K.E. Bennett	11/26/18 2:07:00 PM
Page 23: [23] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [23] Deleted	K.E. Bennett	11/26/18 1:39:00 PM

Page 23: [23] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [23] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [23] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [23] Deleted	K.E. Bennett	11/26/18 1:39:00 PM
Page 23: [24] Deleted	K.E. Bennett	11/26/18 1:51:00 PM
Page 23: [24] Deleted	K.E. Bennett	11/26/18 1:51:00 PM
Page 23: [24] Deleted	K.E. Bennett	11/26/18 1:51:00 PM
Page 23: [24] Deleted	K.E. Bennett	11/26/18 1:51:00 PM
Page 23: [24] Deleted	K.E. Bennett	11/26/18 1:51:00 PM
Page 23: [24] Deleted	K.E. Bennett	11/26/18 1:51:00 PM
Page 23: [25] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [25] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [26] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [26] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [26] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM
Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM

Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM

Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM

Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM

Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM

Page 23: [27] Deleted	K.E. Bennett	11/26/18 1:52:00 PM

Page 23: [28] Deleted	K.E. Bennett	11/26/18 1:53:00 PM

Page 23: [28] Deleted	K.E. Bennett	11/26/18 1:53:00 PM

Page 23: [28] Deleted	K.E. Bennett	11/26/18 1:53:00 PM

Page 23: [28] Deleted	K.E. Bennett	11/26/18 1:53:00 PM

Page 23: [28] Deleted	K.E. Bennett	11/26/18 1:53:00 PM

Page 23: [29] Deleted	K.E. Bennett	11/26/18 1:56:00 PM

Page 23: [29] Deleted	K.E. Bennett	11/26/18 1:56:00 PM

Page 23: [29] Deleted	K.E. Bennett	11/26/18 1:56:00 PM

Page 23: [29] Deleted	K.E. Bennett	11/26/18 1:56:00 PM

Page 23: [29] Deleted	K.E. Bennett	11/26/18 1:56:00 PM

Page 23: [30] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [30] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [30] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [30] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [31] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [31] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [31] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [31] Deleted	K.E. Bennett	11/26/18 2:10:00 PM

Page 23: [32] Deleted	K.E. Bennett	11/26/18 2:11:00 PM

Page 23: [32] Deleted	K.E. Bennett	11/26/18 2:11:00 PM

Page 23: [32] Deleted	K.E. Bennett	11/26/18 2:11:00 PM

Page 23: [32] Deleted	K.E. Bennett	11/26/18 2:11:00 PM

Page 23: [32] Deleted	K.E. Bennett	11/26/18 2:11:00 PM

Page 24: [33] Deleted	K.E. Bennett	11/26/18 2:12:00 PM

Page 24: [33] Deleted	K.E. Bennett	11/26/18 2:12:00 PM

Page 24: [33] Deleted K.E. Bennett 11/26/18 2:12:00 PM

Page 24: [33] Deleted K.E. Bennett 11/26/18 2:12:00 PM

Page 24: [33] Deleted K.E. Bennett 11/26/18 2:12:00 PM

Page 24: [34] Deleted K.E. Bennett 11/26/18 2:13:00 PM

Page 24: [34] Deleted K.E. Bennett 11/26/18 2:13:00 PM

Page 24: [34] Deleted K.E. Bennett 11/26/18 2:13:00 PM

Page 24: [34] Deleted K.E. Bennett 11/26/18 2:13:00 PM

Page 24: [35] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [35] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [35] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [35] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [36] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [36] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [36] Deleted K.E. Bennett 11/26/18 2:16:00 PM

Page 24: [37] Formatted Katrina Bennett 6/5/18 12:05:00 PM

Font: Not Italic

Page 24: [37] Formatted Katrina Bennett 6/5/18 12:05:00 PM

Font: Not Italic

Page 24: [38] Deleted **K.E. Bennett** **11/26/18 2:16:00 PM**

Page 24: [38] Deleted **K.E. Bennett** **11/26/18 2:16:00 PM**

Page 24: [38] Deleted **K.E. Bennett** **11/26/18 2:16:00 PM**

Page 24: [39] Deleted **K.E. Bennett** **11/26/18 2:23:00 PM**

Page 24: [39] Deleted **K.E. Bennett** **11/26/18 2:23:00 PM**

Page 24: [39] Deleted **K.E. Bennett** **11/26/18 2:23:00 PM**

Page 24: [39] Deleted **K.E. Bennett** **11/26/18 2:23:00 PM**

Page 24: [39] Deleted **K.E. Bennett** **11/26/18 2:23:00 PM**

Page 24: [39] Deleted **K.E. Bennett** **11/26/18 2:23:00 PM**

Page 24: [40] Formatted **Katrina Bennett** **6/5/18 12:05:00 PM**

Font: Not Italic

Page 24: [40] Formatted **Katrina Bennett** **6/5/18 12:05:00 PM**

Font: Not Italic

Page 24: [41] Deleted **K.E. Bennett** **11/26/18 2:25:00 PM**

Page 24: [41] Deleted **K.E. Bennett** **11/26/18 2:25:00 PM**

Page 24: [41] Deleted **K.E. Bennett** **11/26/18 2:25:00 PM**

Page 24: [41] Deleted **K.E. Bennett** **11/26/18 2:25:00 PM**

Page 24: [42] Deleted K.E. Bennett 11/26/18 2:25:00 PM

Page 24: [42] Deleted K.E. Bennett 11/26/18 2:25:00 PM

Page 24: [43] Deleted K.E. Bennett 11/26/18 2:26:00 PM

Page 24: [43] Deleted K.E. Bennett 11/26/18 2:26:00 PM

Page 24: [43] Deleted K.E. Bennett 11/26/18 2:26:00 PM

Page 24: [43] Deleted K.E. Bennett 11/26/18 2:26:00 PM

Page 24: [43] Deleted K.E. Bennett 11/26/18 2:26:00 PM

Page 24: [44] Deleted Katrina E. Bennett 9/18/18 4:43:00 PM

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [45] Formatted Katrina E. Bennett 9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [46] Formatted	Katrina E. Bennett	9/18/18 4:43:00 PM

Font: Not Italic

Page 24: [46] Formatted	Katrina E. Bennett	9/18/18 4:43:00 PM

Font: Not Italic

Page 25: [47] Deleted	K.E. Bennett	11/26/18 2:29:00 PM

Page 25: [47] Deleted	K.E. Bennett	11/26/18 2:29:00 PM

Page 25: [47] Deleted	K.E. Bennett	11/26/18 2:29:00 PM

Page 25: [47] Deleted	K.E. Bennett	11/26/18 2:29:00 PM

Page 25: [48] Deleted	K.E. Bennett	11/26/18 2:30:00 PM

Page 25: [48] Deleted	K.E. Bennett	11/26/18 2:30:00 PM

Page 25: [48] Deleted	K.E. Bennett	11/26/18 2:30:00 PM

Page 25: [48] Deleted	K.E. Bennett	11/26/18 2:30:00 PM

Page 25: [48] Deleted	K.E. Bennett	11/26/18 2:30:00 PM

Page 25: [48] Deleted	K.E. Bennett	11/26/18 2:30:00 PM

Page 25: [49] Deleted	K.E. Bennett	11/26/18 2:31:00 PM

Page 25: [49] Deleted	K.E. Bennett	11/26/18 2:31:00 PM

Page 25: [49] Deleted	K.E. Bennett	11/26/18 2:31:00 PM

Page 25: [49] Deleted	K.E. Bennett	11/26/18 2:31:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [50] Deleted	K.E. Bennett	11/26/18 2:38:00 PM

Page 25: [51] Formatted	K.E. Bennett	12/1/18 5:57:00 PM

Not Highlight

Page 25: [51] Formatted	K.E. Bennett	12/1/18 5:57:00 PM

Not Highlight

Page 25: [51] Formatted	K.E. Bennett	12/1/18 5:57:00 PM

Not Highlight

Page 25: [51] Formatted	K.E. Bennett	12/1/18 5:57:00 PM

Not Highlight

Page 25: [52] Deleted	K.E. Bennett	12/1/18 5:52:00 PM

Page 25: [52] Deleted	K.E. Bennett	12/1/18 5:52:00 PM

Page 25: [52] Deleted	K.E. Bennett	12/1/18 5:52:00 PM

Page 25: [53] Deleted	K.E. Bennett	12/1/18 5:53:00 PM

Page 25: [53] Deleted K.E. Bennett 12/1/18 5:53:00 PM

Page 25: [53] Deleted K.E. Bennett 12/1/18 5:53:00 PM

Page 25: [53] Deleted K.E. Bennett 12/1/18 5:53:00 PM

Page 25: [53] Deleted K.E. Bennett 12/1/18 5:53:00 PM

Page 25: [53] Deleted K.E. Bennett 12/1/18 5:53:00 PM

Page 25: [54] Deleted K.E. Bennett 12/1/18 5:58:00 PM

Page 25: [54] Deleted K.E. Bennett 12/1/18 5:58:00 PM

Page 25: [54] Deleted K.E. Bennett 12/1/18 5:58:00 PM

Page 25: [54] Deleted K.E. Bennett 12/1/18 5:58:00 PM

Page 25: [54] Deleted K.E. Bennett 12/1/18 5:58:00 PM

Page 26: [55] Deleted K.E. Bennett 12/1/18 6:03:00 PM

Page 26: [55] Deleted K.E. Bennett 12/1/18 6:03:00 PM

Page 26: [56] Deleted K.E. Bennett 12/1/18 6:03:00 PM

Page 26: [56] Deleted K.E. Bennett 12/1/18 6:03:00 PM

Page 26: [57] Deleted K.E. Bennett 12/1/18 6:04:00 PM

Page 26: [57] Deleted	K.E. Bennett	12/1/18 6:04:00 PM

Page 26: [57] Deleted	K.E. Bennett	12/1/18 6:04:00 PM

Page 26: [57] Deleted	K.E. Bennett	12/1/18 6:04:00 PM

Page 26: [58] Deleted	K.E. Bennett	12/1/18 6:05:00 PM

Page 26: [58] Deleted	K.E. Bennett	12/1/18 6:05:00 PM

Page 26: [58] Deleted	K.E. Bennett	12/1/18 6:05:00 PM

Page 26: [59] Deleted	K.E. Bennett	12/1/18 6:06:00 PM

Page 26: [59] Deleted	K.E. Bennett	12/1/18 6:06:00 PM

Page 26: [59] Deleted	K.E. Bennett	12/1/18 6:06:00 PM

Page 26: [59] Deleted	K.E. Bennett	12/1/18 6:06:00 PM

Page 26: [59] Deleted	K.E. Bennett	12/1/18 6:06:00 PM

Page 26: [60] Formatted	K.E. Bennett	12/1/18 6:20:00 PM

Not Highlight

Page 26: [60] Formatted	K.E. Bennett	12/1/18 6:20:00 PM

Not Highlight

Page 26: [60] Formatted	K.E. Bennett	12/1/18 6:20:00 PM

Not Highlight

Page 26: [60] Formatted	K.E. Bennett	12/1/18 6:20:00 PM

Not Highlight

Page 26: [60] Formatted	K.E. Bennett	12/1/18 6:20:00 PM

Not Highlight

Page 26: [60] Formatted K.E. Bennett 12/1/18 6:20:00 PM

Not Highlight

Page 26: [61] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [61] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [61] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [62] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [62] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [62] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [62] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [62] Deleted K.E. Bennett 12/1/18 6:10:00 PM

Page 26: [63] Deleted K.E. Bennett 12/1/18 6:11:00 PM

Page 26: [63] Deleted K.E. Bennett 12/1/18 6:11:00 PM

Page 26: [63] Deleted K.E. Bennett 12/1/18 6:11:00 PM

Page 26: [64] Deleted K.E. Bennett 12/1/18 6:13:00 PM

Page 26: [64] Deleted K.E. Bennett 12/1/18 6:13:00 PM

Page 26: [64] Deleted K.E. Bennett 12/1/18 6:13:00 PM

Page 26: [64] Deleted	K.E. Bennett	12/1/18 6:13:00 PM

Page 26: [64] Deleted	K.E. Bennett	12/1/18 6:13:00 PM