Responses to Anonymous Reviewer #1

General Comments

This study evaluates changes in Nov-May surface albedo and radiative forcings from land cover change in Norway using six land surface models and a radiative transfer model. The authors identify biases in modeled snow-covered and snowfree albedo for open and forested land cover types relative to MODIS albedo, with consistent positive bias of modeled open area albedo. Overestimation of the change in albedo from to conversion of forest to open led to overestimation of radiative forcing from land use/land cover change relative to MODIS. The authors suggest some model-specific improvements that could reduce modeled αs biases and reduce RF bias relative to MODIS, a strong contribution to the field.

In general, there are a lot of references to the 61-page Supplement in the Discussion section. With only two figures and one table in the main body of the manuscript, there is plenty of room to bring important Supplement findings into the main manuscript.

We thank Anonymous Reviewer #1 for his/her comments. We agree that important supplementary material -- notably information pertaining to key methodological assumptions and detail -- could be incorporated into the main manuscript. We have now shifted text from the supporting material file into the manuscript including a figure and table.

Specific Comments

(1) Three of the six models used in this study calculate direct-beam and diffuse albedo separately, yet only MODIS direct-beam (black sky) albedo is used as the observational benchmark. It would be helpful to see some discussion on why this choice was made. Why not use the full expression of MODIS blue-sky albedo from diffuse (white-sky) and direct-beam (black-sky) to compare all six models on equal ground? It doesn't seem fair to compare MODIS direct-beam to models that do not provide direct-beam.

We elected to go with the intrinsic black-sky albedo rather than calculate the total/blue-sky albedo, since the black-sky albedo under clear sky conditions for most SZAs (below 80 deg) typically dominates the total-sky albedo (Ni and Woodcock, 2000; Wang, 2005; Wang and Zeng, 2009). We checked this by employing a MODIS subset tool (ORNL DAAC, 2014) providing the calculated blue/total-sky albedo for one of our open and forested sites for our study time period. Mean shortwave total/blue-sky albedos at the forested and open site were 2.5% and 2.2% lower than the black-sky albedos, respectively. This does not alter our conclusions regarding the systematic biases identified for the three schemes in question (GISS, JULES All-band, and JSBACH).

We have better explained our assumptions and their implications in section 2.3.

(2) In mid-winter, the solar zenith angle at local solar noon in this region would be quite high. Noted that December values were omitted from the analysis, but isn't SZA greater than 70o at local solar noon for these sites during much of January and early February? Previous versions of MCD43A are considered high quality up to SZA of 70o, but beyond that the anisotropic model becomes unrealistic (Lucht et al., 2000, Schaaf et al., 2002, Stroeve et al., 2005 and Liu et al., 2009; Schaaf et al., 2011). Is this guideline

for appropriate use of MCD43A also true for V006? It would be helpful to see some discussion on the accuracy of MCD43A V006 at high solar zenith angles.

MODIS BRDF/Albedo V005 product is indeed less accurate with SZAa >70-75. To our knowledge this is also applicable to the V006 product. Although we elected to use the January and early February retrievals (i.e., SZA > 70 deg.), we do not believe this decision affects our results and main conclusions as they pertain to the systematic biases connected to the albedo parameterizations evaluated in our study. In any case we add a sentence in the Discussion section that highlights this known MODIS issue in light of our use of Jan. and Feb. retrievals.

(3) The land surface and radiative transfer modeling workflow needs more detail. From what I could gather, the six land surface models were run offline to calculate αs of open and forested lands. Top-of atmosphere radiative forcing was calculated for each of the three study regions at 1o x1o horizontal resolution using the 3D four spectral band, eight stream radiation transfer model using observed MODIS and modeled forest αs, and open αs. Is this correct? I thought I would find more detail in the 61-page supplement but I couldn't find any information on how the radiative transfer model was used with the land surface models. This type of information deserves more space in the methods section of the manuscript. The study regions shown in Figure S1 are much smaller than 1o (maybe 0.2o x0.4o at best?). How was this difference in domain size and resolution of the radiative transfer model reconciled? Is the radiative transfer modeling performed as single 1o x1o column centered over each of the three domains in Figure S1? Or are the domains rounded to the nearest whole degree? Was the entire grid cell assigned forest αs and open αs or were you able to use subgrid parameterization of albedo? A map of the radiative transfer modeling domain for each study region would be helpful for understanding how much existing cropland exists in each grid cell (p. 17344, line 20-21).

We agree that more attention is needed in the Methods section (section 2) surrounding both the albedo and RT modeling workflow. An important point of clarification to which we give more attention in our revision is that we do not run the entire land models offline, but rather, we extract only the equations required to calculate the surface albedos. We have now made this explicitly clear in section 2.1 to absolve any doubt.

Additionally, we add new information to section 2.4 describing more explicitly the steps taken when estimating RFs from both MODIS and predicted albedos.

(4) The TOA modeling has four spectral bands (undefined) but results are presented for two spectral bands, VIS and NIR. How was this addressed? Is the RF reported only for VIS and NIR? Or does the RF reported also include SWIR? If so, how might this affect the relationship between albedo and RF biases?

To clarify how the radiative transfer has been performed in terms of spectral resolution we have added the following description to the manuscript:

The four spectral bands are divided into the spectral regions 300-500 nm, 501-850 nm, 851-1500 nm, and 1501-4000 nm where MODIS VIS albedos are included in the two first bands and MODIS NIR albedos are included into the latter two bands. The reported RF is the integrated over the four spectral bands.

The radiative transfer code has been compared to detailed line-by-line calculations for various applications with agreement of the order of 10% (Myhre et al., 2009; Randles et al., 2013).

(5) In the discussion, I'd like to see a comment on how landscape heterogeneity and surface roughness within the MODIS footprint might also be contributing factors to lower than expected snow-covered albedo over open lands. While gridded at 500 m resolution, the actual observational footprint at high latitudes may include up to 1 km (Wang et al., 2012). Roads, buildings, clusters of trees, uneven snow surfaces and landscape features that cast shadows could all be contributing to lower than expected albedo over open lands in MODIS.

This is another good point, and we have therefore expanded the Discussion to include a discussion of the uncertainties stemming from landscape heterogeneities within the MODIS signal footprint, with relevant references to the work of Cescatti et al. (2012) and Wang et al. (2012).

Technical Corrections

p. 17340, line 6-7

"Unexpectedly, however, biases of equal magnitude were evident in predictions at open area sites." I am not sure why the authors find this to be unexpected, and do not believe that the data presented in Figure 1e and 1f support the claim for "equal magnitude".

What we mean is that we find it "unexpected" relative to the large range of biases for forests and given the lower diversity across parameterizations for completely snow-covered vegetation. Data in Figure 1a-d for some months and cases do in fact support the claim that some of the open-area biases were found to be of "equal magnitude" to those seen for forests. We re-write the confusing sentences in question so as to clarify our semantics.

p. 17342, lines 10-19.

Resolution of MCD43A3 used in this study should be stated somewhere in this paragraph. I assumed 500 m.

Added, thanks.

p. 17342, line 12

Define "winter-spring". I assumed that winter included December through February and spring included March through May. Later in the manuscript winter is defined as January through March (p. 17345, line 18) and November is also included in the analysis. Be clearer in defining "winter" and "spring".

We elected to list the actual dates rather than define "winter-spring" (or seasons) in the revised manuscript.

p. 17343, line 8

Change “12 open area sites…” to “Twelve open area sites…”

Corrected.

p. 17345, line 5

This is the first mention of using spectral bands. Please describe bands and

wavelengths used for VIS and NIR in the MODIS data section.

OK, we defined the spectral bands used in the analysis at the beginning of section 3.1.

p. 17346, line 4

Change “sits” to “sites”

Corrected.

p. 17347, line 18

The authors state, “For JSBACH, the result of having both positive and negative $\Delta\alpha s$ biases…” could you point to a table or figure that supports this?

OK, we have added references to the relevant tables and figures in the Supporting Information that support this.

p. 17347, line 24

There is no Table 3 in the manuscript. Did the authors intend Table S3? If so, there are two Table S3’s in the Supplement. Please correct.

Thanks for pointing this out. Indeed, “Table 3” here should have been Table S3 and there are indeed two Table S3s in Supporting Information. The correct reference here should have been to “Table S7”, which we have corrected here and at all other places in the manuscript that were incorrectly referenced.

p. 17349, line 6-7

Is there any empirical basis for lowering extinction coefficients from 0.3 and 0.4 for NIR and VIS, respectively, to 0.25 and 0.3 in this region? If so, please cite.

What we actually lowered is the “correction factor” used to estimate the extinction coefficient. This implies a slightly higher distribution of vertical leaf area which is more in line with an ellipsoidal leaf angle distribution (Campbell and Norman, 1998; Flerchinger and Yu, 2007; Wang et al., 2007). This serves to lower the extinction coefficient (increase canopy transmittance) to values more in line with those observed in boreal evergreen forests (Aubin et al., 2000; Balster and Marshall, 2000; Pierce and Running, 1988). We have now added the relevant supporting references.

p. 17350, line 28-29

Change “high CC%” to “high canopy cover fraction (CC%)”

Corrected.

p. 17359, Figure 1

The caption references a,b,c…f however the figures lack such labels. Please include labels on the figures and reference Fig 1a, 1b, etc correctly in the main body of the manuscript. No need to state left column, right column if these are labeled correctly. Recommend equation be moved to the text.

Corrected figure. We elect to leave the equations in the captions, however, as they are only needed to interpret the figure.

Supplement

Several tables span page breaks without the table headings repeating on the second page. Either keep the tables on a single page or repeat the headings on the second page.

Corrected. Tables have been fit to single pages.

Supplement, Figure S1

This figure and associated text ought to be in the methods section of the manuscript, not the Supplement

We agree and have moved it to the main manuscript.

Supplement, Table S1

What is H80?

We have added a definition of “H80” in Table S1’s (now Table 1) caption.

References:

Liu et al., 2009. Validation of Moderate Resolution Imaging Spectroradiometer (MODIS) albedo retrieval algorithm: dependence of albedo on solar zenith angle. Journal of Geophysical Research – Atmospheres, 114 (2009), p. D01106.

Lucht, et al. 2000. An algorithm for the retrieval of albedo from space using semiempirical BRDF models. IEEE Transactions on Geoscience and Remote Sensing, 38 (2000), pp. 977–998.

Schaaf, et al. 2002. First operational BRDF, albedo, nadir reflectance products from MODIS. Remote Sensing of Environment, 83 (2002), pp. 135–148.

Schaaf et al. 2011. Commentary on Wang and Zender – MODIS snow albedo bias at high solar zenith angles relative to theory and to in situ observations in Greenland. Remote Sensing of Environment, 115(5), pp. 1296-1300.

Stroeve et al., 2005. Accuracy assessment of the MODIS 16-day albedo product for snow: comparisons with Greenland in situ measurements Remote Sensing of Environment, 94 (2005), pp. 46–60.

Wang et al., 2012. Evaluation of Moderate-resolution Imaging Spectroradiometer (MODIS) snow albedo product (MCD43A) over tundra. Remote Sensing of Environment, 117, pp. 264-280.

References used in our responses:

Aubin, I., Beaudet, M., and Messier, C.: Light extinction coefficients specific to the understory vegetation of the southern boreal forest, Quebec, Canadian Journal of Forest Research, 30, 168-177, 2000.

Balster, N. J. and Marshall, J. D.: Eight-year responses of light interception, effective leaf area index, and stemwood production in fertilized stands of interior Douglas-fir (Pseudotsuga menziesii var. glauca), Canadian Journal of Forest Research, 30, 733-743, 2000.

Campbell, G. S. and Norman, J. M.: An introduction to environmental physics (2nd Ed.), Springer-Verlag, New York, NY, USA, 1998.

Flerchinger, G. N. and Yu, Q.: Simplified expressions for radiation scattering in canopies with ellipsoidal leaf angle distributions, Agricultural and Forest Meteorology, 144, 230-235, 2007.

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Ni, W. and Woodcock, C. E.: Effect of canopy structure and the presence of snow on the albedo of boreal conifer forests, Journal of Geophysical Research, 105, 1879-11888, 2000.

ORNL DAAC: MODIS subsetted land products, Collection 5. Available online [http://daac.ornl.gov/MODIS/modis.html] from ORNL DAAC, Oak Ridge, Tennessee, USA. Accessed Nov. 28, 2014., Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), 2014.

Pierce, L. L. and Running, S. W.: Rapid Estimation of Coniferous Forest Leaf Area Index Using a Portable Integrating Radiometer, Ecology, 69, 1762-1767, 1988.

Randles, C. A., Kinne, S., Myhre, G., Schulz, M., Stier, P., Fischer, J., Doppler, L., Highwood, E., Ryder, C., Harris, B., Huttunen, J., Ma, Y., Pinker, R. T., Mayer, B., Neubauer, D., Hitzenberger, R., Oreopoulos, L., Lee, D., Pitari, G., Di Genova, G., Quaas, J., Rose, F. G., Kato, S., Rumbold, S. T., Vardavas, I., Hatzianastassiou, N., Matsoukas, C., Yu, H., Zhang, F., Zhang, H., and Lu, P.: Intercomparison of shortwave radiative transfer schemes in global aerosol modeling: results from the AeroCom Radiative Transfer Experiment, ATMOSPHERIC CHEMISTRY AND PHYSICS, 13, 2347-2379, 2013.

Wang, S.: Dynamics of surface albedo of a boreal forest and its simulation, Ecological Modelling, 183, 477-494, 2005.

Wang, W. M., Li, Z. L., and Su, H. B.: Comparison of leaf angle distribution functions: Effects on extinction coefficient and fraction of sunlit foliage, Agricultural and Forest Meteorology, 143, 106-122, 2007.

Wang, Z. and Zeng, X.: Evaluation of Snow Albedo in Land Models for Weather and Climate Studies, Journal of Applied Meteorology and Climatology, 49, 363-380, 2009.

Responses to Anonymous Referee #2

General comments:

The article describes an evaluation of six albedo schemes, which are commonly employed in climate models. For three sites in Norway these albedo schemes are driven by meteorological data (snowfall, snow depth, temperature, wind speed) and measurements of vegetation structure (LAI, height, fcover) to compute the surface albedo of forests as well as non-forested area in the vicinity of the meteorological sites. The difference in albedo (forest - non-forest) is then translated by means of a radiative transfer model in a radiative forcing (RF) caused by land cover changes (i.e. deforestation). Both simulated results, albedo and RF, are then compared with surface albedo and RF derived from satellite based observations (MODIS). Additionally, a simple regression model for surface albedo is introduced to further rate the performance of the albedo schemes.

The main scientific question in this context is, how much the albedo of snow covered surfaces is reduced by the presence of forests, i.e. the snow masking effect, and which albedo scheme is reproducing it best. This is an important task with respect to climate modeling as it determines the strength of the snow-albedo feedback in the taiga zone. I think that the approach taken in this study to assess the quality of albedo schemes by driving them with local data and comparing the result with observed albedo has a large potential to contribute to this task. Usually, climate models are evaluated by looking at the differences between their results and observation. That means that in the presence of snow a bias in the simulated albedo may be due to deviations in the modeled snow cover or an inaccurate representation of forest cover in the climate model or a deficient albedo scheme. It is hard to disentangle the single contributions to the overall error. So, it is hardly possible to rate an albedo scheme by this approach. By contrast, in this study the albedo schemes are not used embedded in the climate models but isolated from them and driven directly by observations, so that it is straight forward to rate their performance.

My main criticism to the current manuscript is that the approach of the study is not coherently explained. Also the advantage of this approach is not sufficiently pointed out. This should be done at the end of the introduction. To be honest, I read most of the main text thinking, that surface albedo values of climate model simulations have been evaluated. So, it should be clearly stated that only the albedo schemes employed in climate models are driven by observations to calculate the analysed albedo values. It should be also mentioned in the main text that the albedo schemes have been slightly modified for technical reasons and that they are not identical with the albedo computations done in the climate models (with a reference to the supplement for the details).

After clarification of this essential aspect of the manuscript I would appreciate the publication of this study.

We appreciate the comments by Reviewer 2 who criticized that the main value-added and novelty aspects of our research were poorly presented in the paper. We acknowledge that these indeed were not fully visible in our paper, particularly in the Abstract and Introduction. We have therefore significantly revised the Introduction as per Reviewer 2's suggestions. We have also completely revised the Abstract in a similar manner. We are confident that these revisions should absolve all doubt as to what the main research questions and objectives of our paper are and how we have addressed them methodologically.

Additionally, we include a sentence in the main text pointing out that in some cases the albedo schemes have been slightly modified as per suggested by this reviewer and by Richard Essery.

Specific comments:

(1) I would alter the title to: "Radiative forcing bias of simulated surface albedo changes linked to forest cover modifications at northern latitudes". Albedo is simulated in this study, not the forest cover changes.

We agree that this is a more technically sound title aligning with the paper and have changed the title as per suggested (thanks).

(2) The second line of the abstract contributes to the confusion I already criticised in the general comments. Not whole land surface schemes are used in this study, but only isolated albedo schemes (commonly employed in climate models) have been used for the calculations.

Corrected here and elsewhere in the manuscript.

(3) There should be a description added in section 2, how surface albedo was calculated technically with the six albedo schemes. For example, I guess, that surface albedo was calculated only once per day at noon for each scheme and that the daily cycle is not considered.

This is correct, and we have now added additional explanation in the albedo part of the Methods section (section 2.1).

(4) I would appreciate a few comments, if other sites with similar measurements exist that would allow to extend the analysis to other regions. A few sites with summergreen forest or a few sites with a much drier and colder climate would be interesting.

Indeed, extending the analysis to other forest and climate types would be interesting which we now bring up in our discussion.

(5) Concerning the RF presented in Fig. 2, I would only quote local RF values. The area average RF values scale with the cropland fraction (I think), which is of no interest to the reader (I guess). I would also change the area average RF value mentioned in the abstract to the local RF value.

Yes, we agree and have removed the area averaged RF values from both the Abstract and Figure 2 (now Figure 3).

Technical corrections:

(1) I would add two additional subsection numbers in section 2. One for the paragraph about MODIS albedo (2.1) and one for the station/forest data (2.2). Just for a bit more consistent structure of the subsection numbering.

Ok, we have added new sub-section headings as per suggested.

(2) p. 17340 l. 19 change "an order or" to "an order of"

Corrected.

(3) p. 17341 l. 6 change "covered in snow" to "covered with snow"

Corrected.

(4) p. 17341 l. 18 change "intermodal" instead "intermodel"

Corrected.

(5) p. 17341 l. 19 change "suspect it to be behind the differences" to "suspect it to be the reason for the differences"

Corrected.

(6) p. 17342 l. 7 change "discussion surrounding" to "discussion about"

Corrected.

(7) p. 17346 l. 4 change "sits" to "sites"

Corrected.

(8) p. 17352 l. 26 change "efforts to improved parameterizations" either to "efforts to improve parameterizations" or "efforts towards improved parameterizations"

Corrected.

(9) supplement, S.3.4, change "from temperature and wind in are adapted" to "from temperature and wind are adapted"

Corrected.

Responses to Richard Essery

In discussing differences in surface albedo between forests and snow in open areas, Bright et al. present some interesting results on an important source of uncertainty for radiative forcings in climate models. The work will be worth publishing, but some improvements are required in the structure of the paper. This is an extremely compact paper with an enormous amount of supplementary material that is useful but does not compensate for deficiencies in the paper. Most of the problems can already be identified from statements in the abstract: - results "predicted by land surface schemes of six leading climate models" are not presented; the albedo parametrizations from these schemes are used in isolation, and more information is required on how these parametrizations are run without including them in full land surface models - the emphasis of the paper is unclear. The statements that "the magnitude and sign of the albedo biases varied considerably for forests" and "RF bias was considerably small across models" are contradictory; the models cannot all have small biases if there is a considerable range in their biases. - no justification is given for the statement that "model improvement efforts of recent years are leading to enhanced LULCC climate predictions"

The meteorological data available (page 17342) do not include all of the variables or temporal resolution that would be required for running the full land surface models. How the albedo parametrizations from these models are run with the available data is not adequately explained in either the paper or the supplement. What is meant by "forest structure" in terms of model parameters needs to be explained in the paper, not just the supplement.

We appreciate the constructive comments and critiques of Richard Essery. Many similar yet important comments regarding structure and clarity were also raised by Anonymous Reviewers 1 & 2 and have been addressed in our revision.

Our statements (in Abstract) that: '"the magnitude and sign of the albedo biases varied considerably for forests" and "RF bias was considerably small across models"' are, however, not necessarily contradictory since RF is a metric based on the difference between two albedos, which we had made explicit in both the Results and Discussion sections (for example, positive albedo biases of GISS were approximately equal in magnitude for both Forests and Open areas, which went undetected when taking the difference (Open – Forest) for the RF calculations.

Regarding the point that "the models cannot all have small biases if there is a considerable range in their biases", what we meant is that a large range was present across models for some sub-regions and time periods, yet this bias was not visible when averaging the results across all sub-regions and time periods. We have clarified this in our revised Abstract.

We delete the statement that "model improvement efforts of recent years are leading to enhanced LULCC climate predictions" in the Abstract as we agree that it is not justified.

The meteorological variables presented on page 17342 of our discussion paper are indeed not enough to run the full land models but are, in most cases, enough to execute the albedo parameterizations. In the limited cases in which they are insufficient we had noted this in the Supporting Information. However, we agree that this information is too important not to place in the main paper and have now make it clearly visible in the main paper (new section 2.2) that additional meteorological input variables are sometimes required, with new text elaborating how they have been obtained (computed) using the existing observational dataset and to which schemes the belong. Forest structural variables are now better described in the main paper .

Minor corrections:

page 17340, line 19 "an order of magnitude spread"

Corrected.

17340, 24 Insert Boisier et al. (2012) reference here for LUCID

OK.

17341, 18 "intermodal spread"

Corrected.

17345, 21 "r = 1" here looks like it refers to a correlation, but the correlation of what is not clear.

Changed to "1:1 line"

17345, 26 "positive biases occurred for the VIS band"

Revised as suggested.

17346, 4 "at Open sites"

Corrected.

17349, 14 Table S4?

Corrected.

17350, 29 If "CC%" is referred to in the paper it needs to be explained in the paper, not just in the supplement.

We have now defined it in the paper.

17351, 18 “on the underlying datasets”

Corrected.

17352, 25 Replace the hyphen with a comma.

OK.

Figure 1 caption The data shown in (a) – (d) are observed and modelled albedos, not correlations between them.

Corrected.

Figure 2 caption (a) shows albedo differences, not albedo changes. The two rank scales and four NME scales on (b) are not explained in the caption.

Corrected.

Radiative forcing bias of simulated surface albedo modifications linked to ~~simulated~~ forest cover changes at northern latitudes

RUNNING TITLE: On albedo bias in climate models

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Article Type: Primary Research Article

Abstract

In the presence of snow, the ~~persistent~~ bias in the prediction of surface albedo ~~prediction seen in~~ by many climate models remains difficult to correct due to the difficulties of separating the albedo parameterizations from those describing snow and vegetation cover and~~–~~ structure. This can be overcome by extracting the albedo parameterizations in isolation, by ~~–and implementin~~executing them with observed meteorology and information on vegetation structure, and by comparing the resulting predictions to observations. Here, we employ an empirical dataset of forest structure and daily meteorology for three snow cover seasons and for three case regions in boreal Norway to compute and evaluate predicted albedo to those based on daily MODIS retrievals. ~~Both the predicted and MODIS albedos for f~~Forest~~ed~~ and ~~surrounding~~adjacent open area albedos ~~s~~ are subsequently used to estimate bias in top-of-the-atmosphere (TOA) radiative forcings (RF) from albedo changes (Δα, Open - Forest) connected to ~~Simulated land use/land cover change (LULCC) radiative forcings (RF) from~~ land use and land cover changes (LULCC).

~~changes in surface albedo (Δα) predicted by~~ the albedo parameterizations of ~~land surface schemes of six leading climate models were compared to those based on daily MODIS retrievals for three regions in Norway and for three winter-spring seasons.~~ As expected, given the diversity of approaches by which snow masking by tall-statured vegetation is parameterized~~ in the different models,~~~~,~~ the magnitude and sign of the albedo biases varied considerably for forests.~~;~~ ~~Albedo~~Large ~~unexpectedly, however, b~~biases ~~of equal equal magnitudemagnitude were for some months~~ at the open sites were also ~~found~~detected~~evident in predictions at open area sites,~~ which was unexpected given that -these sites were snow-covered throughout most of the analytical time period~~,~~ ~~and given that albedo parameterizations thus~~therefore eliminating ~~the effect of the~~potential biases linked to -snow-

masking parameterizations~~varied less across models for such conditions~~. ~~These~~ Biases at the open sites~~biases latter~~ were mostly ~~positive~~positive, ~~and~~ exacerbating~~ed~~ the strength of vegetation masking effects and hence the simulated LULCC $\Delta\alpha$ RF. Despite the large biases in both forest and open area albedos ~~by~~by some schemes in some ~~some of the schemes in some mo~~ months and years, ~~over the three-year period Nov. – May~~ the mean $\Delta\alpha$ RF bias over the three-year period (Nov. – May) was considerably small across models (-~~0.08~~2.1 ± ~~0~~1.04 Wm^{-2}; 21% ± 11%); 4 of 6 models had normalized mean absolute errors less than 20%~~ (3-year regional mean)~~. Identifying systematic sources of the albedo prediction biases proved challenging, although for some schemes clear sources were identified.

~~Our study should provide some reassurance that model improvement efforts of recent years are leading to enhanced LULCC climate predictions.~~

Keywords: ~~empirical~~observation, LULCC, prediction, vegetation masking, model, climate impact, land surface, climate model~~, radiative forcing, surface albedo, bias~~

1. Introduction

Albedo change radiative perturbations due to land use and land cover change (LULCC) have long been considered some of the strongest climate forcing mechanisms at global and regional scales (Cess, 1978; Otterman, 1977), yet results from recent historical LULCC modeling studies reveal an order of~~r~~ magnitude spread in the temperature response from albedo change forcings (Brovkin et al., 2006; Lawrence et al., 2012; Pongratz et al., 2010). This is likely because, in regions and months with snow cover, the interactions between vegetation and snow significantly complicate the relationship between the change in forest cover fraction and surface albedo (α_s) (de Noblet-Ducoudré et al., 2012). Outcomes of model inter-comparison studies (LUCID) (Boisier et al., 2012) employing identical LULCC prescriptions suggest that, apart from the way individual land surface models (LSMs) implement LULCC in their own land cover map (i.e., differences in biogeography), model differences in the way α_s is parameterized could be a significant source of this spread (de Noblet-Ducoudré et al., 2012; Pitman et al., 2009). Recent attributional analysis by Boisier et al. (2012) suggests that the contribution from the latter is indeed comparable to the former and worthy of further investigation, particularly given the importance of albedo radiative feedbacks when ground or canopy surfaces are covered ~~in~~ with snow (Crook and Forster, 2014; Hall and Qu, 2006).

Simulated α_s over snow-covered forests by climate models is often biased high (Essery, 2013; Loranty et al., 2014; Roesch, 2006). While most climate models distinguish between snow intercepted in forest canopies and snow on the ground, many differ in how they parameterize the fractions of ground and canopy that are covered with snow for given masses of lying and intercepted snow (Essery, 2013; Qu and Hall, 2007). This is likely because, rather than trying to simulate the complex processes of canopy snow interception and unloading as is done by many sophisticated, physically-based snow models (Essery et al., 2013; Essery et al., 2009) – many climate models must employ simplified parameterizations to reduce computational demands. In their assessment of α_s feedbacks simulated by 14 CMIP5 models, Qu and Hall (2014) ~~find~~ found that the largest ~~intermodal~~ intermodel spread in α_s ~~occurring~~ occurred in northern latitude regions and suspected it to be ~~behind~~ the reason for the differences in the large range of local feedbacks. As with their previous inter-comparison analysis (Qu and Hall, 2007), Qu and Hall (2014) assert that parameterizations of snow masking in many CMIP5 models may still require improvement.~~, suggesting further that winter observations over heavily vegetated surfaces such as the boreal forest should be used to constrain modeled α_s because of the vastly different parameterizations employed in the CMIP5 models for vegetation snow masking.~~

~~Climate models are typically evaluated by looking at differences between their results and observation. In the presence of snow, a bias in the simulated albedo may be due to deviations in the modeled snow cover or to an inaccurate representation of forest cover in the climate model. Thus it is difficult to unravel the single contributions to the overall error, making it difficult to benchmark albedo schemes by this approach. By contrast, in this study the albedo schemes are not embedded in the climate models but are isolated and driven directly by observation, making it easier to evaluate their performance.~~

We hypothesize that parameterizations of snow masking by vegetation can be refined and improved in many climate models~~ and that local calibration with empirical observation can enhance prediction accuracy~~. To this end, we evaluate albedo ~~α_s~~ parameterizations ~~schemes~~ ~~of~~inof six prominent climate models in greater detail in order to pinpoint major sources of bias and inter-model variability. Rather than running the full land model, we extract only the requisite equations (parameterizations) enabling albedo prediction~~, driven with~~ using observed forest structure and daily meteorology. Climate models are typically evaluated by looking at differences between their results and observation. In the presence of snow, a bias in the simulated albedo may be due to deviations in the modeled snow cover or to an inaccurate representation of forest cover (biogeography) in the climate model. Thus it is difficult to unravel the single contributions to the overall error, making it challenging to benchmark albedo schemes by this approach. By contrast, in this study the albedo schemes are not embedded in the climate models but are isolated and driven directly by observation, making it easier to evaluate their performance. Predicted albedos for both forest and open areas are compared to daily MODIS retrievals spanning three snow cover seasons in three case regions of boreal Norway. Radiative forcings from the conversion of forests to open lands are then computed, providing an additional metric for benchmarking errors in ~~predicted albedo associated with LULCC~~the simulated albedo. ~~Using a comprehensive empirical dataset of forest structure, meteorology, and daily MODIS~~ ~~α_s~~ ~~retrievals spanning three winter-spring seasons in three case regions of boreal Norway, we then estimate~~ ~~$\Delta\alpha_s$~~ ~~radiative forcings connected to simulated forest cover changes (LULCC) and compare it to the MODIS-based forcings. We then jointly~~We c~~develop a physically-based regression model and c~~ompare the ~~its~~ performance of the six albedo schemes ~~to~~ to that in which albedo is predicted with a purely empirical model developed in parallel~~existing schemes~~, concluding with a discussion ~~surrounding~~ about the efforts required to improve albedo prediction accuracy ~~in~~ by climate models.

2. Material and Methods

2.1. MODIS albedo

We employed Version 006 (v006) MCD43A 1-day daily Albedo/BRDF product having 500 m ~~x~~by 500 m spatial resolution (Wang and Schaaf, 2013; Wang et al., 2012), taking the direct beam ("black-sky") α_s at local solar noon for visible (VIS; 0.3-0.7 µm) and near infrared (NIR; 0.7-5.0 µm) spectral bands for ~~the winter-spring seasons~~the time periods spanning Jan. ~~1, 2007~~ through May ~~9, 2009~~2007 and Nov. through May 2007-2008. The v006 product uses multiple clear sky views available over a 16-day period to provide daily α_s values that represent the best BRDF possible with the day of interest emphasized. This includes as many overpasses that are available per day (while earlier versions of the algorithm, including the Direct Broadcast version, were limited to only 4 observations per day (Shuai, 2010)), enabling it to better capture the daily albedo with an algorithm that more strongly emphasizes all contributions from the single day of interest (Wright et al., 2014).

2.2. Forest structure and meteorology

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Structural attributes like leaf area index (LAI), canopy height, and canopy cover fraction were derived from regional aerial LIght Detection and Ranging (LIDAR) campaigns undertaken in June of 2009 following Solberg *et al.* (2009). The maximum, minimum, and median values of these attributes connected to each MODIS pixel included in the analysis are presented in Table 1.

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Table 1. Minimum, maximum, and median tree height (H80), canopy cover fraction, and LAI in the sampled evergreen needleleaf forests of each study region (sampled June, 2009). H80 is the 80th percentile of laser scanning first echoes, corresponding to canopy surface height in meters above ground which is correlated to biomass and used as a proxy for tree height.

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Study Region	Sample Area	Tree height, (H80; m)	Canopy cover fraction	LAI (m^{-2} m^{-2})

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	(km^2)									
(Number of MCD43A pixels)		Min	Max	*Median*	Min	Max	*Median*	Min	Max	*Median*
Flisa *(n=65)*	14.0	3.1	15.8	*11.8*	25%	77%	*63%*	0.55	2.35	*1.73*
Rena *(n=34)*	7.3	5.7	13.0	*9.8*	50%	80%	*63%*	1.31	1.82	*1.52*
Drevsjø *(n=36)*	7.7	3.2	10.2	*7.5*	27%	52%	*40%*	0.43	1.21	*0.81*
Regional Mean	29.0[a]	4.0	13.0	*9.7*	34%	69.7%	*55.3%*	0.76	1.79	*1.35*

[a] Value is column sum.

Daily meteorological observations of mean and maximum wind speed (ms^{-1}), mean and maximum near-surface air temperatures (˚C), snow depth (cm), and precipitation (mm) were taken from measuring stations in the municipalities of Drevsjø (675 m), Flisa (200 m), and Rena (250 m) located in eastern Norway (Figure 1) in the county of Hedmark ~~(Figure S1)~~(Norwegian Meteorological Institute, 2013). Additional meteorological information not available directly, such as snow density and snowfall, were computed with empirical models and the available observations as inputs. For example, precipitation was partitioned into snow and rain following the empirical analysis of Dai (2008) in which rain occurred more frequently than snow over land when air temperatures exceeded 1.2 ºC. Snow density was computed with snow depth, air temperature, and wind speed based on the empirical work of Meløysund *et al.* (2007).

Site-specific air temperatures were adjusted using the station-measured observations and an environmental lapse rate of -6.5 ºC/km. All three sub-regions lie in Köppen-Geiger climate zone ”Dsc” (boreal) but experience variations in snow fall amount and frequency and the temporal extent of the snow cover season (additional meteorological information may be found in Supporting ~~Online Material (SOM)~~Information ~~and Figure S2~~).

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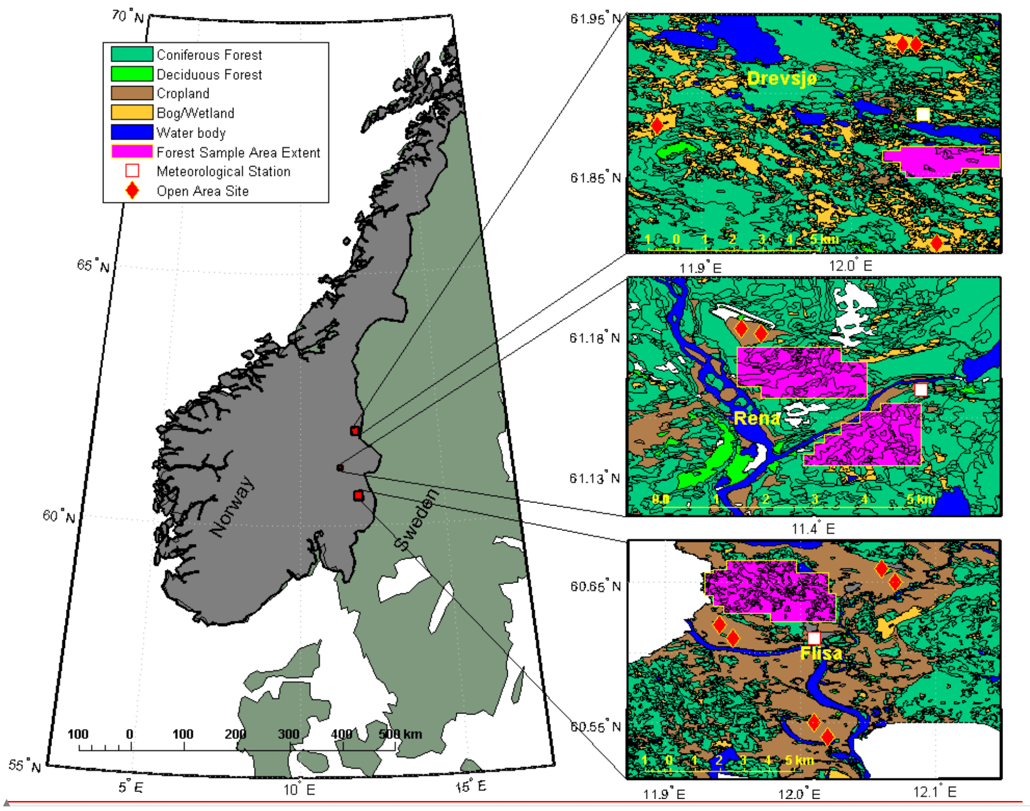

Figure 1. Study regions showing the location of the open ("Cropland" or "Bog/Wetland") and coniferous forested sites included in the analysis. Meteorological station locations are also indicated.

Local forest management plans were used to identify forest stands of pure (>95% volume, m^3 ha^{-1}) evergreen needleleaf forest cover within a ~5 km radius and ~50 m altitude range of a weather monitoring station. Evergreen needleleaf species in the region included Scots Pine (*Pinus sylvestris* L.) and Norway Spruce (*Picea abies* (L.) H. Karst.). ~~12~~ Twelve open area sites within the same 5 km proximity to a weather station were selected in order to simulate forcings associated with regional LULCC (forest to open), shown in Figure 1. In total, ~~250~~ 135 forested MODIS pixels (approximately ~~52~~,~~300~~ 900 hectares) and 12 open area pixels (8 cropland, 4 wetland/peatland) were included in the sample. ~~(Figure S1).~~

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2.~~1~~3. Albedo parameterizations in climate models

The ~~particular land surface models from which the~~albedo parameterizations ~~-~~chosen for the analysis (Table ~~1~~2) were selected because they are widely employed in climate/earth system models and because ~~their α_s schemes~~they are diverse with respect to the parameterization of ground masking by vegetation, which can be classified according to three prevailing methods introduced in Qu & Hall (2007) (and later described in Essery (2013)). Briefly, the first method estimates radiative transfer between the vegetation canopy and the ground surface; the second method combines the vegetation and ground albedos with weights determined by vegetation cover; and the third method combines the snow-free and snow albedo with weights determined by snow cover. Varying degrees of ~~model~~ complexity in albedo parameterizations stem from the way snow albedo metamorphosis effects are ~~parameterized~~ treated and the way vegetation structure is utilized. ~~(SOM section S3).~~

We note that we do not run the entire land models offline; rather, we extract only the equations (parameterizations) required to calculate the surface albedos ~~-~~ of both open terrain and forests. ~~-~~ In some (albeit limited) cases, certain parts of the albedo parameterizations have been slightly modified for technical reasons, rendering them not fully identical to those implemented in the full model (see section ~~SX for details~~S3).

Direct beam ("black-sky") albedos are calculated at local solar noon to be compatible with the MODIS retrievals. The albedo parameterizations of JSBACH and GISS II do not differentiate between direct and diffuse beam components and are assumed to represent the total- or "blue-sky" albedo. ~~However,~~The direct beam ~~albedos~~component, however, ~~-~~typically dominates the total albedo under clear-sky condi~~c~~tions (Ni and Woodcock, 2000; Wang, 2005; Wang

Formatted: Font: (Default) Times New Roman, 12 pt and Zeng, 2009) ~~(XX), and for snow covered conditions, it can often resemble the daily mean albedo (XX)~~and were thus deemed reasonable for purpose of comparison. ~~.~~

2.~~2~~4. Regression modeling

Non-linear multiple regressions are performed using the forest structure and meteorological observations as predictor variables. The functional form of the models are adapted from several important physically-based parameterizations found in many current albedo schemes. Eq. (1) is the best performing model:

$$\alpha_s = k_1 + k_2(1-\mathrm{e}^{-LAI}) + k_3 \tanh(d/k_4)\left(\mathrm{e}^{-k_5(LAI)} + \left[1-\frac{1}{1+\mathrm{e}^{-k_6 T^{MAX}}}\right]\right) \quad (1)$$

where *LAI*, *d*, and T^{Max} are leaf area index, snow depth, and maximum daily (24-hr.) temperature, respectively. k_1 is the ground albedo (directional hemispherical) without the forest canopy scaled by a canopy radiative fraction term $(1-\mathrm{e}^{-LAI})$ and the parameter k_2, with k_2 representing the maximum albedo difference at the highest observed LAI values. See ~~SOM~~ Supporting Information (section S4) for a detailed overview and description of the regression model and its theoretical underpinnings, its parameters (Table ~~S6~~S5), and its performance statistics (Table ~~S6~~S5).

2.~~3~~5. Radiative forcing

Top-of-atmosphere (TOA) radiative forcing simulations for the conversion of forest (evergreen needleleaf only) ~~forest~~ to open land ($\Delta\alpha_s$, Open – Forest) is computed using a 3-D four spectral band, eight-stream radiative transfer model (Myhre et al., 2007) based on the discrete ordinate method (Stamnes et al., 1988). The four spectral bands are divided into the spectral regions 300-500 nm, 501-850 nm, 851-1500 nm, and 1501-4000 nm where MODIS VIS albedos are included in the two first bands and MODIS NIR albedos are included into the

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Formatted: Font: (Default) Times New Roman, 12 pt, Font color: Auto latter two bands. The reported RF is the integrated over the four spectral bands. The radiative transfer code has been compared to detailed line-by-line calculations for various applications with agreement of the order of 10% (Myhre et al., 2009; Randles et al., 2013).

The model is run with a 3-hr. time step with a horizontal resolution of 1° x 1° and a vertical resolution of 40 layers. Meteorological data from the ECMWF is used in the radiative transfer simulations and several atmospheric aerosol types are included in the model (Myhre et al., 2007). ~~Regional RF from~~ LULCC RF is estimated by taking the difference in the net shortwave radiative flux at TOA after ~~changing~~ setting the monthly mean α_s of the entire 1° x 1° grid cell ~~and normalizing to the share of existing cropland contained within each grid cell~~ (centered over the domains of case study region) first to that of open lands then to that of forests.

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Table ~~1~~2. Albedo parameterizations included in the analysis and their ~~Land surface models included in the study~~ associated land and climate models.

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Land model origin of ~~(~~α_s ~~scheme)~~parameterizations	**Climate Model**	**Snow albedo**	**Vegetation masking effect**[b]	**Forest structure**	**Technical documentation**	**Other supporting references**
CLASS	CGCM4; CanCM4	prognostic procedure	type 2	yes	(Verseghy, 2009)	(Verseghy et al., 1993)
CLM4.0	NCAR CCSM4; NCAR CESM; Nor-ESM	prognostic procedure	type 1	yes	(Oleson et al., 2010)	(Dickinson, 1983; Flanner and Zender, 2006; Sellers, 1985)
GISS II	GISS GCM II; GISS GCM ModelE	prognostic procedure	type 3	no	(Hansen et al., 1983)	(Matthews, 1984)
JULES[a] (2-stream)	UKMO HadGEM2	prognostic procedure	type 3	yes	(Best, 2009)	(Marshall, 1989; Sellers, 1985; Wiscombe and Warren, 1980)
JULES[a] (all-band)	UKMO HadCM3	diagnostic procedure	type 3	yes	(Best, 2009)	(Essery et al., 2001)
JSBACH	MPI-ESM	diagnostic procedure	type 2	yes	(Reick et al., 2012)	(Otto et al., 2011)

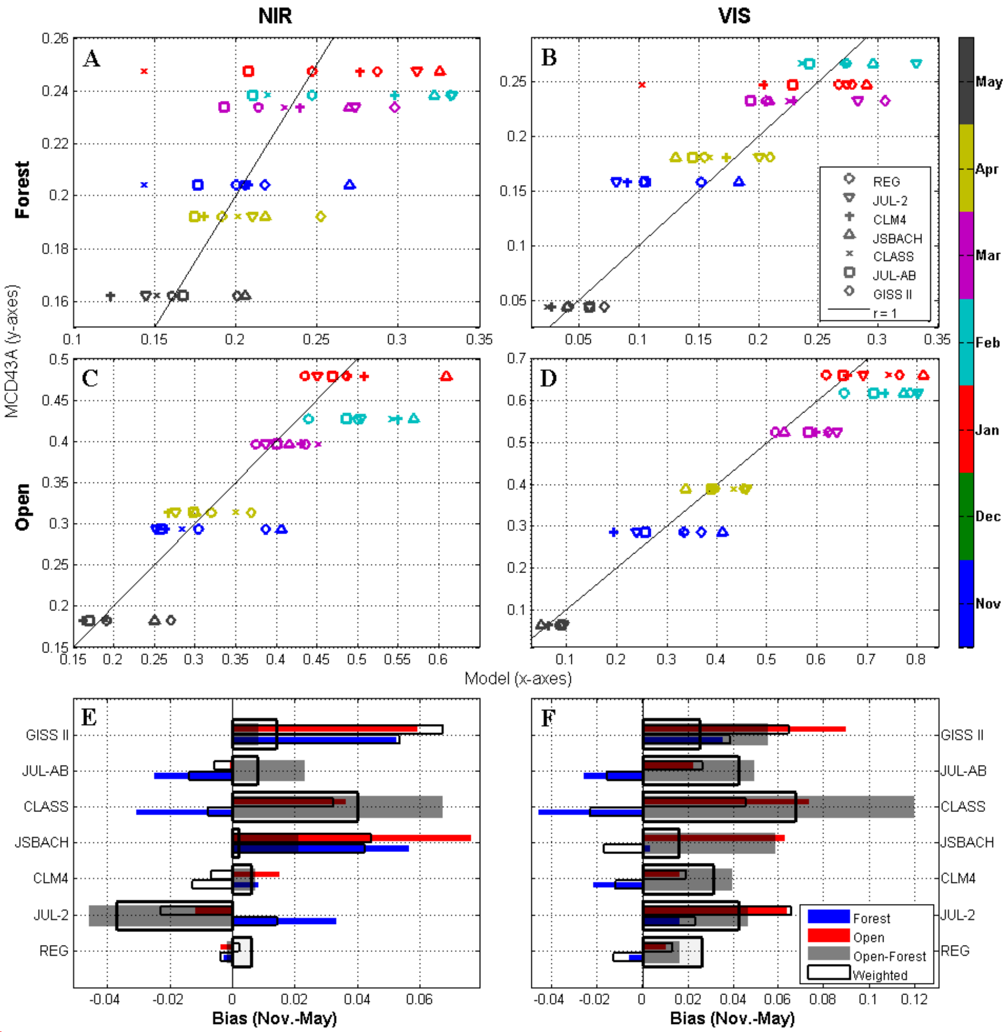
[a] Formerly MOSES

[b] Classification based on Qu & Hall (2007)

3. Results

3.1 Albedo

When looking at regional averages in predicted α_s presented in Figure ~~1~~2, no single model apart from the regression model ("REG") performed consistently well across all months at both Forest and Open sites and for both spectral bands. Starting with the NIR band (Fig. ~~1~~2, left column), JSBACH showed clear positive biases at both Open and Forest sites for most months. Positive biases in GISS II were more prevalent for Forest although positive biases were also found at Open sites for months with partial snow cover (Nov., Apr., May). Large positive biases for the JULES 2-stream ("JUL-2") scheme were limited to Forest and to winter months of Jan., Feb., and March. With the exception of February, slight negative biases by JUL-2 at the Open sites were found in all months except Feb.; this was true also for the JULES All-band scheme ("JUL-AB") with the exception of Mar. The largest difference between the two JULES schemes occurred for Forest, where JUL-AB consistently underpredicted α_s in all months except May. Large negative biases in Forest by CLASS were found in Nov. and Jan., with smaller negative biases in Feb.



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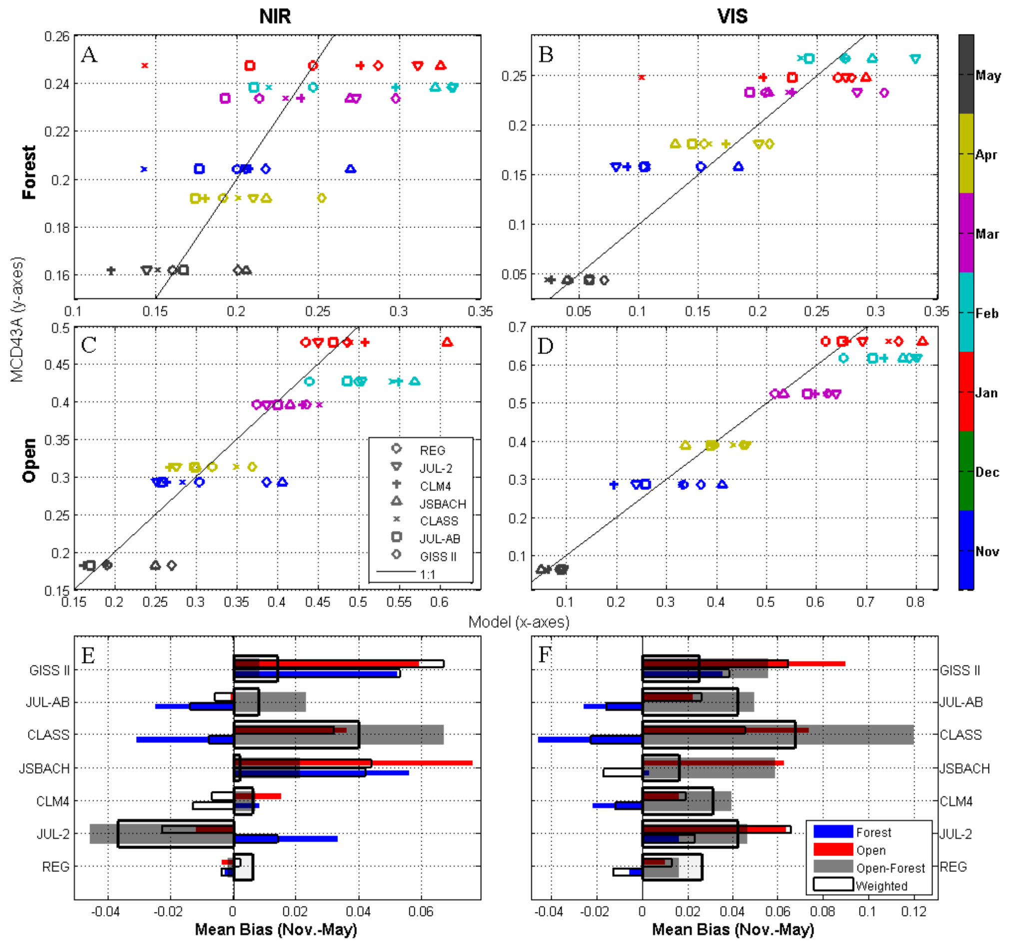


Figure ~~1~~2. A-D): ~~Correlations between the o~~Observed (MCD43A, y-axes) and modeled (x-axes) direct-beam albedos (monthly means, 2007-2009) in evergreen needleleaf forests (A & B)) and adjacent open areas (C & D) for both near-infrared ~~(left column, "NIR")~~ and visible bands ~~(right column, "VIS")~~ averaged across all three study regions; E) ~~NIR and~~& F): ~~VIS~~ Nov.-May mean bias (regional and monthly means, 2007-2009) and insolation-weighted mean bias. A), C), and E) = VIS band; B), D), and F) = NIR band. High solar zenith angles inhibited the number of sufficient MODIS retrievals in December, thus December mean biases were excluded from the Nov.-May mean; $MB = \frac{1}{N}\sum_{i=1}^{N}(\alpha_{Model} - \alpha_{Obs.})$

Moving on to the VIS band (Fig. ~~1~~2, right column), most schemes overpredicted α_s during ~~winter~~ months ~~(~~Jan. – Mar.~~)~~ at the Open sites. The largest spread (i.e., standard deviation (SD)) at the Open sites occurred during Nov. (SD = 0.08), where the largest negative bias was found for CLM4 and positive bias for JSBACH. Like in the NIR band, results varied more at the Forest sites where biases across months were more evenly distributed around zero (“~~r=~~1:1 line”). Again, here we found positive biases by JUL-2 yet negative biases by JUL-AB during Jan.-April.~~.~~ Positive biases by JSBACH were mostly confined to Nov., Jan., and Feb. at both Open and Forest sites~~.~~. Unlike the NIR band in which positive biases at Open sites by GISS II were limited to Nov., Apr., and May – ~~for the VIS band~~ positive biases occurred for the VIS band ~~occurred~~ in all months; however, the positive biases in Forests seen for the NIR band during Nov., Feb., and Apr. were reduced. Like the NIR band, large negative biases were found for CLASS for Nov., Jan., and Feb.

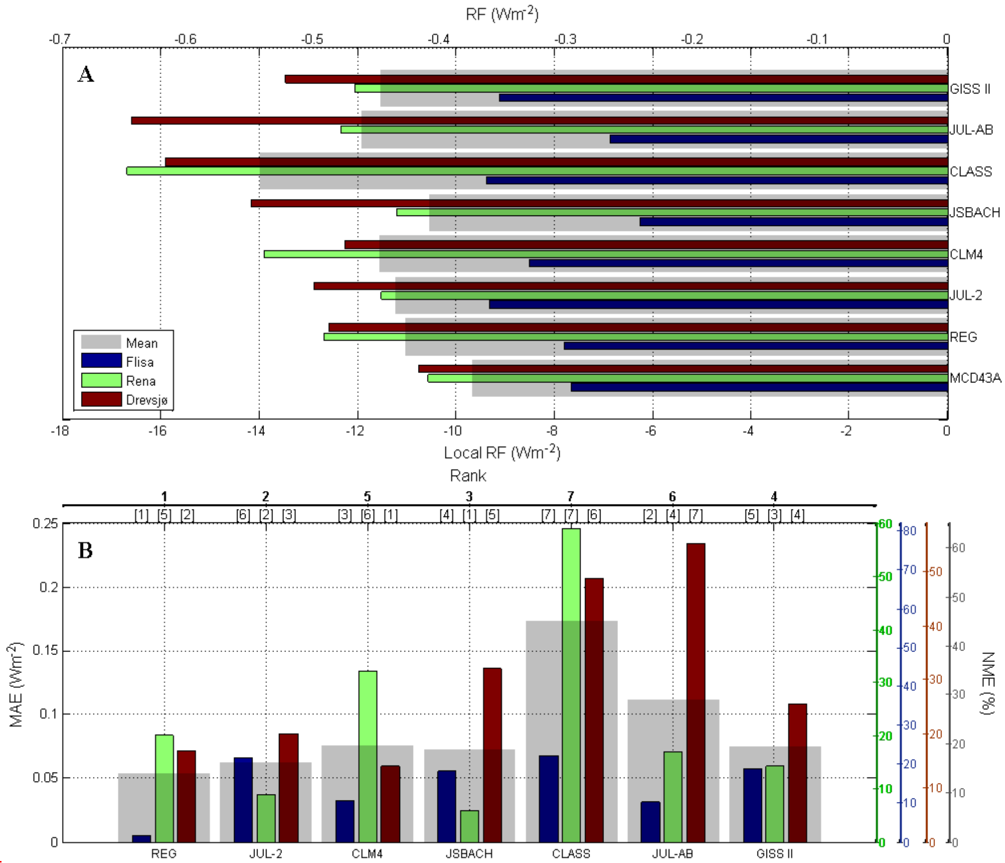
In general, Figure ~~1~~ 2 shows that the inter-model spread was smaller for the VIS band predictions relative to NIR, and at Open sites relative to Forest sites. Figure ~~1~~ 2 also indicates that the inter-model spread in α_s predictions for both bands and land cover types was larger during Nov. – Feb. and smaller during Mar. - May. With the exception of JUL-2 in the NIR band, all models overpredicted Nov. – May mean $\Delta\alpha_s$ (Fig. ~~1~~ 2 E & F, “Open – Forest”) in both spectral bands. Models with negative α_s biases at Forest sites and positive α_s biases at Open sites – such as CLASS and JUL-AB – led to some of the largest positive $\Delta\alpha_s$ biases. For some schemes like GISS II and JSBACH, positive α_s biases at both Open and Forest sites offset each other resulting in low $\Delta\alpha_s$ biases, particularly in the NIR band. Only for the NIR band (Fig. ~~1~~ 2 E) did any model underpredict $\Delta\alpha_s$. Here, JUL-2 under- and overpredicted α_s at Forest and Open sites, respectively.

Monthly α_s biases were often reduced when weighted by the relative share of monthly insolation during Nov.-May, as seen in Figure ~~1~~ 2 particularly for the JSBACH and CLASS schemes, which suggests that a large share of the bias occurred during winter months.

3.2 Radiative Forcing

Nov. – May mean (2007-2009) TOA RF from simulated LULCC (Δα, Open – Forest) are presented in Figure ~~2A~~ 3A for each of the three case study regions. In Rena and Drevsjø, all models overpredicted $\Delta\alpha_s$ and thus simulated LULCC RF. No clear patterns emerged regarding relationships between RF error, model, and study region; RF errors by REG, CLM4, and CLASS were larger in Rena (green bars) relative to Drevsjø (red bars) – while RF errors were larger for the JULES models, JSBACH, and GISS II for Drevsjø relative to Rena. One would expect a larger spread in the modeled RF for Drevsjø given the larger inherent variability in vegetation structure in the forest sample (~~SOM~~ Table ~~S~~1) and given the fundamental differences in the way each albedo scheme handles vegetation structure (SI ~~SOM~~ section S3), yet we found the largest inter-model spread occurring in Rena (RF SD = 0.075), where the normalized mean errors (NME) ranged from 6% - 58% for JSBACH and CLASS, respectively (Fig. ~~2B~~3B, green right-hand y-axis). For Drevsjø, the inter-model spread was smaller (RF SD = 0.067), with RF NME ranging from 14% - 54% for CLM4 and JUL-AB respectively. One possible explanation is that Rena experienced more frequent precipitation events, more fluctuating maximum daily temperature (above and below freezing), and a snowpack that tended to melt more rapidly in early spring than in Drevsjø (~~SOM~~ Figure S~~Figure S2~~1) – all of which complicated the prediction of ground and forest canopy α_s in the presence of snow.

The inter-model spread was lowest in Flisa (RF SD = 0.05), with RF NME ranging from 2% for the Regression model and 22% for CLASS, respectively. In Flisa, JSBACH and JUL-AB underestimated the strength of the vegetation masking effect ($\Delta\alpha_s$ bias) and thus the simulated LULCC RF. Together with CLASS, these two schemes also led to some of the largest RF spreads across sub-regions by any single model, where RF NME for JUL-AB ranged from 10% - 54% for Flisa and Drevsjø, respectively; for CLASS 22% - 58% for Flisa and Rena, respectively; and for JSBACH from 6%-32% for Flisa and Drevsjø, respectively.



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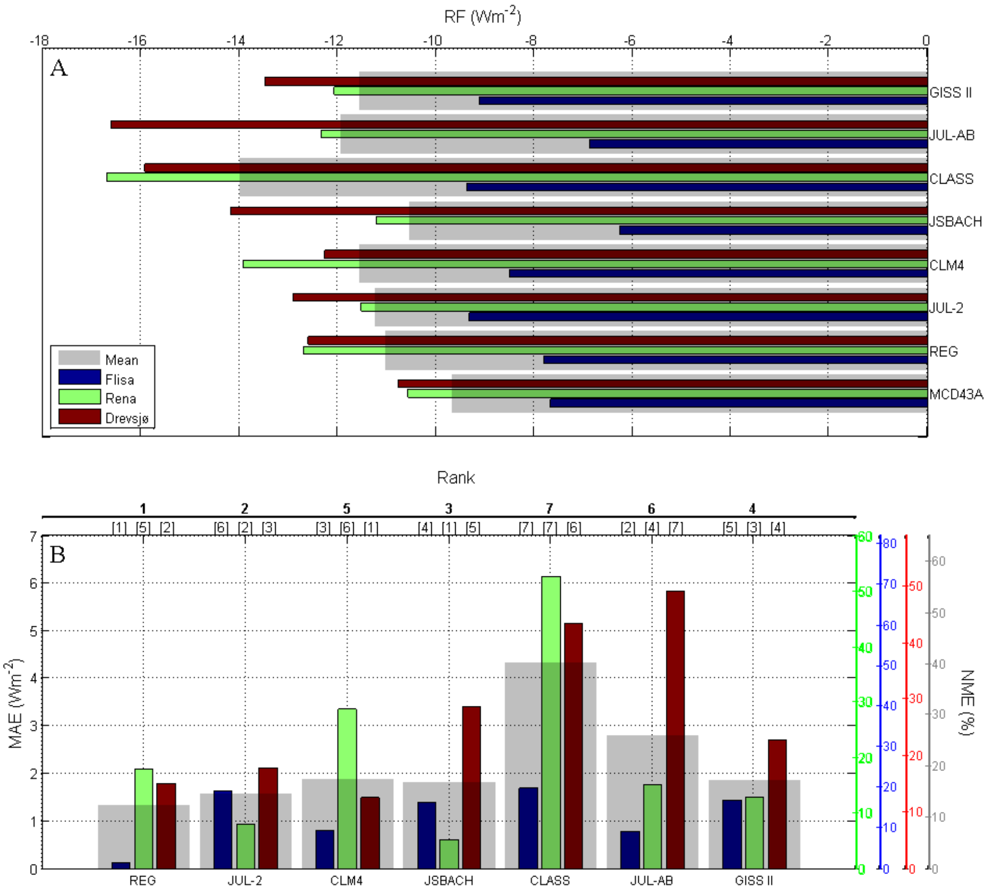

Figure ~~2~~3. A) Radiative forcing (RF) from simulated vs. observed (MCD43A) albedo ~~changes~~ differences (Open - Forest), 2007-2009 Nov. – May mean (excluding December). ~~The lower x-axis shows the difference between Open and Forest, whereas the upper x-axis show RF values weighted by the cropland fraction (same for all regions);~~ B) Mean Absolute Error (MAE) , Normalized Mean absolute Error (NME) , and ~~model~~ rank, 2007-2009 Nov.-May mean. Rank values in bold correspond to the regional mean, whereas individual case region ranks are listed over each bar (colors defined in A) legend). Right-hand y-axis (NME) colors correspond to individual bar colors.~~;~~ $$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|RF_{Model} - RF_{Obs.}\right| ;$$

$$NME = \sum_{i=1}^{N}\left|RF_{Model} - RF_{Obs.}\right|\left(\sum_{i=1}^{N}RF_{Obs.}\right)^{-1}$$

For JSBACH, the result of having ~~both~~ a positive $\Delta\alpha_s$ bias in Drevsjø (Table S6; Figures S25 & S28) and a negative $\Delta\alpha_s$ bias~~es~~ in Flisa (Table S6; Figures S23 & S26) is a regional mean RF (Fig. ~~2A~~3A, grey bar) that most closely resembled the MODIS based RF.~~;~~ ~~w~~With MAE (or NME) as a metric, however, JSBACH only ranked 3rd of 7 (Fig. ~~2B~~3B, top). Although not ranked 1st in all sub-regions, REG led to the most accurate regional mean RF prediction (MAE/NME, Fig. ~~2B~~3B, grey).

It is worth reiterating that some schemes such as that of GISS II severely overpredicted α_s at both Open and Forest sites (~~Tab. 3~~Fig. 2) which was not reflected in $\Delta\alpha_s$ or $\Delta\alpha_s$ RF, thereby giving the impression that the scheme ranked relatively high in accuracy.

5. Discussion

~~We hypothesized that climate model parameterizations of vegetation masking effects on surface albedo in boreal winter and spring could be further refined and improved in land surface models to increase prediction accuracy, although it is evident from our analysis that – for evergreen needleleaf forests – most of the existing schemes already do a reasonably good job at predicting~~ ~~α_s~~ ~~in the presence of snow, leaving little room for improvement. Given the multitude of vegetation structural, meteorological, and other site-specific physical factors involved in shaping the total~~ ~~α_s~~ ~~of the forest canopy and underlying surface, normalized mean absolute prediction errors (NME) of <20% in our~~ ~~$\Delta\alpha_s$~~ ~~RF simulations is considered a~~

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~~remarkably high accuracy for climate models that must depend on reduced complexity schemes (relative to 3D radiative transfer models or sophisticated snow-ice physics models).~~

A ~~surprising~~ notable finding of our study is that parameterizations of open area α_s – which is governed mostly by the albedo of snow from Jan. through early April – contributed as much to $\Delta\alpha_s$ prediction error as that of forests (Fig. ~~1~~2). The bias was mostly positive although there is some evidence that MODIS may underestimate the albedo of cold dry snow (Jin et al., 2002; Stroeve et al., 2005; Wang and Zender, 2010) – particularly in VIS bands (Wang and Zender, 2010) . Jin et al. (2002), for example, assert that there may be up to a 10% negative bias in the MODIS pure dry snow albedo (Jin et al., 2002), which could partially explain why most models in our study tended to overestimate α_s during the coldest months of Jan. and Feb. (Figure ~~1~~2). An additional source of negative MODIS albedo bias could stem from the spatial heterogeneity of the landscape comprising the actual pixel signature, which could extend up to 500 m beyond the specified spatial footprint at high latitudes (Cescatti et al., 2012; Wang et al., 2012) and thus include the spectral signatures of built structures, other vegetation cover (trees), vegetation shadowing (from trees), etc. We note also that Jan. and most of Feb. are months with solar zenith angles >70º for our case study regions; at these angles the atmospheric correction algorithm degrades and the uncertainty in the MODIS retrievals is increased (Lucht et al., 2000; Schaaf et al., 2002; Stroeve et al., 2005). Factoring in any potential negative MODIS snow α_s bias would reduce some of the positive open area biases (Figure ~~1~~2~~; SOM~~) but not all of it, particularly for CLASS and JSBACH, whose positive open area α_s biases were particularly large during months with snow cover. Snow α_s was reset to a maximum after a fresh snowfall event (Tab. ~~S3~~ S2 & ~~S4~~S3); however, MODIS albedo retrievals were far below the prescribed maximum snow albedo values of these two schemes after fresh snowfall events (Fig.'s ~~S24~~S23-~~26~~ 25 for JSBACH and Fig.'s ~~S30~~S29-~~32~~ 31 for CLASS), particularly for the VIS band.

The two schemes with regional mean RF NMEs (Fig. ~~2B~~3B) above 20% were the CLASS and JUL-AB schemes. For CLASS, RF NME >20% was realized for all three sub-regions. The $\Delta\alpha_s$ RF bias of CLASS was due to overpredictions at open area sites and underpredictions at forested sites. The latter is due to the parameterization of canopy transmittance that is based on an extinction coefficient that incorporates a correction factor of 0.~~3~~ 6 and 0.~~4~~ 8 for NIR and VIS bands, respectively (Eq.'s S10-S11). Lowering the~~se~~ correction factor to 0.~~25~~ 5 and 0.~~3~~ 6 for NIR and VIS bands, respectively, lowers the extinction coefficient and increases canopy transmittance, ~~serves to~~which serves to reduce ~~reduce~~ the negative albedo biases in forests~~,~~ – ~~–~~particularly at high solar zenith angles (Nov. – Feb.). The lower extinction coefficient is in line with more recent observations in boreal evergreen forests (Aubin et al., 2000; Balster and Marshall, 2000). As aforementioned, at the open sites the VIS albedo constant of 0.95 for fresh snow was too high; the maximum observed VIS albedo after a fresh snowfall event was 0.88 (all study regions), and adjusting to 0.90 would alleviate some of this bias (disregarding potential MODIS biases).

Although JUL-AB (formerly MOSES v. 2.2) ranked 6 of ~~th/~~7 overall when considering only the regional mean RF MAE and NME ~~(Tab. 4)~~, in two of the three study regions (Flisa and Rena) it performed quite well, with RF NMEs of <11% and <16% for Flisa and Rena, respectively. The large RF NME for Drevsjø was a result of a severe negative bias in the predicted α_s of forests (Fig. ~~S11~~S10), which resulted in large positive $\Delta\alpha_s$ biases (Tab. ~~S3~~S7). The explanation is due to the use of vegetation-specific snow albedo parameters that were too low for forests in this region – forests that were characterized as having the lowest median tree heights, LAIs, and canopy cover fractions out of the three forested sub-regions (Table ~~S~~1).

Of the existing land model schemes included in this study, the albedo parameterizations of JUL-2 performed best in the LULCC RF simulations (Fig. ~~2~~3), although we note that it underestimated the strength of the vegetation masking effect ($\Delta\alpha_s$) in the NIR band while overestimating it in the VIS band (Fig. ~~1~~2) (consistent across all three individual study regions (Tab. ~~S3~~S6)) which may have had offsetting effects in the RF simulations. A closer inspection of the daily α_s time series (Section S.5.2) hints that forest albedo (~~S15~~S14-~~17~~16) may be too sensitive to snow depth (Fig. ~~S2~~S1) – an important variable in the parameterization of snow cover fraction (Eq. S2). For example, α_s predictions were biased positive at snow depths above 0.6 m (typical in Rena and Drevsjø during the winter-spring of 2008 and 2009) while biased negative at Flisa during 2007 and 2008 for which snow depths never exceeded 0.4 m. This same sensitivity of forest α_s on snow depth was also found for the GISS II scheme – another Type 3 scheme – resulting in positive α_s biases in forests. This sensitivity to snow depth was not evident for JUL-AB – the third Type 3 scheme. This is because, unlike GISS II and JUL-2, snow albedo is vegetation-dependent and constrained by satellite observation (MODIS).

In agreement with findings in Essery (2013), we generally find that no single type of scheme (as described in section 2.1 and in Qu & Hall (2007)) stood out as performing better or worse relative to the others. In their latest CMIP5 simulations, Qu and Hall (2014) assert that type 2 schemes – or those which parameterize albedo as a function of vegetation cover rather than snow cover – generally tended to overestimate the strength of the snow albedo masking effect ($\Delta\alpha_s$) due to negative biases in forest α_s predictions. For JSBACH – a Type 2 scheme – we did not detect this bias; rather, we found positive biases in Forest in both bands, particularly during the snow season which is consistent with findings of Brovkin *et al.* (2013) and Hagemann *et al.* (2013). NIR albedo predictions in Flisa and Rena during snow-free periods were also biased high (figures in ~~SOM~~ SI section S.5.4) resulting in underestimations of NIR $\Delta\alpha_s$, which we attributed to a snow-free vegetation albedo constant that was too high (Table ~~S4~~S3). The positive RF bias seen at Drevsjø (Fig. ~~2~~3) stemmed from negative biases in the springtime (Mar. – May) VIS α_s in forests (Fig. S29). This may be attributed to the default use of 1 as the stem area index (SAI) used in the masking parameterization (Reick et al., 2012); observational evidence suggests this may be too high in boreal regions in spring (Lawrence and Chase, 2007).

While the simulated $\Delta\alpha_s$ RF by GISS II appeared relatively robust (Fig. ~~2~~3), α_s predictions in Forest and Open were strongly positively biased in both spectral bands. In forests, this could be attributed to two main factors: i) a dependence on snow-free albedo constants that were too high, particularly when applied at the denser (i.e., high canopy cover fraction~~CC%~~, Tab. ~~S~~1) sites of Flisa and Rena; ii) a strong dependency on snow depth and/or lack of explicit representation of forest structure in the masking expression which led to overpredictions in Rena and Drevsjø (Figs. ~~S40~~ S39 & ~~S41~~S40) – regions that experienced snow depths greater than 60 cm for much of the winter and early spring in 2008 and 2009 (Mar. – late Apr.). NIR biases at the open sites (Figures ~~S36~~S35-~~38~~37) were attributed to the use of snow-free vegetation constants that were too high (Tab. ~~S5~~S4).

Sources of RF biases in CLM4 were harder to discern, as the sign of the predicted $\Delta\alpha_s$ bias was not consistent across study sites and months. $\Delta\alpha_s$ bias was negative and mostly limited to March and April at Flisa and Rena (Tab. ~~S3~~S6). $\Delta\alpha_s$ bias was positive at Drevsjø and occurred mostly in April and May due to overpredictions in both NIR and VIS α_s in Forest and underpredictions in both NIR and VIS α_s at Open sites (Fig.'s ~~S18~~S17-~~23~~22).

Not surprisingly, the purely empirical α_s model presented here (Eq. 1) calibrated with local forest structure and meteorological observations performed best on average throughout the region (i.e., Fig. ~~2~~3; MAE, NME, and Rank). However, to our surprise, it did not rank first in all study regions; it ranked 5th in Rena which was the region having the fewest forest structure, meteorological, and MODIS albedo retrievals. This highlights the high performance dependencies of purely empirically-based models ~~to~~ on the underlying datasets to which they are calibrated. Although it is tempting to recommend its application over existing modeling schemes in boreal regions, rigorous evaluation efforts would be needed to assess the degree of transportability and reliability when applied in other regions having different forest structures and climate regimes ~~(Bright et al., 2014)~~ (Bright et al., 2015).

5.1 Conclusions

~~Simulated seasonal~~ LULCC radiative forcings (RF) from changes in simulated land surface albedo ($\Delta\alpha_s$) as predicted by the albedo parameterizations employed by six~~six of the world's~~ leading climate models were evaluated using observed meteorology and forest structure for a case region in Norway and by comparing to MODIS daily albedo retrievals. Compared to RF ~~simulations~~ estimations based on~~based on~~ MODIS albedo~~albedo~~, ~~all six models plus an additional empirical model developed here~~most of the albedo schemes overestimated the magnitude of the simulated regional mean RF (Fig. ~~2~~3) by overestimating $\Delta\alpha_s$ (Fig. ~~1~~2), although results varied between three sub-regions within the broader case study region. For instance, in a sub-region characterized as having the highest forest productivity and lowest seasonal snow cover of the three (Flisa), ~~two of the models~~ albedo schemes of two land models (JSBACH and JULES All-band) underestimated $\Delta\alpha_s$ RF ~~(JSBACH and JULES All-band)~~.

Efforts to uncover sources of systematic albedo biases proved challenging as no clear discernible patterns could be detected across study regions or between the different types of schemes (section 2.~~1~~3), although some systematic sources of bias in forest α_s were identified for the albedo schemes of CLASS, JULES All-band, JSBACH, and GISS II ~~schemes~~. Severe negative albedo bias in winter months by CLASS -- evident across all three study regions -- was attributed to the parameterization of canopy transmittance. For GISS II, persistent positive α_s biases were linked to snow-free vegetation albedos (both VIS and NIR bands) that were too high and to a snow cover masking parameterization that did not explicitly account for differences in forest structure. Biases in forests in the JULES All-band scheme can be easily alleviated by adjusting (in our case increasing) the vegetation-dependent snow albedo values for "Evergreen Needleleaf" forest, which, in our study, were based on MODIS latitude band averages (Gao et al., 2005). Similarly for JSBACH, forest biases can be easily reduced by lowering the snow-free vegetation albedo value in the NIR band.

~~Nevertheless~~Despite the albedo biases identified here in both forests and open areas, the normalized mean absolute error (NME) of the three-year regional mean RF from the LULCC simulations was below 20% for four of the six albedo schemes, which is a remarkably high accuracy for climate models considering that they must depend on reduced complexity land surface schemes (relative to 3D radiative transfer models or sophisticated snow-ice physics models). Although we have only evaluated evergreen needleleaf forests, extending this~~given the complexities involved in parameterzing the albedo of forests in boreal winter and spring (in the presence of snow), given the diversity of climate regimes and forest structure types that models must be designed to accommodate, and given the reduced complexity~~

~~requirements of albedo parameterizations by global climate models – our study should give some reassurance to climate modelers that recent efforts to improved parameterizations of vegetation masking effects are leading to more accurate predictions of surface albedo and hence climate change predictions linked to LULCC.~~ or similar empirical analyses to other forest types or climate regimes would give additional insight into the albedo predictive capacities of the parameterizations employed in the current generation of climate models.

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