Dear Dr. Roche,

Point-by-point responses to the referee comments on the manuscript *gmd-2014-59 "Evaluation of North Eurasian snow-off dates in the ECHAM5.4 atmospheric GCM"* are given below. The page and line numbers refer to the marked-up version of the revised manuscript, where deletions are marked with red and additions with blue colour. For convenience, running line numbers are used.

Please note that one more coauthor (Kari Luojus, Finnish Meteorological Institute) has been added to the revised manuscript. He provided extensive help with snow cover fraction datasets (analyzed in response to a comment by Ref. #2) and he also commented on the revised manuscript.

Sincerely, on behalf of myself and my coauthors,

Petri Räisänen

Response to comments by Richard L. H. Essery

We thank Richard L. H. Essery for his constructive comments on the manuscript. Point-by-point responses to the comments are provided below. The referee comments are written in *italic* font, and our responses in normal font.

Comment: *Räisänen et al. investigate the ability of a specific atmospheric climate model (ECHAM5) to reproduce the annual duration of snow cover for Northern Eurasia, and assess the possibility of improving the simulations by constraining model fields to be closer to reality or changing model parameter values. Although by no means the first such investigation, this is an interesting and worthwhile study. For the benefit of readers who are not familiar with the details of current practice in modelling snow processes, it should be pointed out that there are climate models that address all of the limitations of ECHAM5 identified by the authors: unrealistic temperature dependence of snow albedo, combined energy balance for subgrid snow and snow-free land fractions, and lack of snow shading by forest canopies. A good exemplar of the state of the art in snow parametrizations for climate modelling is given by the CLM land-surface model used in the CESM climate model; see http://www.cesm.ucar.edu/models/cesm1.0/clm/CLM4_Tech_Note.pdf.*

Response: The fact that there are climate models with more sophisticated treatment of snow than that in ECHAM5.4 (in particular the CESM model) is mentioned in the revised manuscript (at the end of the Discussion section). Please see also our response to the last comment.

Change in the manuscript: This issue is discussed on p. 27–28 (lines 710–720) of the revised manuscript.

Comment: *page 3672, lines 21-22 (also 3673, 28 and 3681, 20-21). Please consider doi:10.1029/2010EO450004.*

Response and change: In the revised manuscript, these sentences are rewritten so that the use of parentheses is eliminated. See p. 2 (lines 20–21); p. 3 (line 51); and p. 12 (lines 276–278).

Comment: *3673, 23. Derksen and Brown (doi:10.1029/2012GL053387) is another important recent work evaluating CMIP5 snow cover simulations.*

Response and change: This reference has been added to the Introduction of the revised manuscript. See p. 4, lines 59–61.

Comment: *3679, 25. Brackets required around LAI + SAI.*

Response and change: This is corrected in the revised manuscript. See Equation (8) on p. 10.

Comment: *3684, 18. "locally exceeds 20 days" or "exceeds 20 days locally" would be better.*

Response and change: Thanks. We prefer the first form. The correction is on p. 16, lines 382–383 of the revised manuscript.

Comment: *3685, 14. Snow does not necessarily persist longer in forests than on open ground – the recent review of observations by Lundquist et al. (doi:10.1002/wrcr.20504) shows shorter duration for forests in warmer regions.*

Response: The discussion of this issue is modified in the revised manuscript. Thus, it is mentioned that the later snow-off in forests than on open ground is consistent with the findings of Lundquist et al. (2013) for regions with relatively cold winters, but it is also noted that the opposite behaviour has been observed in regions with warmer winters. A brief discussion on the various (opposing) physical mechanisms influencing the difference in snow-off timing between forested and non-forested regions is also added.

Change in the manuscript: On p. 17, lines 411–414, the note about "conventional wisdom" has been deleted, so that this sentence now reads: *The more negative differences for the forest snow courses than for the open-terrain snow courses indicate that snow tends to persist longer in forests than on open ground.* The issue is then further discussed on p. 17 (lines 419–430). Further, there is a slight change of wording on p. 17, line 695: *explains delayed* is replaced by *acts to delay*.

Comment: *3686, 27. Again, less snow is often observed to accumulate in forests due to canopy interception than on nearby open ground that is not affected by wind scour; see, for example, Figure 4 in Lundquist et al. or Essery et al. (doi:10.1175/2009BAMS2629.1).*

Response: The finding of more accumulation in forests than on open ground seems to be a robust feature for the current dataset (it also holds true when the comparison is restricted to those grid cells and years with both forest and open-terrain observations). It is mentioned in the revised manuscript that the opposite has been observed in several previous studies (which have, however, mainly considered lower-latitude sites).

Change in the manuscript: This is discussed on p. 20 (lines 506–513) in the revised manuscript.

Comment: *3687, 14. "makes snow-off occur".*

Response and change: This is corrected in the revised manuscript (p. 21, line 528).

Comment: *3693, 25. For future work with CMIP5 model outputs, it would be interesting to see if the CLASS land surface scheme (which is an unusual example of a model with separate energy budgets for snow and snow-free land) in the CanCM4 climate model behaves differently from ECHAM5.*

Response: At the end of the Discussion section (Section 6) in the revised manuscript, it is mentioned that there are climate models in which the snow scheme addresses either some or all of the deficiences identified for ECHAM5 in this work, and which might therefore be expected to behave better (or at least differently) than ECHAM5. The CESM/CLM4 and CanCM4/CLASS are mentioned as specific examples.

Change in the manuscript: This is discussed on p. 27–28 (lines 710–720).

Response to Anonymous Referee #2

We thank Referee #2 for his/her constructive comments on the manuscript. Below, the referee comments are written in *italic* font, and our responses in normal font.

General Comments

This paper utilizes in situ snow course measurements and satellite passive microwave estimates of snow off date to evaluate the ECHAM4.5 atmospheric GCM. Because neither the in situ measurements, satellite data, nor model simulations provide direct values of snow off date, clear explanations and justifications are provided for the derivation of snow off date from these three sources. A set of historical ECHAM4.5 sensitivity simulations were utilized to show the model response to nudged parameters related to atmospheric circulation, and changes to the parameterization of surface albedo in the model. In situ measurements from Sodankyla, Finland provide convincing evidence that early snow melt in the simulations, despite a cold temperature bias, are due to the failure to calculate the energy budget separately over snow-covered and snow-free fractions of the grid cell. Explanation for the regions with a late snow melt bias are somewhat less convincing, but the attribution to the lack of vegetation canopy shading in the model seems sound. I have a number of suggestions that will hopefully improve the final version of the manuscript.

Comment: *1. The introduction provides clear information on the background and context for this study, but some fundamental citations on simulated versus* *observed snow albedo feedbacks are missing. I suggest consideration of the following:*

Qu, X., and A. Hall. 2007. What controls the strength of snow-albedo feedback? Journal of Climate. 20: 3971-3981. DOI: 10.1175/JCLI4186.1

Qu, X., and A. Hall. 2014. On the persistent spread in snow-albedo feedback. Climate Dynamics. 42:69-81. DOI 10.1007/s00382-013-1774-0.

Fletcher, C., H. Zhao, P. Kushner, and R. Fernandes. 2012. Using models and satellite observations to evaluate the strength of snow albedo feedback. Journal of Geophysical Research. VOL. 117, D11117, doi:10.1029/2012JD017724.

Response and change: These references are mentioned in a paragraph on snow-albedo feedbacks that has been added in the Introduction in the revised manuscript. See p. 4, lines 69–78.

Comment: *2. Page 3676 lines 26–27: "The ECHAM5 snow scheme considers both SWE intercepted by the canopy and SWE on the ground, the latter being more interesting for this study." Recent work with the Community Land Model has shown the importance of snow-canopy processes as a source of simulation error in snow albedo (http://onlinelibrary.wiley.com/doi/10.1002/2014JD021858/abstract). While the importance of these processes are certainly model dependent, the role of snow-vegetation interactions can be significant.*

Response: The reason for including this sentence in the original manuscript was that obviously, snow-off time depends *directly* on SWE on the ground only, so it is more relevant to describe the latter in detail. It was, however, not our intention to give the impression that snow-canopy processes are unimportant in general.

Change in the manuscript: To avoid the impression that snow-canopy processes are unimportant, we have deleted the words "the latter being more interesting for the present study", and we also added a reference for the canopy snow scheme, should the reader be interested in its details:

Roesch, A., Wild, M., Gilgen, H., and Ohmura, A.: A new snow cover fraction parametrization for the ECHAM4 GCM, Clim. Dynam., 17, 933–946, 2001.

See p. 7, lines 139–141, in the revised manuscript.

Comment: *3. Page 3678 line 6: what is the depth threshold for determining 100% snow cover in the model?*

Response: In fact, the snow cover never reaches 100%. The snow cover fraction is parameterized using a *tanh* function which approaches asymptotically 95% with increasing SWE, and also depends on the subgrid-scale standard deviation of surface elevation, as described in Roesch et al. (2001; reference provided above).

Change in the manuscript: This is discussed on p. 7 (lines 156–162) in the revised manuscript.

Comment: *4. 1978–2006 covers the CMIP5 historical simulation time period. Rapid reductions in spring SCE, including northern Eurasia, has occurred between 2007 and 2012, as described in:*

Derksen, C., and R. Brown. 2012. Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. Geophysical Research Letters. 39: L19504 doi:10.1029/2012GL053387

Are there any implications on the results of this study related to the 1979–2006 time period? Most CMIP5 models do not capture the observed spring snow reductions over the past 7 years, but the radiometer derived snow off dataset would allow evaluation of model performance during this recent period of rapid change. It is not necessary to add these years to the current paper, but some statements on this issue could be added to the Discussion.

Response: The extent of the model runs was determined by the availability of input and validation data at the time that the work related to this paper was started (which, unfortunately, was a few years ago). It is pertinent to point out that the simulation period excludes the years 2008–2012 with a rapid reduction in late spring snow cover. Other than that, we prefer not to speculate on this issue in the manuscript, (i) for brevity, (ii) because such a discussion would indeed be speculative, and (iii) because it seems very likely that including these years would not change the conclusions of the paper in any substantial way.

To expand a bit on this reply, it should be recalled that the paper deals with the evaluation of the *mean* snow-off date and related quantities over the period

1979–2006. Extending the period to 2012 would most likely cause only small quantitative changes in the results. First, it would only increase the number of analyzed years from 28 to 34, so that the years 2007–2012 would have a weight factor of only 18% for the mean values. Second, the simplifications of the model physics, such as the rather unsatisfactory treatment of the surface energy budget in the presence of fractional snow cover, would probably have largely similar effects even for these years.

Of course, as Derksen et al. (2012) show that climate models in general fail to capture the rapid reduction in snow cover in 2008–2012, this could also be true of ECHAM5. In that case, ECHAM5's tendency towards too early snow-off would be less pronounced during these years than during 1979–2006. Even if it proved to be so, it may be asked how relevant this would be. While climate change is expected to result in reduced springtime snow cover and earlier snow-off, the observed acceleration of this trend might be, at least in part, a manifestation of internal climate variability. In general, climate simulations cannot be expected to match the observed internal variability.

Were this paper focused on trends in snow-off time, extending the period to 2012 would be of more interest. We opted to leave out the analysis of trends (i) to keep the length of the paper reasonable, and (ii) because uncertainties related to internal variability (both modelled and observed) would play a larger role than in the case of mean values for the whole period.

Change in the manuscript: The following sentence has been added on p. 8–9, lines 187–189: *Note that the years 2008–2012 during which a rapid reduction in Northern Hemisphere May–June snow cover has been observed (Derksen and Brown, 2012) fall outside this period.*

Comment: *5. This study utilizes a small number of model runs, 3 or 1 depending on the experiment. Was internal model variability with respect to snow parameters quantified at all? A small standard deviation in the 28 year mean snow off date from 3 model runs is used to justify the small number of members. But how does the model variability compare to the observed variability in snow off date? I suggest a panel be added to Figure 2 which shows the standard deviation in satellite derived snow off date as is provided in Figure 2d for the reference simulations.*

Response: As emphasized above, the focus of this paper is on the time-mean snow-off date averaged over 1979–2006. And, as noted in the referee comment, the effect of internal model variability on this is quantified by the standard deviation in Fig. 2d. The figure suggests that the 28-year mean value is a relatively robust quantity, even when derived from a single model run. We also looked at the differences in the mean annual cycle of SWE between the three runs in the REF experiment, with the same basic conclusion (figure not shown).

A comparison of interannual standard deviation of snow-off date in the REF experiment and in the satellite data shows that the std. dev. in ECHAM5 is generally similar to the observations, though with some regional differences.

Change in the manuscript: The interannual standard deviation of snow-off date is shown in Fig. 3e,f of the revised manuscript (originally Fig. 2), and is discussed on p. 16 (lines 393–399).

Comment: *6. Page 3681 lines 5-11: I was confused by the terminology in this paragraph with respect to 'snow melt date' and 'snow off date'. 'Snow melt' is the onset of wet snow, which the radiometer measurements are very sensitive to. 'Snow off' date is the time when the land surface is free of snow, and occurs at some time lag after snow melt onset. The snow course data can be used to evaluate both of these terms in the radiometer dataset through the use of the snow status flag (for melt onset) or snow depth (snow off when snow depth = zero). It's not clear in this paragraph how the microwave snow off estimates were calibrated. It seems snow melt information was used for calibration but the microwave dataset also provides the snow off date. It's important to clarify this description since the in situ measurements, satellite data, and model simulations each provide indirect values of snow off date.*

Response: First, we note that on p. 3681, line 8 of the original manuscript "snow-off date" should be used instead of "snowmelt date" (which in our opinion is an ambiguous term — it can refer to anything between the onset of snow melt and snow-off). This is corrected in the revised manuscript.

Regarding the calibration of the microwave dataset, the terms "temporary melting" and "continuous melting" both refer to a situation where there is no snow left at the weather station to be measured, "continuous melting" indicating summer(!). While this terminology might not be the clearest possible, we prefer to use these terms to be consistent with the description of the microwave satellite algorithm in Takala et al. (2009; cited in the manuscript) and with the original documentation of the INTAS-SCCONE dataset. However, the meaning of these terms is clarified in the revised manuscript.

Change in the manuscript: The relevant sentence now reads (p. 11, lines 262–266): *Specifically, for the calibration data, the snow-off date was defined as the last event during spring when the station snow status flag changed from "snow depth is correct" to "temporary melting" or "continuous melting", both of which refer to a situation in which there is no snow left at the station.*

Comment: *7. The potential differences in how the satellite radiometer and snow course datasets characterize 'snow off' is a source of uncertainty in the model evaluation. I suggest a plot be added which shows a comparison between the microwave and snow course derived snow off dates (i.e. as a scatter plot) for those grid cells where both datasets are available.*

Response: We have added a scatter plot showing the relation between snow-off date in the satellite and snow course datasets. To be most consistent with the model-to-observation comparisons in the paper, the scatter plot is presented in terms of time-mean values for 1979–2006 (using only those years with available snow course data also for the satellite data), at T63 resolution. The comparison shows that on average, the snow-off date derived from the satellite data is 5 days later than that derived from the snow course data, although some of the grid cells feature substantially larger (positive and negative) differences.

Change in the manuscript: The scatter plot is shown in Fig. 2 of the revised manuscript, and it is discussed in the last paragraph of Section 4 (p. 14–15, lines 347–359).

Comment: *8. Figure 5 shows the differences in simulated versus satellite retrieved surface albedo. Is it possible to determine if these differences are driven by snow cover fraction biases or albedo parameterization uncertainties? I suggest adding panels to Figure 5 which show spatial patterns of snow extent or snow fraction bias in the model compared to an observational baseline.*

Response: There are several potential causes for the albedo differences, including the parameterization of snow albedo, snow cover fraction, vegetation effects, and inevitably, also observational inaccuracy. It would be quite difficult to disentangle comprehensively the role of these factors, but to shed some light on this issue, snow cover fraction and vegetation are considered in the revised manuscript. (Please also see our response to the next comment).

Thus, we have added figure panels with snow cover fraction biases, along with related discussion, in the revised manuscript. It is of note, though, that the choice of an observational baseline for snow cover fraction is not a trivial issue. After considering a few alternatives, we chose to use the European Space Agency GlobSnow snow extent dataset (Metsämäki et al. 2015). The primary reason for choosing this dataset, rather than (e.g.) those described in Brown and Robinson (2011) or Zhao and Fernandes (2009), is that the fractional snow retrieval in GlobSnow uses the SCAmod method designed ecpecially to enable accurate snow mapping including forests, which cover a large part of the Northern Eurasia. A downside of GlobSnow is that (springtime) data is only available since 1997. However, this should not be a major issue for the comparison with the albedo biases in 1982–2006, because ECHAM5's albedo biases are similar from one year to another. In fact, the spatial correlation between albedo biases for 1997–2006 and 1982–2006 is $\approx$0.99 for March through May and $\approx$0.98 for June.

It is found that the REF simulation underestimates snow cover fraction compared to GlobSnow throughout most of Northern Eurasia even in March (when the amount of snow is close to maximum), but that the bias is most pronounced in the snow melt season (in April–May in Western Russia, and in June in the Taymyr peninsula), consistent with too early snow-off. It is concluded that underestimated albedo in the tundra region in spring is a consequence of both underestimated snow cover fraction and unrealistic temperature dependence of snow albedo.

References:

Brown, R.D. and Robinson, D.A., Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty, The Cryosphere, 5, 219–229, www.the-cryosphere.net/5/219/2011/, 2011

Metsämäki, S., Pulliainen, J., Salminen, M., Luojus, K., Wiesmann, A., Solberg, R., Böttcher, K., Hiltunen, M., Ripper, E., Introduction to GlobSnow Snow Extent products with considerations for accuracy assessment, Remote Sensing of Environment, 156, 96–108, doi: 10.1016/j.rse.2014.09.018., 2015

Zhao H. and Fernandes, R., Daily snow cover estimation from Advanced Very High Resolution Radiometer Polar Pathfinder data over Northern Hemisphere land surfaces during 1982-2004, J. Geophys. Res., 114, D05113, doi:10.1029/2008JD011272, 2009.

Change in the manuscript: The GlobSnow dataset is introduced on p. 12–13, lines 292–302. The comparison of snow cover in the REF experiment with GlobSnow data is shown in Fig. 6 (panels b,d,f,h) and discussed on p. 18–19 (lines 444–470). Furthermore, the discussion of albedo biases in the ALB2 and ALB2_NDG experiments is modified to account for the low bias in snow cover fraction (on p. 24, lines 604–607). Finally, underestimated snow cover is also mentioned as a factor contributing to the albedo bias in Conclusions (p. 28, line 743).

Comment: *9. Given the potentially important role of forest cover in this study, it would be helpful to provide an observationally derived forest classification and a dominant plant functional type map for ECHAM4.5 as extra panels in Figure 2.*

Response: ECHAM5.4 is run here in its default configuration (i.e., without the JSBACH land-biosphere module), in which the description of vegetation is rather simple. No plant functional type map is explicitly defined. Rather, the only relevant vegetation parameters for the current work are forest fraction and leaf area index. These parameters, along with the forest fraction derived from the GlobCover 2009 dataset (Bontemps et al. 2011; Arino et al. 2012) are shown in a new figure in connection with the discussion of modelled vs. observed albedo, rather than as extra panels in Fig. 2. This figure clearly shows a strong connection between forests and positive albedo biases in the REF experiment. In particular, the most pronounced biases in central and eastern Siberia are associated with deciduous needleleaf forests with very low LAI in March–April.

References:

Arino, O., Ramos Perez, J. J., Kalogirou, V., Bontemps, S., Defourny, P., and Van Bogaert, E.: Global land cover map for 2009 (GlobCover 2009), European Space Agency (ESA) and Université Catholique de Louvain (UCL), doi:10.1594/PANGAEA.787668, 2012.

Bontemps, S., Defourny, P., Van Bogaert, E.; Arino, O., Kalogirou, V., and Ramos Perez, J. J.: GLOBCOVER 2009 Products description and validation report. Université Catholique de Louvain (UCL) and European Space Agency (ESA), Vers. 2.2, 53 pp., http://epic.awi.de/31014/16/GLOBCOVER2009_Validation_Report_2-2.pdf, 2011.

Change in the manuscript: A new figure showing the GlobCover forest fraction, ECHAM5 forest fraction and LAI in ECHAM5 has been added (Fig. 7 in the revised manuscript). This figure is discussed on p. 19 (lines 471–484). In addition, the GlobCover dataset is introduced in Section 3 (p. 13, lines 303–306).

Editorial Changes

Comment: *The term 'fields' is used throughout the paper to refer to non-forested areas. I suggest changing this to 'open' which better captures non-forested regions both above (i.e. tundra) and below the treeline.*

Response and change: The term "open-terrain" snow course is used in the revised manuscript. A footnote explaining that this terminology differs from the original data source is added on p. 12.

Comments:

Page 3687 line 14: change 'snow-off to occur' to 'snow-off occur'
Page 3689 line 11: change to 'The changes in snow-off timing ...'
Page 3690 line 23: change 'represented' to 'presented'

Response and changes: Thanks for pointing out these. These are corrected in the revised manuscript. The corrections can be found on p. 21 (line 528), on p. 23 (line 580) and on p. 24 (line 624).

Other changes in the manusscript

In addition to those listed above, there are only very minor changes in the revised manuscript:

- A side effect of the responses to comments 8 and 9 by Referee #2 is that Section 5.1 has become rather long. To make it a bit more manageable for the reader, we split it into two subsections: 5.1.1. *Snow-off timing*, and 5.1.2. *Other snow-related quantities.*
- On p. 21, line 529, *western Finland* was replaced by *Fennoscandia*. A couple of the grid points discussed here are, in fact, in Sweden and Norway.
- Several very small changes to correct typographic and language errors, to eliminate repeated definition of the acronyme SWE, etc.

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Evaluation of North Eurasian snow-off dates in the ECHAM5.4 atmospheric GCM

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Abstract

The timing of springtime end of snow melt (snow-off date) in Northern Eurasia in version 5.4 of the ECHAM5 atmospheric GCM is evaluated through comparison with a snow-off date dataset based on space-borne microwave radiometer measurements and with Russian snow course data. ECHAM5 reproduces well the observed gross geographical pattern of snow-off dates, with earliest snow-off (in March) in the Baltic region and latest snow-off (in June) in the Taymyr Peninsula and in northeastern parts of the Russian Far East. The primary biases are (1) a delayed snow-off in southeastern Siberia (associated with too low springtime temperature and too high surface albedo, in part due to insufficient shielding by canopy); and (2) an early bias in the western and northern parts of Northern Eurasia. Several sensitivity experiments were conducted, where biases in simulated atmospheric circulation were corrected through nudging and/or the treatment of surface albedo was modified. While this alleviated some of the model biases in snow-off dates, 2 m temperature and surface albedo, especially the early bias in snow-off in the western parts of ~~the~~ Northern Eurasia proved very robust and was actually larger in the nudged runs.

A key issue underlying the snow-off biases in ECHAM5 is that snow melt occurs at too low temperatures. Very likely, this is related to the treatment of the surface energy budget. On one hand, the surface temperature T_s is not computed separately for the snow-covered and snow-free parts of the grid cells, which prevents T_s from rising above 0 °C before all snow has vanished. Consequently, too much ~~(too little)~~ of the surface net radiation is consumed in melting snow ~~(~~and too little in heating the air~~)~~. On the other hand, ECHAM5 does not include a canopy layer. Thus, while the albedo reduction due to canopy is accounted for, the shielding of snow on ground by the overlying canopy is not considered, which leaves too much solar radiation available for melting snow.

1 Introduction

Snow cover is one of the most important elements in the climate and hydrology of the Northern Hemisphere. Large areas of the Eurasian and North American continents are covered by seasonal snow. The varying snow cover affects directly the surface energy balance by interfering with the energy storage, net radiation and fluxes of sensible and latent heat. A significant positive feedback mechanism of the snow, albedo and solar radiation amplifies the climatic effects related to the snow cover: decreasing snow cover reduces the surface albedo and increases the amount of absorbed solar radiation at the surface, leading to increased melting and further reduction in the snow cover. The snow-albedo feedback is largest when changes in snow cover area are linked with substantial changes in regional albedo (Brown, 2000). This coincides with the maximum influence of snow cover on surface net radiation in spring, typically in April and May, when ~~the~~ strong solar radiation and snow cover co-exist (Groisman et al., 1994). Snow cover also serves as a fresh water reservoir, thus regulating run-off in winter and spring, and influencing soil moisture content. Typically, delayed snow melt can increase spring and summer soil moisture content which can further contribute to cooler and wetter weather conditions even after the snow melt (Cohen, 1994), and conversely for early snow melt (Wetherald and Manabe, 1995; Rowell and Jones, 2006; Kendon et al., 2010).

The key climatic role of snow cover has prompted a wide range of observational and modelling studies on the topic. These include several intercomparisons of snow conditions simulated by atmospheric and fully coupled general circulation models (GCMs) with observational data ~~(Foster et al., 1996; Frei and Robinson, 1998; Frei et al., 2003, 2005; Roesch, 2006; Brutel-Vuilm~~ Most recently, Brutel-Vuilmet et al. (2013) evaluated the snow cover simulated by models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5). In terms of the multi-model average, the models reproduced the observed snow cover extent very well, with a slight tendency toward too late ~~(early)~~ snow melt in Eurasia ~~(~~and too early snow melt in northern North America~~)~~. However, there was still substantial inter-model dispersion around the multi-model average. Moreover, the results highlighted two issues already found in earlier intercomparison studies. First, the interannual variability in Northern Hemisphere snow cover extent was underestimated by almost all models, which was already noted by Frei and Robinson (1998) in an analysis of Atmospheric Model Intercomparison Project, phase 1 (AMIP1) models. Second, the models underestimated considerably the observed negative trend in snow cover in spring (for years 1979–2005), which is similar to the findings of Roesch (2006) for CMIP3 models. Derksen and Brown (2012) further demonstrated, for a subset of eight CMIP5 models, that the models failed to capture the rapid decline in Northern Hemisphere late spring (May–June) snow cover observed in 2008–2012.

Regarding the reasons for biases in modeled snow conditions, the intercomparison studies have, in general, not been very conclusive. Most attention has been paid to biases in simulated air temperature (Foster et al., 1996; Räisänen, 2008) and total precipitation or snowfall (Foster et al., 1996; Roesch, 2006; Brutel-Vuilmet et al., 2013). Frei et al. (2005) further suggested that the exclusion of subgrid-scale treatments for terrain and land cover contributed to overestimated ablation rate of snow in spring over North America in AMIP2 models.

Multi-model intercomparisons have also demonstrated that the strength of snow-albedo feedback (SAF) varies substantially among both CMIP3 (Hall and Qu, 2006; Qu and Hall, 2007; Fletcher et al., 2012) and CMIP5 models (Qu and Hall, 2014) . There is a strong correspondence between the SAF evaluated based on transient climate change experiments and based on the seasonal cycle. Model results for the seasonal SAF fall on both sides of the corresponding observational estimates (Hall and Qu, 2006; Fletcher et al., 2012; Qu and Hall, 2014) . The simulated SAF is strongly influenced by the climatological surface albedo of snow-covered land, which shows a surprisingly large spread even among the CMIP5 models. Presumably, this is related to how vegetation masking of snow-covered land is treated (Qu and Hall, 2007, 2014) .

The focus of the current work is narrower than in the multi-model intercomparisons discussed above, which, however, allows for more in-depth analysis. We look in detail at the performance of a single model, the ECHAM5 atmospheric GCM (Roeckner et al., 2003,

2006) in simulating the timing of snow melt in spring in Northern Eurasia, north of latitude 55° N. Specifically, we focus on the average timing of the end of the snow melt season (i.e., the snow-off date; the day when all snow accumulated during the winter has vanished). Snow-off dates simulated by ECHAM5 are compared with snow-off dates derived from two observational datasets: first, a satellite dataset based on data from passive multichannel microwave radiometers (Takala et al., 2009), and second, Russian in-situ snow course measurements (Bulygina et al., 2011a). The geographical focus on Northern Eurasia is motivated by the vast area of the continent, which makes Eurasian snow conditions important for understanding the planetary climate as a whole.

The performance of a slightly earlier version of ECHAM5 in simulating the Northern Hemisphere snow depth, snow-covered area and surface albedo was assessed by Roesch and Roeckner (2006). By using snow products based on visible and microwave remote sensing data, they found that ECHAM5 reproduces the amplitude and phase of the annual snow depth cycle quite precisely, however, with a slight overestimation of the snow depth in late winter and spring over Eurasia. The present work builds on Roesch and Roeckner (2006) but goes deeper in analyzing the regional details and causes underlying the biases in modelled ~~snow-off-dates~~snow-off dates. Thus, while it is shown that in ECHAM5 simulations, snow-off tends to occur too late in the eastern part of Northern Eurasia (especially southeastern Siberia) and too early in the western and northern parts, the most fundamental issue is that snow-off occurs at lower-than-observed air temperatures. The likely main reason for this are simplifications inherent to the model's surface energy budget calculation in the presence of partial snow cover and in the treatment of forest canopy. This highlights the need to consider carefully the treatment of the surface energy budget in the models, in addition to the fidelity of simulated temperature and precipitation fields.

The rest of this paper is organized as follows. First, in Sect. 2 we introduce the ECHAM5 model and the experiments conducted. In Sect. 3, the observational datasets used in this work are described. Section 4 addresses the non-trivial issue of the definition of snow-off dates. Results are reported in Sect. 5, both for the default version of ECHAM5 and for sensitivity experiments, in which biases in simulated atmospheric circulation were corrected through nudging and/or the treatment of surface albedo was modified. The reasons underlying the biases in modeled snow-off dates are further discussed in Sect. 6, followed by conclusions in Sect. 7.

2 Model and experiments

2.1 Model description

Version 5.4 of the ECHAM5 atmospheric general circulation model (Roeckner et al., 2003, 2006) was used. The dynamical part of ECHAM5 is formulated in spherical harmonics, while physical parameterizations are computed in grid point space. The simulations reported were conducted at horizontal resolution T63 (corresponding to a grid-spacing of 1.875°) with 31 layers in the vertical and model top at 10 hPa. A semi-implicit time integration scheme is used for model dynamics with a time step of 12 min. Model physical parameterizations (Roeckner et al., 2003) are invoked at every time step, except for radiation, which is computed once in two hours.

The snow scheme in ECHAM5 is relatively simple: the snow water equivalent (SWE; $\mathrm{kg\,m^{-2}}$) is a prognostic quantity, but changes in snow density or grain size are not considered. In the presence of snow, the top of the snow layer is treated as the top of the soil model. For snow-free and snow-covered land alike, the surface temperature is determined through the surface energy balance, while the thermal diffusion equation is used to calculate the soil (or snow) temperature profile. Five layers within the topmost 10 m are considered, with thicknesses of 0.065 m, 0.254 m, 0.913 m, 2.902 m and 5.700 m, respectively. For snow-free land, spatially varying volumetric heat capacity and thermal diffusivity are prescribed for five soil types according to the FAO soil map (Gildea and Moore, 1985; Henderson-Sellers et al., 1986). For snow-covered land the procedure is the same except that the thermal properties are modified. For example, if snow fills the top soil layer completely, and the second layer partially, the thermal properties of snow are used for the top layer while a mass-weighted mixture of soil and snow properties is used for the second layer. A constant snow density of 330 $\mathrm{kg\,m^{-3}}$ is assumed in this procedure.

The ECHAM5 snow scheme considers both SWE intercepted by the canopy (Roesch et al., 2001) and SWE on the ground ~~, the latter being more interesting for this study~~(Roeckner et al., 2003) . The budget equation for snow on the ground accounts for snowfall through the canopy, sublimation/deposition, melting, and unloading of snow from the canopy due to wind. The snow melt rate M is computed from the surface energy budget equation:

$$C_\mathsf{L}\frac{\partial T_\mathsf{s}}{\partial t} = R_\mathsf{net} + H + \mathsf{LE} + G - M, \qquad (1)$$

where C_L is the heat capacity of the surface layer, T_s the surface temperature, R_net the surface net radiation, H the sensible heat flux, LE the latent heat flux, and G the ground heat flux (all defined positive when the surface layer gains energy). A preliminary estimate for T_s at the next time step (T^*) is obtained by considering everything else but snow melt ($M = 0$). If T^* exceeds the melting point ($T^* > T_0 = 0\,^\circ$C), the snow melt rate is inferred from the condition that the heat consumed in melting snow restores T_s to T_0:

$$M = \frac{C_\mathsf{L}}{L_\mathsf{f}}\left(\frac{T^* - T_0}{\Delta t}\right), \qquad (2)$$

where L_f is the latent heat of fusion and Δt the model time step.

The snow cover fraction on the ground (SCF) is diagnosed following Roesch et al. (2001) :

$$\mathsf{SCF} = 0.95\tanh\left(100 h_\mathsf{sn}\right)\sqrt{\frac{1000 h_\mathsf{sn}}{1000 h_\mathsf{sn} + 0.15\sigma_z + \epsilon}}, \qquad (3)$$

where h_sn is SWE expressed in metres of liquid water, σ_z (m) is the subgrid-scale standard deviation of surface elevation and ϵ is a small number used to avoid division by zero for totally flat and snow-free grid cells.

The parameterized grid-mean surface albedo depends on the specified background albedo, the fractional forest area of the grid cell, the snow cover on the canopy, the snow cover on the ground~~(diagnosed based on SWE and subgrid-scale standard deviation of surface elevation)~~, and a specified snow albedo. While a complete description of the parameterization can be found in Roeckner et al. (2003), two details are mentioned here to provide a background for the sensitivity tests in Sect. 2.2.3. First, the albedo of snow on land (α_{sn}) depends on the surface temperature T_{s} according to

$$\alpha_{\mathrm{sn}} = \alpha_{\mathrm{sn,\,min}} + (\alpha_{\mathrm{sn,\,max}} - \alpha_{\mathrm{sn,\,min}})\, f(T_{\mathrm{s}}) \tag{4}$$

where

$$f(T_{\mathrm{s}}) = \min\left[\max\left(\frac{T_0 - T_{\mathrm{s}}}{T_0 - T_{\mathrm{d}}}, 0\right), 1\right] \tag{5}$$

and $\alpha_{\mathrm{sn,\,min}} = 0.3$, $\alpha_{\mathrm{sn,\,max}} = 0.8$, $T_0 = 0\,^{\circ}\mathrm{C}$ and $T_{\mathrm{d}} = -5\,^{\circ}\mathrm{C}$. Second, the albedo of snow-covered forests is parameterized according to

$$\alpha_{\mathrm{for}} = \mathrm{SVF}\alpha_{\mathrm{g}} + (1 - \mathrm{SVF})\alpha_{\mathrm{can}}, \tag{6}$$

where α_{g} is the ground albedo ($\alpha_{\mathrm{g}} = \alpha_{\mathrm{sn}}$ if the ground is completely snow-covered), α_{can} is the albedo of the canopy (0.2 for completely snow-covered canopy) and the sky view factor SVF depends on the leaf-area index (LAI):

$$\mathrm{SVF} = e^{-\mathrm{LAI}}. \tag{7}$$

2.2 Experiments

A total of six ECHAM5 experiments were conducted~~at resolution T63L31~~. All experiments were run for years 1978–2006, and years 1979–2006 were used for analysis of the results. Note that the years 2008–2012 during which a rapid reduction in Northern Hemisphere May–June snow cover has been observed (Derksen and Brown, 2012) fall outside this period. All simulations used observed sea surface temperatures (SST) and sea ice (AMIP Project Office, 1996), and some of them used nudging fields and/or observed albedo fields that likewise included “real” year-to-year variations (see below). The concentrations of well-mixed greenhouse gases were held constant following AMIP II guidelines (AMIP Project Office, 1996), at 348 ppmv for CO_2, 1650 ppbv for CH_4, 306 ppbv for N_2O, 280 pptv for CFC-11, and 484 pptv for CFC-12. For aerosols, a climatological distribution was assumed (Tanré et al., 1984). The distribution of ozone, vegetation area and LAI followed a presribed climatological seasonal cycle.

Three of the experiments (REF, ALB1 and ALB2) were run in an ordinary climate simulation mode. In the remaining three experiments (REF_NDG, ALB1_NDG and ALB2_NDG), four model fields were nudged towards ERA-Interim reanalysis data (Dee et al., 2011): vorticity (relaxation time scale 6 h), divergence (48 h), atmospheric temperature (24 h) and logarithm of surface pressure (24 h). Nudging acts to minimize the errors in simulated atmospheric circulation, which is one of the possible causes for differences between simulated and observed snow-off dates.

2.2.1 REF and REF_NDG

The reference experiment (REF) and the corresponding nudged experiment (REF_NDG) used the default version of ECHAM5.4. To evaluate the impact of model internal variability on the results, three runs were conducted for the REF experiment. The runs were started from different initial dates (1, 2 and 3 January 1978, respectively), which is sufficient for ensuring that within a few weeks, the weather conditions in the three runs become essentially independent of each other. Where not otherwise stated, the mean value of these three runs is reported. REF_NDG, as well as ALB1, ALB1_NDG, ALB2 and ALB2_NDG consist of a single run for years 1978–2006.

2.2.2 ALB1 and ALB1_NDG

Surface albedo influences strongly the energy available for melting snow in spring. In an attempt to eliminate errors in surface albedo, in the experiments ALB1 and ALB1_NDG the model's albedo field over continents was replaced by prescribed surface albedos based on observations. Monthly-mean albedos in the CLARA-SAL dataset derived from AVHRR satellite data (Riihelä et al., 2013) were applied. Since this dataset starts from year 1982, for years 1978–1981 the average annual cycle of CLARA-SAL albedo for years 1982–2006 was employed. While this approach is instructive for diagnostic purposes, it has the major weakness that the albedo is independent of simulated land-surface properties, including snow cover.

2.2.3 ALB2 and ALB2_NDG

In an attempt to reduce biases in ECHAM5's surface albedo field while keeping it interactive, experiments ALB2 and ALB2_NDG were conducted. Two modifications were implemented in ECHAM5's surface albedo parameterization. First, for snow-covered forests, the sky-view factor in Eq. (7) was replaced by

$$\mathrm{SVF} = e^{\underline{-\mathrm{LAI}+\mathrm{SAI}}\;\underline{-(\mathrm{LAI}+\mathrm{SAI})}} \tag{8}$$

Here, the stem area index (SAI) assumes a constant value of 2 for all forest types, following the Biosphere–Atmosphere Transfer Scheme (Dickinson et al., 1993). This modification was motivated by Roesch and Roeckner (2006), who noted that ECHAM5 overestimates the total surface albedo in eastern Siberia in the dormancy season of deciduous needleleaf trees, and ascribed this problem to the fact that the shadowing of the ground below the canopy by stems and branches is neglected. Second, the value of $\alpha_{\mathrm{sn,\,min}}$ in Eq. (4) was increased from 0.3 to 0.6. This was motivated by the findings of Pedersen and Winther (2005) and Mölders et al. (2008), who note that for ECHAM5's snow albedo parameterization, and also for ECHAM4 for which $\alpha_{\mathrm{sn,\,min}} = 0.4$, snow albedo decreases too early and too fast during snowmelt.

3 Observational data

~~Five~~ Seven observational datasets were used in the present work. First, a snow-off date dataset based on remote sensing of snow with space-borne microwave radiometer measurements (Takala et al., 2009) was used for evaluating snow-off dates in the ECHAM5 simulations. The Eurasian region is well suited for remote sensing of snow melt for two reasons. First, temperatures in much of the Eurasian region are very low in winter-time, which leads to the formation of a dry snow pack. Second, as tundra is the predominant surface type, the snow conditions are relatively homogeneous over extended areas in the absence of e.g. mountain regions with a complicated topography. These properties are profitable for microwave instruments that measure highly contrasting surface brightness temperatures for dry vs. melting snow related to the progression of spring.

The remote-sensing dataset utilized measurements by the Scanning Multichannel Microwave Radiometer (SMMR; Knowles et al., 2002) onboard Nimbus 7 for years 1978–1987 and measurements by the Special Sensor Microwave/Imager (SSM/I) (Armstrong et al., 1994) onboard the Defence Meteorological Satellite Program (DMSP) satellites D-11 and D-13 for years 1988–2007. A time-series thresholding algorithm based on the brightness temperature difference between vertically polarized radiances around 37 GHz and 19 GHz was used to determine the snow-off date for each year (see Takala et al., 2009 for details). The snow-off dates (given as day-of-year from 1 to 180) are provided at a nominal resolution of $25\,\mathrm{km} \times 25\,\mathrm{km}$.

The snow-off date estimates in the microwave dataset were calibrated against the INTAS-SCCONE observations (Kitaev et al., 2002; Heino and Kitaev, 2003) of snow depth and snow melt flag at Eurasian, mostly Russian, weather stations. Specifically, for the calibration data, the ~~snowmelt~~ snow-off date was defined as the last event during spring when the station snow status flag changed from “snow depth is correct” to “temporary melting” or “continuous melting”, both of which refer to a situation in which there is no snow left at the station. Thus, in principle, the microwave dataset is targeted at presenting the final snow-off date at each station. This is discussed further in Sect. 4.

Second, snow course measurements made in Russia (or the former Soviet Union) were used for evaluating both the simulated snow-off dates and the seasonal cycle of ~~snow water equivalent (SWE)~~SWE. These data were acquired from the Russian Hydrometeorological Centre; http://meteo.ru/english/climate/snow1.php (Bulygina et al., 2011a). The “routine snow surveys” dataset contains data from 517 meteorological stations (288 within the region considered here), for which either ~~field~~ open-terrain[1] or forest snow course measurements (or both) have been performed. These are a subset of the 958 stations considered in Bulygina et al. (2011b). ~~The snow water equivalent (SWE)~~

The SWE was measured at 100 ~~(200)~~ meter intervals along ~~a forest (field) snow course~~ the forest snow courses, which had a total length of 1 km, and at 200 meter intervals along the open-terrain snow courses with a total length of ~~1 (~~2~~)~~ km. Typically, measurements are provided at 10 day intervals in winter and 5 day intervals in spring (starting from March or April). The data availability varies, however, and not all stations provide data throughout the period 1979–2006 considered here. To compare with ECHAM5, the SWE values were regridded to the T63 grid, by averaging the SWE values over the stations if several stations existed in a grid cell. The procedure for estimating the snow-off date from the snow course data is described in the Appendix. We include in our analysis those grid cells for which the snow-off date could be determined for at least five years during 1979–2006.

Third, for surface albedo, we employ the monthly mean version of the CLARA-SAL dataset (Riihelä et al., 2013), which is based on a homogenized AVHRR radiance time-series. These data provide black-sky albedo values from January 1982 onwards. The data, originally given at a $0.25^\circ \times 0.25^\circ$ resolution, were averaged to the T63 grid for comparison with modelled values, and for use as input for the ALB1 and ALB1_NDG experiments (Sect. 2.2.2).

Fourth, for snow cover fraction, we use version 2.0 of the snow extent (SE) dataset created in the European Space Agency’s (ESA) Data User Element project

[1] The term “open-terrain snow courses” is used here instead of the term “field snow courses” used in Bulygina et al. (2011a, b) . These refer to non-forested snow courses in general, some of which are above (or north of) the treeline.

GlobSnow (Metsämäki et al., 2015) . The GlobSnow SE is based on data acquired by the ERS-2/ATRS-2 and Envisat/AATSR satellite instruments, and is provided on a $0.01^\circ \times 0.01^\circ$ grid. Here, monthly-mean data averaged to the T63 grid are used. The years for which there is springtime snow cover data both for GlobSnow and the current ECHAM5 experiments are 1997–2006, but 2002 was discarded due to issues with data quantity and quality. While longer-term snow cover datasets exist (Zhao and Fernandes, 2009; Brown and Robinson, 2011) , GlobSnow was selected for the present study because its retrieval algorithm was specifically designed to enable accurate snow mapping also in forests, which cover a large part of Northern Eurasia.

Fifth, information on forest cover from the GlobCover 2009 dataset (Bontemps et al., 2011; Arino et al., 2012) is used, along with the GlobSnow snow cover data, to aid the interpretation of the differences between modelled and observed albedo fields.

Sixth, for 2 m air temperature, Climate Research Unit (CRU) land surface air temperature data, version 3 (CRUTEM3; Brohan et al., 2006) ~~was~~ is employed.

~~Fifth~~Seventh, daily measurements of snow depth and diurnal-mean temperature conducted at the Finnish Meteorological Institute Arctic Research Centre at Sodankylä (67.37° N, 26.63° E, 179 m a.s.l.) in January–June 1979–2006 are employed for a detailed comparison with ECHAM5 experiments in Sect. 6. The Sodankylä site belongs to the northern boreal forest zone with the snow type of taiga, which is typical of most of Northern Eurasia.

4 Definition of snow-off date

Snow-off date is evaluated in ECHAM5 based on daily-mean SWE values. There are several possible methods for defining the snow-off date, the most obvious ones being (1) the first snow-off date (i.e., the first day with zero SWE after a winter's SWE maximum) and (2) the final snow-off date (i.e., the day following the last day with SWE > 0 in spring). In some cases, the first and final snow-off dates differ substantially. As an example, Fig. 1 shows the time series of SWE for spring 1988 for a grid point in western Russia (60.6° N, 39.4° E) in one of the REF runs. The first snow-off date is day 99 (8 April), but three separate short periods with snow occur after it, the final snow-off date being day 129 (8 May).

In this paper, we use the first snow-off date for ECHAM5 because it is a more robust indicator of model behavior than the final snow-off date. The first snow-off date represents an integral measure of how much snow accumulates during the winter and how fast it melts in the spring. In contrast, when the final snow-off date differs from the first snow-off date, it is, in essence, determined by the last occurrence of solid or mixed-phase precipitation in spring. This makes the final snow-off date much more sensitive to day-to-day weather patterns in spring than the first snow-off date.

Even when setting aside potential issues related to spatial and temporal resolution, the definition of snow-off date in ECHAM5 results is not fully compatible with how the snow-off date is derived from the microwave satellite data. As noted in Sect. 3, the satellite snow-off date represents, in principle, the final snow-off date rather than the first snow-off date; that is, it can be affected by secondary periods of snow after the first snow-off date. Nevertheless, the use of final snow-off date in ECHAM5 for comparison with the satellite data would be problematic. The secondary periods of snow after the first snow-off date in ECHAM5 are often short and the values of SWE very low (e.g., SWE $\sim 0.1\,\mathrm{kg\,m^{-2}}$ for the last two periods of snow in Fig. 1) so it is unclear whether they would really be detected by the satellite algorithm. Thus, we opt to use the first snow-off date for ECHAM5, but acknowledge that this may contribute towards an early bias in snow-off dates when compared with the satellite data.

~~Finally, in~~ In the comparisons with the snow course data, the snow-off date in ECHAM5 is evaluated as the first snow-off date, but using SWE for only those days for which snow course measurements are available (i.e., every 5th or 10th day). This is fully consistent with how the snow-off date is derived from the snow course data (see the Appendix).

Figure 2 compares time-average snow-off dates derived from the snow course data and the satellite data, for each ECHAM5 grid cell separately. While these estimates are, of course, strongly correlated (r=0.775), there is an appreciable scatter among them. For some grid cells, the difference between satellite and snow-survey snow-off dates is more negative than −10 days, and for many more grid cells (especially in Siberia, in particular between 100° E and 120° E) more positive than 10 days. The mean difference between the satellite and snow survey snow-off dates is 5.1 days, while the rms difference is 12.2 days. The positive mean difference is, in principle, consistent with the notion that the satellite snow-off date may be in some cases influenced by secondary periods of snow after the first snow-off date; however, the substantial scatter indicates that there must be other factors at play. Unraveling the causes of these differences falls beyond the scope of this paper. Rather, we focus on what can be concluded from the model behaviour, given the observational uncertainty.

5 Results

5.1 Reference experiment REF

5.1.1 Snow-off timing

The geographical distribution of the mean snow-off date during the period 1979–2006 in the satellite retrievals is shown in Fig. 3a. In general, springtime snow-off progresses gradually from the southwestern parts of the domain towards the northern and eastern parts. Earliest snow-off occurs in the Baltic Sea area (around 20° E), before day 90 (end of March). An area of rather early snow-off dates can also be found in eastern Siberia where around the latitude 60° N snow melts right after day 120 (beginning of May). Snow melts latest in the Taymyr Peninsula (around 75° N, 100° E), after day 170 (about 20 June). Snow also persists until June in parts of Russian Far East (east of 160° E). In addition to the general southwest-to-northeast gradient, some orographic effects can be detected. In the Ural Mountains (60° E) and in the Scandinavian (about 20° E) and Verkhoyansk (130° E) mountain ranges, snow melts later than in the surrounding regions, by up to 30 days in the Ural region. Although mountainous areas are problematic to handle in algorithms based on microwave radiometer data (Mialon et al., 2008; Pulvirenti et al., 2008), these features are expected on physical grounds: colder temperatures and orographically enhanced precipitation favour later snow melt.

The REF experiment (Fig. 3b) reproduces well the general pattern of snow-off dates seen in the satellite data, the snow-off being latest in the Taymyr Peninsula (between days 150 and 160) and earliest in the Baltic Sea region (around day 80). However, in most of Northern Eurasia, snow melts earlier in the model results than in the satellite retrievals (Fig. 3c). The difference to the satellite retrievals is mainly 5–20 days ~~, but exceeds locally~~ but locally exceeds 20 days in Northern Europe. On the contrary, in eastern Siberia and in some far eastern parts of Russia, snow melts locally over 10 days later in REF than in the satellite data. The orographic effects seen in Fig. 3a are absent in the model results, presumably because the model resolution (T63) is too coarse for describing them.

Figure 3d displays the standard deviation in the 28 year mean (1979–2006) snow-off date among the three runs included in the REF experiment. For most of Northern Eurasia, the standard deviation is less than 2 days, with larger values mainly confined to the south-western part of the domain and the Scandinavian coastline. In general, the standard deviation is much smaller than the respective differences between REF and the satellite data. This provides a justification for including only a single model run in the sensitivity experiments. Finally, Fig. 3e and f show the interannual standard deviation of snow-off dates for the satellite retrievals averaged to the model grid and for the REF simulation, respectively. Overall, the magnitude and the geographic pattern of the standard deviation are similar for the model results and for the observations, typical values ranging from 5–6 days in central and eastern Siberia to $\sim$ 20 days in the Baltic Sea region. Naturally, there are some differences in the details, such as, for example, a smaller standard deviation of snow-off dates in REF than in the satellite dataset in western Siberia.

Figure 4a compares the snow-off dates in the REF experiment with those derived from the snow course data. The general tendency towards too early snow-off dates in the west (about 30–90° E) and too late snow-off dates in the east in REF as compared with the snow course data is in qualitative agreement with the corresponding comparison with satellite data (Fig. 3c). However, the positive differences in the east, indicating delayed snow-off in ECHAM5, are more widespread and more pronounced than those in Fig. 3c, exceeding 20 days at some locations. Figure 4b and c show a similar comparison as Fig. 4a, but separately for ~~field~~ open-terrain and forest snow courses. It is seen that particularly in the west, the model snow-off dates are rather close to those derived from the ~~field~~ open-terrain snow courses, the differences being only slightly negative, and in some cases slightly positive. In contrast, a comparison with the forest snow courses west of 90° E shows a persistent negative bias, indicating too early snow melt in the model. The ~~differences are more negative~~ more negative differences for the forest ~~courses than the field courses because – as conventional wisdom indicates – in spring~~ snow courses than for the open-terrain courses indicate that snow tends to persist longer in forests than on open ground. For those grid cells (located mainly in western Russia) that have both forest and ~~field~~ open-terrain courses, the snow clearance occurs on average 10.5 days later for the forest courses. In ECHAM5, however, neither snow-off dates nor SWE values are defined separately for the forested and non-forested parts of a grid cell.

The later snow-off for forests is consistent with the findings of Lundquist et al. (2013) for locations with cold winters (December-January-February (DJF) mean temperatures colder than $-6\,^{\circ}\mathrm{C}$, which applies to most of Northern Eurasia). However, the opposite behaviour (earlier snow-off in forests than on open ground) was observed in climates with warm winters (DJF mean temperature > $-1\,^{\circ}\mathrm{C}$). In general, several factors influence the relative timing of snow-off in forests and on open ground (e.g., Essery et al., 2009; Strasser et al., 2011) . During the accumulation season, the interception and subsequent sublimation of canopy snow reduces accumulation of snow in forests, while wind-blown snow from open areas may be deposited around forest edges, thus increasing the snow depth. In spring, less solar radiation is available for melting the snow under a forest canopy than on open ground, but increased downwelling longwave radiation may partly compensate for this.

5.1.2 Other snow-related quantities

To set the stage for further discussion, 2 m air temperature (T_2), surface albedo, SCF and SWE are considered. Figure 5 shows a comparison of T_2 in REF and in the CRU data for the extended spring season (March through June). A cold bias prevails through most of the spring and peaks at -7 K in southeastern Siberia in April. Positive temperature biases occur in the Taymyr region (throughout the spring) and in the Russian Far East (mainly in March and April).

~~Figure~~The left half of Fig. 6 displays a comparison of surface albedo in the REF experiment with the CLARA-SAL dataset. Two pronounced biases appear. First, in agreement with ~~the findings of Roesch and Roeckner (2006)~~Roesch and Roeckner (2006) , a positive bias prevails in the central and eastern parts of Siberia for much of the spring, especially in March and April. Second, a negative albedo bias occurs in the northernmost parts of Northern Eurasia (especially in the Taymyr region) in May and June, and in northern Fennoscandia especially in April. Some understanding of the albedo biases can be gained by considering the snow cover fraction along with forest fraction and LAI.

The right half of Fig. 6 shows monthly-mean SCF differences between the REF simulation and the GlobSnow dataset for the years 1997–2006, excluding 2002. Although this period is shorter than the period 1982–2006 used for the albedo comparison, the REF vs. CLARA-SAL albedo differences for these two periods are very similar, with monthly spatial correlations of 0.98–0.99. Interestingly, ECHAM5 underestimates SCF compared to GlobSnow almost throughout the Northern Eurasia, with the exception of parts of southeast Siberia in May, where snow-off is delayed in the REF simulation. During March and April, the GlobSnow SCF is very high (0.99–1) through much of the central and northern parts of Northern Eurasia. For ECHAM5, SCF is typically 0.90–0.95 in non-mountainous regions, but locally only $\approx$ 0.75–0.8 in the Verkhoyansk range in Eastern Siberia, where SWE is relatively low (60–80 kg m^{-2}) and subgrid orographic variability is fairly large, $\sigma_z \approx 250$ m (see Eq. (3)). The largest negative SCF differences to GlobSnow occur, however, in the snowmelt season, in April and May in the western parts of Northern Eurasia and in June in the Taymyr peninsula, consistent with the too early snow-off in these regions. The small negative SCF biases that appear in June in southern and western parts of Northern Eurasia in Fig. 6h are, however, artifacts related to clouds misinterpreted as snow in the GlobSnow dataset.

The impact of SCF biases on surface albedo is best discernible in tundra (i.e., forest-free) regions (see Fig. 7a,b for the distribution of forests). In particular, the strong negative albedo bias in June in the Taymyr peninsula in Fig. 6g is related to insufficient snow cover in the REF simulation. The negative albedo bias in the northernmost parts of Fennoscandia and Russia in May can also be partly ascribed to underestimated SCF. However, especially in the Taymyr peninsula, the albedo bias (≈ -0.24, averaged over land grid points north of 72.5° N) is larger than the SCF bias (≈ -0.12). Very likely, this is related to the unrealistically low value (0.3) assumed for the albedo of "warm" snow ($T_s \geq 0$ °C).

The positive albedo bias that prevails in central and eastern Siberia (and to a lesser extent, in parts of western Russia) in March and April is related to the treatment of forests. Indeed, the regions with most pronounced positive albedo bias are associated with a high forest fraction (locally higher than 0.9) in the GlobCover 2009 dataset (Fig. 7a). In ECHAM5, the forest fraction is somewhat smaller, typically $\approx$ 0.5–0.6. This difference should be interpreted with caution, however, as the dominant GlobCover land cover class in forested parts of Siberia is "open needleleaved deciduous or evergreen forest", which has a canopy coverage of 15%-40% when viewed from directly above. The reason why the albedo bias is especially large in central and eastern Siberia is related to the LAI. There, the LAI in ECHAM5 is very low in the dormancy season of deciduous needleleaf trees, including March and April (Fig. 7c). When only the leaves (and not the stems and branches) are considered in the computation of the sky-view factor (Eq. (7)), this results in very little shading of the snow surface by the forest. Therefore, as previously discussed by Roesch and Roeckner (2006) , the albedo is overestimated substantially.

Figure 8 shows the average annual cycle of SWE in the REF experiment and in the snow course measurements, for the entire Northern Eurasia and for two subregions denoted as Western Russia (55–70° N, 30–70° E) and Eastern Siberia (55–70° N, 100–140° E). Note that grid cells without snow course data are not included in the averages, and therefore, for example, the average over the entire Northern Eurasia gives more weight to the western and southern parts of the region than its eastern and northern parts, especially when considering ~~field~~ open-terrain snow courses. With this caveat in mind, we note that the domain-mean annual cycle of SWE over the entire Northern Eurasia in REF agrees well with the snow course data, although the maximum is slightly higher and occurs 5–10 days earlier than observed (Fig. 8a). There are, however, regional differences. For Western Russia (Fig. 8b), the simulated maximum SWE is very close to that observed, but SWE starts to decrease earlier than observed in the spring, in agreement with the too early snow-off days in Figs. 3c and 4a. In contrast, for Eastern Siberia, the REF experiment overestimates substantially the accumulation of snow during winter (Fig. 8c), and the timing of maximum SWE and snow melt is delayed, which is again consistent with Fig. 4a.

When considering the ~~field~~ open-terrain snow courses only, the simulated SWE maximum is higher than observed for all three regions (Fig. 8d–f), and the overestimate is especially pronounced for Eastern Siberia. In contrast, when compared with the forest snow courses, the simulated maximum SWE is slightly too low for the entire Northern Eurasia (Fig. 8g) and for Western Russia (Fig. 8h) and only moderately overestimated for Eastern Siberia (Fig. 8i). ~~Although the geographical distribution of forest and field courses is not identical, this reflects the fact~~ The more positive ECHAM5 vs. observation differences for open-terrain than forest snow courses suggest that in reality (but not in ECHAM5), more snow ~~tends to accumulate~~ accumulates in forests than on open ground. We verified that this also holds true when the comparison is restricted to grid cells and years with both forest and open-terrain observations. It is worth noting that often the opposite has been reported (though mainly for sites at lower latitudes): less accumulation in forests due to sublimation of intercepted snow or due to midwinter melt induced by the larger downwelling longwave flux in forests (Essery et al., 2009; Strasser et al., 2011; Lundquist et al., 2013) .

The delayed snow-off in the REF experiment in central and eastern Siberia is physically consistent with the low temperature bias and high albedo bias in spring. On one hand, overestimated surface albedo keeps the absorbed solar radiation low, which favours cold temperatures and delays the onset of snow melt. On the other hand, delayed snow melt provides a positive feedback by keeping the albedo high. Furthermore, too large accumulation of snow in winter contributes to the delayed snow-off in Eastern Siberia (Fig. 8c). Similarly, underestimated albedo and overestimated T_2 in spring in the Taymyr region are consistent with the snow vanishing too early. For Western Russia, however, the main reason for the earlier than observed snow-off dates (Figs. 3c and 4a) seems to be that at least in a domain-average sense, snow melt starts somewhat too early (Fig. 8b). Intriguingly, this occurs in spite of a slightly negative temperature bias in spring (Fig. 5).

5.2 Sensitivity experiments

The sensitivity experiments show that both nudging and changes in the treatment of surface albedo have substantial impacts on the snow-off date simulated by ECHAM5 (Fig. 9). Nudging makes snow-off ~~to~~ occur earlier in most of ~~northern~~ Northern Eurasia, with largest effect (over 15 days) in southeastern Siberia and locally in ~~western Finland~~Fennoscandia. The earlier snow-off in REF_NDG is both due to higher temperatures (as discussed below) and due to slightly reduced snowfall in eastern Siberia, as reflected in the seasonal cycle of SWE in Fig. 8c, f and i. However, in the Taymyr region, snow-off is delayed by more than 5 days in REF_NDG as compared with REF (Fig. 9a). Use of observed (CLARA-SAL) albedo in ALB1 likewise makes the snow melt earlier in southeastern Siberia and later in the Taymyr region, with larger impact in the latter (ALB1–REF differences of ≈ -5 days and ≈ 15 days, respectively; Fig. 9b). In general, snow-off is delayed somewhat in the northern parts of Northern Eurasia, and also in central Russia. For the ALB2 experiment with changed albedo parameterization, snow-off occurs up to 5 days earlier in southeastern Siberia than in REF (Fig. 9c). This is very similar to the ALB1 experiment, and results from the modification of the sky-view factor in the calculation of surface albedo in forested regions. However, due to the increase of the albedo of "warm" snow ($T_\mathrm{s} \geq 0\,^\circ$C) from 0.3 to 0.6, snow-off is delayed in the northeastern parts of the Russian Far East and particularly in the Taymyr region, locally by 5–10 days. This response is qualitatively similar but somewhat weaker than that in ALB1. Finally, when nudging is combined with changed treatment of albedo (ALB1_NDG and ALB2_NDG; Fig. 9c and e), the earlier snow-off in southeastern Siberia and delayed snow-off in the Taymyr region become even more pronounced. In southeastern Siberia, the difference to REF reaches locally -20 days.

Figures 10 and 11 compare the snow-off dates in all ECHAM5 experiments with the snow-off dates derived from microwave satellite data and Russian snow course data, respectively. In spite of the inter-experiment differences noted above, all free-running (i.e., non-nudged) simulations show the same basic pattern of differences compared to the satellite data (Fig. 10): too early snow-off dates in the west, along with regions of delayed snow-off in eastern parts of northern Eurasia. The ALB1 and ALB2 experiments show some improvement in southeastern Siberia, where the positive bias in snow-off date is reduced but not eliminated. Furthermore, the negative bias in the Taymyr region is reduced in the ALB2 experiment with changed snow albedo parameterization, and turned into a slight positive bias in ALB1, which uses observation-based CLARA-SAL albedo data.

Nudging eliminates entirely the positive bias in snow-off date in southeastern Siberia as compared with the satellite data. As a consequence, the REF_NDG experiment features an early bias throughout ~~northern~~ Northern Eurasia (Fig. 10b), with largest biases in the west. Likewise, for the nudged simulations with albedo changes (ALB1_NDG and ALB2_NDG), snow-off generally occurs earlier than in the satellite data, the most notable exception being that for ALB1_NDG, near-zero or even positive differences (i.e., delayed snow-off) appear in the Taymyr region.

It should be recalled that the early bias in snow-off dates compared with the satellite data may be, in part, an artifact related to differences in the definition of snow-off time between the ECHAM5 simulations and the satellite data (Sect. 4). Indeed, when compared with the snow course data (Fig. 11), all free-running simulations feature delayed snow-off in eastern Siberia and in the Russian Far East. The differences between REF, ALB1 and ALB2 are rather small in comparison with their biases with respect to the snow course data. Even for the nudged simulations (REF_NDG, ALB1_NDG, and ALB2_NDG), positive differences indicating delayed snow-off prevail for many measurement stations in Eastern Siberia and in the Russian Far East, although slightly negative differences occur for some stations. In the western parts of Northern Eurasia, however, all simulations feature negative biases, snow-off occurring 10–20 days earlier than in the snow course data for many stations in western Russia. The negative biases are, in general, slightly larger for the nudged simulations, especially in the westernmost parts of Russia. Furthermore, as noted in Sect. 5.1 for the REF experiment, the negative biases are especially pronounced when compared with forest snow courses.

The changes in snow-off ~~time~~ timing are influenced by, and they feed back on, simulated 2 m air temperature (Fig. 12) and surface albedo (Fig. 13) in the sensitivity experiments. For brevity, only mean values over the months of April and May are shown. All experiments feature a cold bias in southeastern Siberia, which amounts down to -7 K in REF (Fig. 12a). Consistent with the earlier snow melt (Fig. 9), this bias is reduced in ALB1 (Fig. 12c) and ALB2 (Fig. 12e), and especially in the nudged experiments (Fig. 12b, d and f). A slight negative temperature bias (≈ -2 to -1 K) prevails in large parts of western and central Russia, and this feature varies only slightly between the experiments. Positive temperature biases are seen in all experiments in the Taymyr region and in parts of the Russian Far East.

Figure 13 displays surface albedo differences from the CLARA-SAL data for the REF, REF_NDG, ALB2 and ALB2_NDG experiments (for ALB1 and ALB1_NDG, the differences are zero by construction). It is seen that the high albedo bias in southeastern Siberia is reduced substantially in both REF_NDG and ALB2, and it is eliminated completely in ALB2_NDG. In the case of ALB2 and ALB2_NDG, the modified computation of the sky-view factor in the albedo parameterization for forested regions contributes to this. For REF_NDG, however, the change in surface albedo stems entirely from changes in meteorological conditions, the reduced negative temperature bias (Fig. 12b) leading to both lower snow albedo and reduced snow cover. However, all four experiments show some common biases, most distinctly an underestimation of albedo compared to the CLARA-SAL data in the northern parts of Northern Eurasia and in the Russian Far East. Interestingly, the use of a higher value for the albedo of “warm” snow (0.6 instead of 0.3 when $T_\mathrm{s} \geq 0\,^\circ\mathrm{C}$) in the ALB2 and ALB2_NDG experiments reduces somewhat the negative bias in the Taymyr region but does not eliminate it. ~~Given that the Taymyr region is almost completely snow-covered in May in the model simulations, this~~ A negative SCF bias likely contributes to the remaining albedo bias, the average difference to GlobSnow data in the Taymyr peninsula being $\Delta\mathrm{SCF} \approx -0.08$ both in April and May. However, it still appears that snow albedo is underestimated in May, which suggests that even the value of 0.6 is too low at least in this region.

6 Discussion

The analysis of the sensitivity experiments in Sect. 5.2 showed that nudging and changes in the treatment of surface albedo in the presence of snow alleviated some of the model biases in snow-off dates, 2 m temperature and surface albedo. Nevertheless, many of the biases seen in Figs. 10–13 are quite similar for all experiments. Regarding the timing of springtime snow-off, the results are somewhat ambiguous for the eastern parts of Northern Eurasia, due to large differences between observational snow-off date estimates from satellite and snow course data, and hence in the resulting model biases. For western Russia, however, comparisons with the satellite data and the snow course data indicate unanimously that snow-off occurs too early in ECHAM5 for all experiments, with only moderate variations due to nudging or changes in the treatment of surface albedo (Figs. 10 and 11). Moreover, surprisingly, the too early snow-off co-occurs with a slight negative temperature bias in the snow-melt season (Fig. 12).

To shed more light on the seemingly contradictory biases in temperature and snow-off dates, a detailed comparison of ECHAM5 results with observations at Sodankylä in Finnish Lapland is ~~represented~~presented. The black line in Fig. 14a displays the mean seasonal cycle of snow depth measured at Sodankylä in 1979–2006, for days of year 1–165 (i.e., from 1 January until 14 June). The other curves show the corresponding seasonal cycle of SWE for four ECHAM5 experiments (REF, REF_NDG, ALB1 and ALB2). While there is no one-to-one correspondence between snow depth and SWE, due to variations in snow density, it is clear from Fig. 14a that in three of the four ECHAM5 experiments (REF, REF_NDG and ALB2), snow melt occurs earlier than in the observations, by roughly 10–15 days. This is consistent with Fig. 3c, which indicates that in the Finnish Lapland, snow-off in the REF experiment occurs ~ 15 days earlier than in the satellite data. The exception is that in the experiment ALB1, which prescribes surface albedo from the AVHRR-based CLARA-SAL dataset, the timing of snow melt coincides well with the observations.

Figure 14b shows a comparison for the seasonal cycle of 2 m air temperature. From mid-March (day 75) onwards, all ECHAM5 simulations underestimate the average T_2 systematically. The average underestimate in the primary snow melt season (mid-April to mid-May; days 105–135), is ≈ 1.8 K for REF, REF_NDG and ALB2, and ≈ 3.5 K for ALB1. Thus the Sodankylä site represents a case where snow melt (and snow-off) occurs earlier in ECHAM5 than in the observations, in spite of a negative temperature bias in the snow melt season.

The problems with representing correctly the relationship between snow melt timing and temperature become even more obvious, when the temperature data are composited with respect to the snow-off date. Thus, for each year in 1979–2006, the snow-off date ("day 0") was defined as the first day after the winter's snow maximum completely without snow (in ECHAM5) or with snow depth equal to zero in the morning (in the observations), and the average T_2 was computed for each day in the range from 45 days before snow-off to 15 days after snow-off (Fig. 14c). Note specifically that as "day 0" represents the first completely snow-free day, snow actually vanishes sometimes during "day $-$ 1", and "day $-$ 2" is (generally) the last day with snow persisting throughout the day.

It is clear from Fig. 14c that ECHAM5 substantially underestimates T_2 in the snow melt season. Strikingly, this depends quite little on the experimental details such as nudging or changed treatment of surface albedo. The negative bias in T_2 culminates just before snow-off, being ≈ -7 K on "day $-$ 2". Furthermore, it is noted that in ECHAM5, the average T_2 reaches 0 °C as late as "day $-$ 1", during which the snow vanishes in the model. In the observations, the average T_2 reaches 0 °C already on "day $-$ 20", and climbs to 7 °C by "day $-$ 1". It is further seen that in ECHAM5, there is a substantial jump in temperature from "day $-$ 2" (the last day with snow throughout the day) to "day 0" (the first completely snow-free day), 2.9–3.9 °C depending on the experiment, whereas the observed change is only 1.0 °C. A similar composite analysis of temperature with respect to snow-off date was repeated for ECHAM5 for the entire ~~northern~~ Northern Eurasia, and it confirmed that the behaviour seen in Fig. 14 is quite universal. In particular, throughout the region, the average T_2 stayed below 0 °C until and including "day $-$ 2" (not shown).

The likely main reason for the fact that T_2 simulated by ECHAM5 stays close to 0 °C in the snow melt season is that the surface energy budget (and hence surface temperature) is not computed separately for the snow-free and snow-covered parts of the grid cell. Rather, while snow cover fraction is taken into account in defining grid-mean properties like surface albedo and roughness length, a single snow-covered energy balance computation is performed (Eq. 1).

As explained in Sect. 2.1, the amount of snow melt is determined from the condition that, when the surface temperature T_s would rise above 0 °C without considering snow melt, the heat consumed in melting snow restores T_s to 0 °C (Eq. 2). Here, T_s refers to the grid-mean surface temperature, not the temperature of melting snow. Therefore, as long as there is any snow left in the grid cell, T_s is not allowed to rise above 0 °C, irrespective of the snow cover fraction. Naturally, this acts to suppress the sensible heat flux (or even makes it negative), so 2 m air temperature cannot rise much above 0 °C either. In reality, in a region with partial (patchy) snow cover, surface temperature is kept to zero only in the patches of melting snow. In the snow-free patches, T_s, and consequently, T_2, can rise substantially above 0 °C. Furthermore, local temperature advection from snow-free to snow-covered patches and subsidence associated with a "snow breeze" circulation can increase T_2 over the latter (e.g., Yamazaki, 1995; Liston, 1995).

In summary, the use of a single surface energy budget computation leads to a misrepresentation of grid-mean surface fluxes in the presence of fractional snow cover (Liston, 2004): too much energy is spent in melting snow, and too little in warming the air and the ground. Consequently, T_2 stays too low in the snow melt season (Fig. 14c). This likely explains why ECHAM5 features a persistent cold bias in springtime T_2 even in regions where snow-off occurs earlier than observed (Figs. 10–12).

In addition, there is another factor related to the treatment of surface energy budget that may contribute to the too early snow-off: ECHAM5 does not include a canopy layer. In ECHAM5, forests influence the energy budget through changing the surface albedo and roughness length, but, for example, the shading of the surface by the canopy is not considered. Since forests reduce the surface albedo in the presence of snow (or more precisely, the combined albedo of the surface and the canopy) in ECHAM5, this implies that the amount of solar radiation available for snow melt at ground is increased in forests. In reality, the opposite happens, which ~~explains delayed~~ acts to delay springtime snowmelt in forests relative to non-forested areas (Strasser et al., 2011). This may explain why, in comparison with the snow course data, ECHAM5's tendency toward too early snow-off is more pronounced for forest than ~~field~~ open-terrain measurements (Fig. 4b–c).

Recently, Brutel-Vuilmet et al. (2013) found that, while there is still substantial intermodel dispersion among the CMIP5 models, on average the spring-time snow melt is slightly delayed in Northern Eurasia. Taken at face value, the default version of ECHAM5 agrees with this result for the eastern parts of Northern Eurasia, while in the west, snow vanishes too early (Figs. 3 and 4). However, such regional features are not discussed in Brutel-Vuilmet et al. (2013), and moreover, a rigorous comparison with their results is difficult due to the different datasets and analysis methods used (e.g., Brutel-Vuilmet et al., 2013, used only monthly data). An interesting question for further research is how well the CMIP5 models are able to represent the relationship between spring-time temperature and snow-off timing. In particular, is the problem of snow melt occurring at too cold grid-mean temperatures, as demonstrated in the current study, an exception or the rule for the CMIP5 models? A priori, we would expect some of the models to behave better (or at least differently) than ECHAM5. A prime example is the CLM4 land-surface model (Oleson et al., 2010) employed in the Community Earth System Model (CESM) (Hurrell et al., 2013) , which addresses all the main limitations of ECHAM5 identified in this work: the energy budget computation is separated for the snow-covered and snow-free parts of a grid cell, the computation of radiative fluxes at the snow surface accounts for the shading by the overlying forest canopy, and the snow albedo computation is more rigorous, based on radiative transfer modelling and a prognostic effective radius of snow grains. The CLASS land surface scheme (Verseghy, 2000) used in the CanCM4 climate model (von Salzen et al., 2013) also separates the energy budgets for snow-covered and snow-free land.

7 Conclusions

In the present work, we have evaluated the timing of springtime snow-off in Northern Eurasia in the ECHAM5 (version 5.4) atmospheric GCM. Simulated snow-off dates were compared with a snow-off date dataset based on space-borne microwave radiometer measurements and with Russian snow course data. The primary conclusions are as follows:

- In general, the default version of ECHAM5 reproduces well the observed geographic pattern of snow-off dates, with earliest snow melt (snow disappearing in March) in the Baltic region, and latest snow melt (in June) in the Taymyr region and parts of the Russian Far East. However, compared to the satellite data, snow-off occurs too early in the western parts of Northern Eurasia, and also in the northernmost regions like the Taymyr peninsula, with largest differences (locally over 20 days) in Northern Europe. On the contrary, in southeastern Siberia and in some far eastern parts of Russia, snow melts locally over 10 days later than in the satellite data. Comparison with the Russian snow course data confirms the pattern of too early snow-off in the west and too late snow-off in the east, although the former is slightly less pronounced, and the latter more pronounced, than in the corresponding comparison with the satellite dataset.

- The later than observed snow-off in southeastern Siberia is associated both with overestimated snow accumulation during winter and a springtime cold bias, which exceeds -6 K in April. The latter is, in part, related to an overestimation of surface albedo, which ~~has been ascribed to~~ arises from insufficient shadowing of the snow surface by the canopy in ECHAM5 in the dormancy season of deciduous needleleaf trees. In contrast, surface albedo is underestimated in late spring especially in the Taymyr region, ~~probably~~ both due to underestimated snow cover and because an unrealistically low albedo (0.3) is assumed for "warm" snow ($T_s \geq 0\,^{\circ}$C). This promotes too early snow-off in this region.

- Several sensitivity experiments were conducted, where biases in simulated atmospheric circulation were corrected through nudging and/or the treatment of surface albedo was modified. Both nudging and surface albedo modifications alleviated some of the model biases in snow-off dates, 2 m temperature (T_2) and surface albedo. In particular, it proved possible to reduce substantially the biases in snow-off date in southeastern Siberia and in the Taymyr region. In contrast, the early bias in snow-off in the western parts of ~~northern~~ Northern Eurasia was not reduced appreciably in any of the experiments; rather it was slightly increased by nudging. Furthermore, surprisingly, this early bias in snow-off was accompanied by a slight negative bias (≈ -2 to -1 K) in springtime T_2, both for the default version of ECHAM5 and for the sensitivity experiments.

- The combination of a too early snow-off with a cold springtime temperature bias implies that temperature stays too low in the snow melt season. In fact, as long as there is any snow left on the ground, the daily-mean T_2 simulated by ECHAM5 rarely rises above $0\,^{\circ}$C. In contrast, as demonstrated for the Sodankylä site in Finnish Lapland, the observed daily-mean T_2 typically climbs several degrees above $0\,^{\circ}$C before all snow has vanished.

- The likely main reason for the fact that T_2 in ECHAM5 stays close to $0\,^{\circ}$C in the snow melt season is that the surface energy budget (and hence the surface temperature T_s) is not computed separately for the snow-free and snow-covered parts of the grid cell. Thus, even if the diagnosed snow cover fraction is well below 1, the grid-mean T_s is not allowed to rise above $0\,^{\circ}$C. This acts to suppress the sensible heat flux (or even makes it negative), so T_2 cannot rise much above $0\,^{\circ}$C either, and leaves too large a fraction of the grid-mean surface net radiation to be consumed in melting snow.

– There is another factor related to the treatment of surface energy budget, which also likely contributes to the too early snow-off: ECHAM5 does not include a canopy layer. Thus, in particular, the shielding of snow on ground by the overlying canopy is not accounted for, which leaves too much solar radiation available for melting snow. This may explain why the early bias of snow-off in ECHAM5 in western Russia is especially pronounced when compared with snow course measurements made in forests.

Overall, the present study highlights the fact that snow-off timing in an atmospheric GCM depends on the simulation of a number of processes: large-scale circulation and temperature (which mainly determine the snowfall during winter), computation of snow properties on ground, treatment of surface albedo, and in general, the surface energy budget (which plays a key role for snow melt). In such a situation, as often in climate modeling, compensating errors are likely, so that improving any single process in the model may either improve or deteriorate the agreement with observations. An example of this is that for ECHAM5, the general tendency towards too early snow-off becomes clearer when biases in atmospheric circulation and temperature are corrected by nudging. This exposes more clearly the problems related to the treatment of surface energy budget, especially in the presence of partial snow cover and forests. Beyond that, an obvious area for further development would be the snow scheme itself, which is rather simplistic in ECHAM5. Only the SWE and snow temperature are computed, with no consideration of snow density and snow grain size. Furthermore, the temperature dependent snow albedo scheme in ECHAM5 is very simple and, as demonstrated in this and previous work, to some extent unrealistic.

Finally, according to our preliminary tests, snow melt also occurs at too low (grid-mean) temperatures in the Max Planck Institute's newest atmospheric GCM, ECHAM6 (Stevens et al., 2013). Like ECHAM5, ECHAM6 does not define separately the surface temperature for the snow-free and snow-covered parts of a grid cell. It is an intriguing question to which extent this issue pertains to other global and regional climate models.

Appendix A: Determination of snow-off dates based on Russian snow course data

In the Russian snow course data (Bulygina et al., 2011a), SWE measurements are typically provided at 10 day intervals in winter and 5 day intervals in spring (starting from March or April). A major issue in defining the snow-off date based on these data is, however, that in the absence of snow, SWE measurements are generally not reported. Thus one cannot always be sure whether missing data indicates that there is no snow left to be measured, or that the measurement was not performed for some other reason. To define the snowmelt date, we adopted the following procedure.

1. The observation date with maximum SWE (d_{max}) for the winter was located.

2. The part of the SWE timeseries after d_{max} was studied, and cases were sought in which a valid measurement of SWE was followed by missing data, with the corresponding dates denoted by $d_{\mathrm{miss}-1}$ and d_{miss}.

3. In such cases, it was assessed whether the missing data could plausibly indicate the absence of snow. For this end, we evaluated the statistics of SWE changes between two observation times (either 5 or 10 days apart from each other) within one month of the date in question, considering all years for which the station reported data. If the change in SWE from $d_{\mathrm{miss}-1}$ to d_{miss} required for all snow to melt by the time d_{miss} (i.e., $\Delta\mathrm{SWE\_required} = -\mathrm{SWE}_{\mathrm{miss}-1}$) was within two standard deviations ($\sigma_{\Delta\mathrm{SWE}}$) of the mean value ($\overline{\Delta\mathrm{SWE}}$) of SWE changes for the time of the year, that is,

$$\Delta\mathrm{SWE\_required} \geq \overline{\Delta\mathrm{SWE}} - 2\sigma_{\Delta\mathrm{SWE}}, \tag{A1}$$

   it was assumed that the missing SWE value at day d_{miss} indicates the absence of snow ($\mathrm{SWE}_{\mathrm{miss}} = 0$).

4. If the missing value was deemed to be zero, all subsequent missing values were also interpreted as zero, until (possibly) a positive SWE value was found.

5. After the SWE time series was corrected as outlined above, the snow-off date was determined. Data for three observation days were used: the first observation day (d_{zero}) with corrected SWE $= 0$ after the winter's SWE maximum (d_{max}), and the two observation days preceeding it with SWE > 0 (denoted as d_{m2} and d_{m1}, with SWEs of SWE$_{m2}$ and SWE$_{m1}$, respectively). If linear extrapolation based on the values SWE$_{m2}$ and SWE$_{m1}$ suggested all snow to have melted before d_{zero}, the snow-off date was computed as

$$d_{\text{snow-off}} = d_{m1} + (d_{m1} - d_{m2}) \frac{\mathrm{SWE}_{m1}}{\mathrm{SWE}_{m2} - \mathrm{SWE}_{m1}}, \tag{A2}$$

otherwise, it was assumed that $d_{\text{snow-off}} = d_{\mathrm{zero}}$.

6. Finally, if the SWE reached values higher than 20 kg m^{-2} after the determined snow-off date, the case was considered suspicious; thus this winter's data for this snow course were ignored in further analysis. Cases in which the above algorithm failed to find a snow-off date were likewise ignored in the subsequent analysis.

Clearly, the above algorithm involves some arbitrary choices (especially the criterion of 2 standard deviations in Eq. (A1) and the limit of 20 kg m^{-2} in step (6) of the algorithm). However, a number of sensitivity tests were conducted regarding the choice of these parameters, and it was found that the statistics of model vs. observation differences were largely insensitive to them. For example, changing the criterion of 2 standard deviations in Eq. (A1) to either 1 or 3 standard deviations changed the average model vs. observation difference in snow-off dates by less than 1 day.

Lastly but importantly, to compare ECHAM5's snow-off dates with the snow course data as consistently as possible, the simulated SWE time series were first subsampled according to the availability of the snow course data (i.e., including only the days with measurements), and the snow-off dates for ECHAM5 were then determined according to the algorithm outlined above. For comparison with satellite data, however, the simulated snow-off dates were derived from the complete time series of daily-mean SWE.

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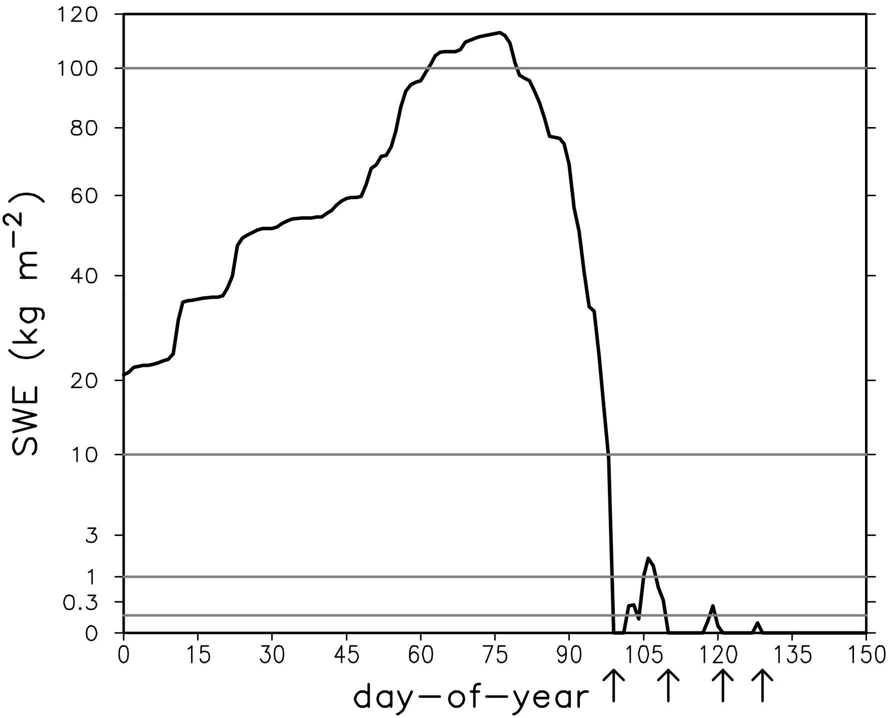

Figure 1. Time series of snow water equivalent ($\mathrm{kg\,m^{-2}}$) in days 0–150 of year 1988 for a grid cell in western Russia (60.6° N, 39.4° E) for one of the ECHAM5 runs included in the REF experiment (SWE plotted in a square root scale for a better viewing of small values). The grey horizontal lines correspond to SWE values of 100 $\mathrm{kg\,m^{-2}}$, 10 $\mathrm{kg\,m^{-2}}$, 1 $\mathrm{kg\,m^{-2}}$, and 0.1 $\mathrm{kg\,m^{-2}}$. The four arrows at days 99 (8 April), 110 (19 April), 121 (30 April) and 129 (8 May) indicate possible snow-off days (first day with SWE $= 0$ after a period with SWE > 0). The first snow-off day is employed in this paper for comparison with observational data.

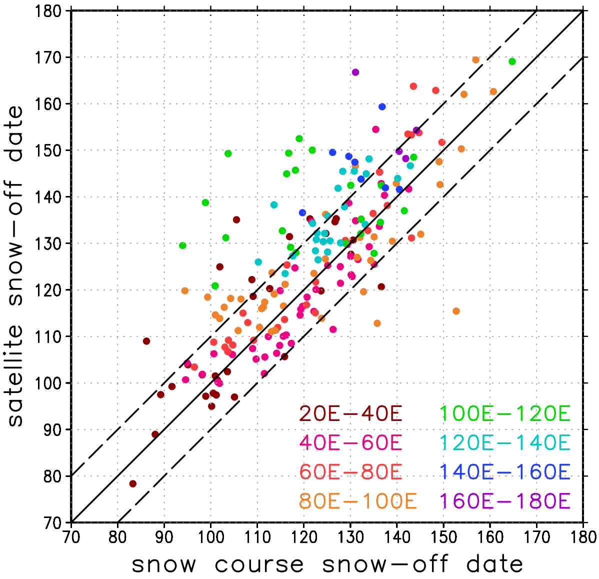

Figure 2. The relationship between time-mean snow-off dates based on the snow course data and the satellite retrievals. The satellite snow-off dates were averaged to the T63 horizontal resolution and screened according to the availability of snow course data. Only those grid cells for which the snow-off date in the snow course data could be determined for at least five years during 1979–2006 are included. The data points are colour-coded according to longitude. The solid diagonal line indicates equal snow-off dates for the two datasets, while the dashed diagonals correspond to a difference of $\pm$10 days.

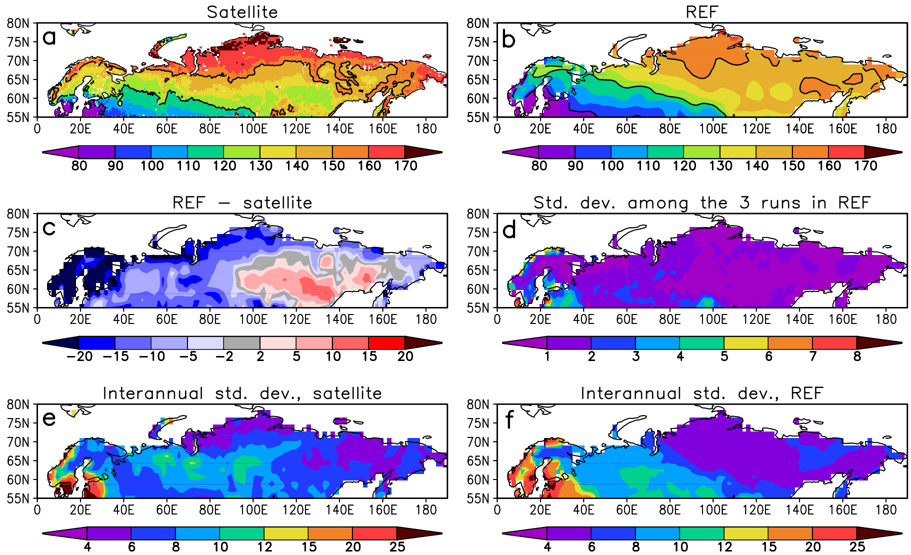

Figure 3. Mean snow-off date in years 1979–2006 based on **(a)** the satellite retrievals and **(b)** the REF experiment. Unit: day of year (Julian day). Snow-off dates of 90, 120 and 150 corresponding approximately to the beginning of April, May and June are indicated with black lines. **(c)** The difference in the average snow-off date between the REF experiment and the satellite retrievals. For computing the difference, the satellite snow-off dates were averaged to the model grid. **(d)** The standard deviation (σ_{n-1}) in 28 year mean snow-off date among the $n = 3$ differently initialized runs included in the REF experiment. **(e)** The standard deviation of yearly snow-off dates in the satellite retrievals (for snow-off dates averaged to the model grid), and **(f)** in the REF experiment (computed first separately for the three runs in REF and then averaged).

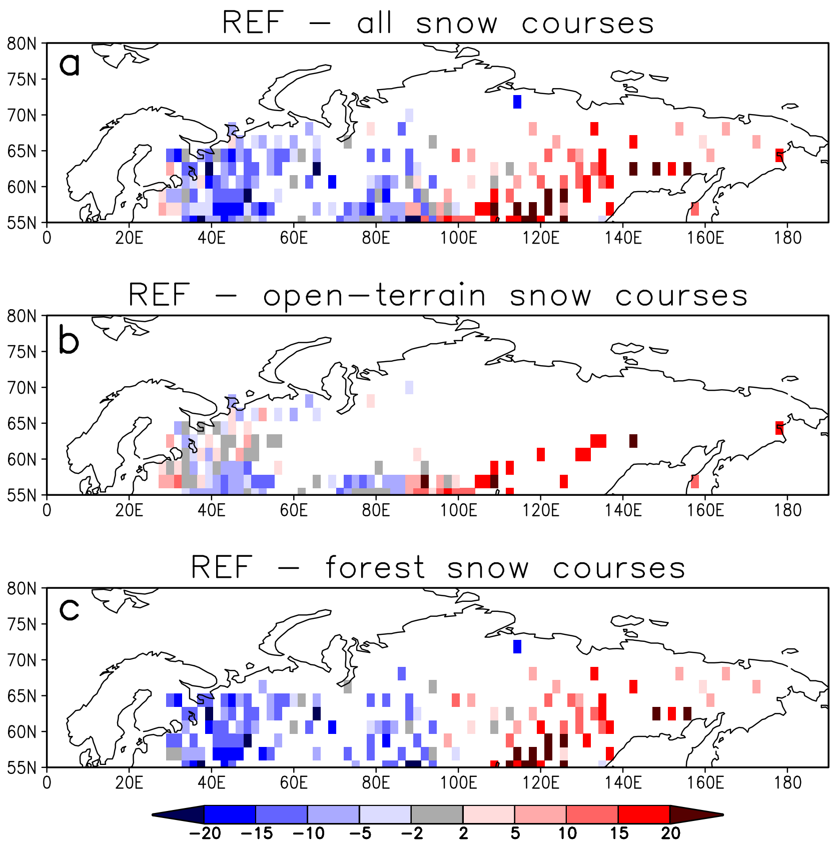

Figure 4. The difference in the average snow-off date for years 1979–2006 between the REF experiment and Russian snow course data for **(a)** all snow courses, **(b)** ~~field~~ open-terrain snow courses, and **(c)** forest snow courses. Only those grid cells with ~~snowmelt~~ snow-off data for at least five years are included.

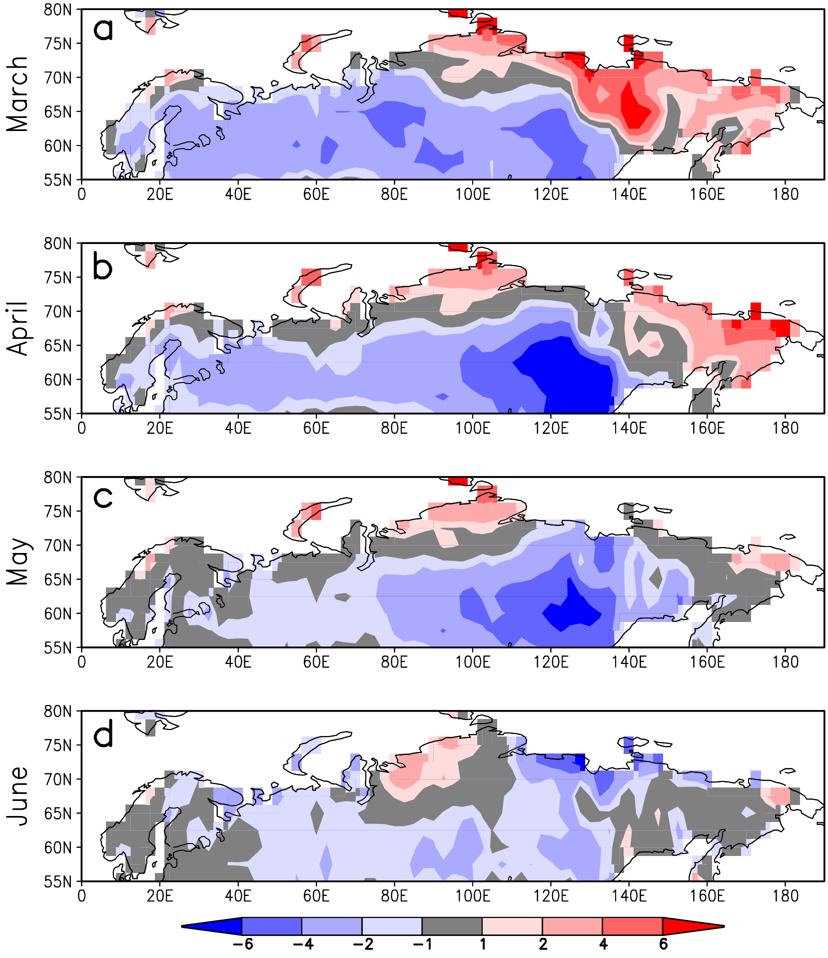

Figure 5. Differences in 2 m air temperature [K] for years 1979–2006 between the REF experiment and the CRUTEM3 dataset for the months of March, April, May and June.

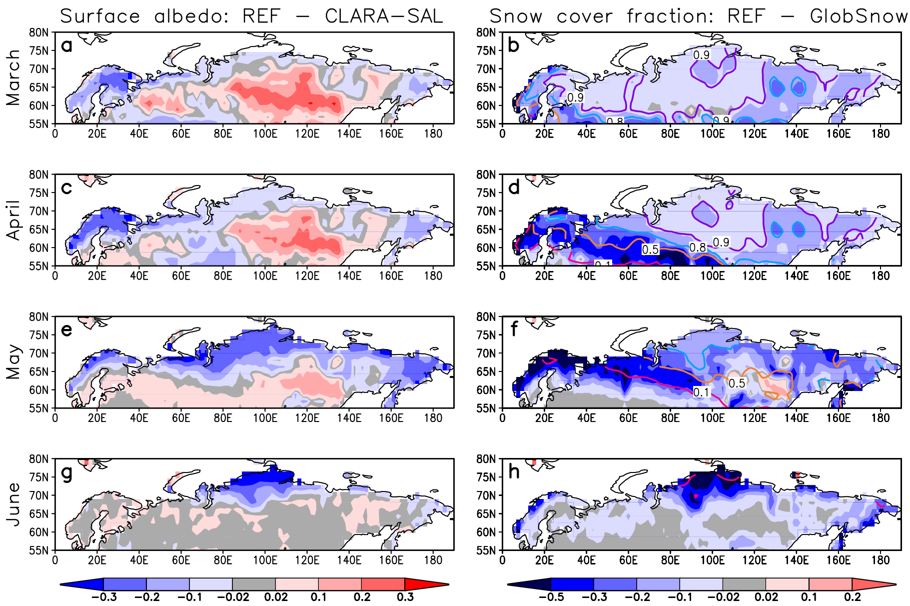

Figure 6. (a,c,e,g): Differences in surface albedo for years 1982–2006 between the REF experiment and the CLARA-SAL dataset for the months of March, April, May, and June. **(b,d,f,h)**: Corresponding differences in snow cover fraction for years 1997–2006 (excluding 2002) between the REF experiment and the GlobSnow dataset. The coloured contours (magenta = 0.1; orange = 0.5; blue = 0.8; and violet = 0.9) indicate the snow cover fraction in REF.

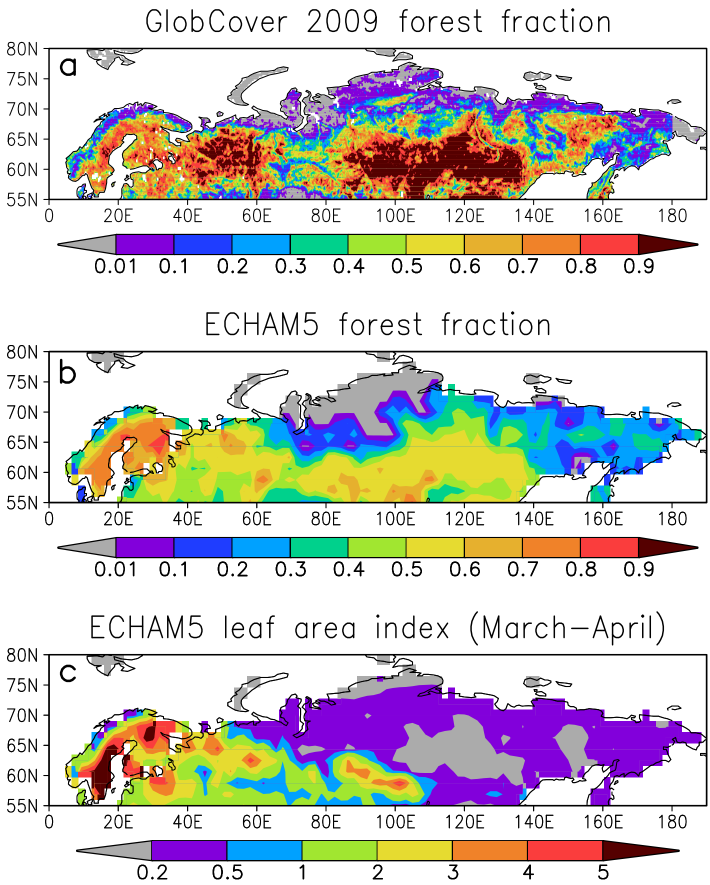

Figure 7. **(a)** Forest fraction in the GlobCover 2009 land cover map (computed as the sum of land cover classes 40, 50, 60, 70, 90 and 100). **(b)** Forest fraction assumed in the ECHAM5 simulations. **(c)** Leaf area index assumed in the ECHAM5 simulations, averaged over the months of March and April.

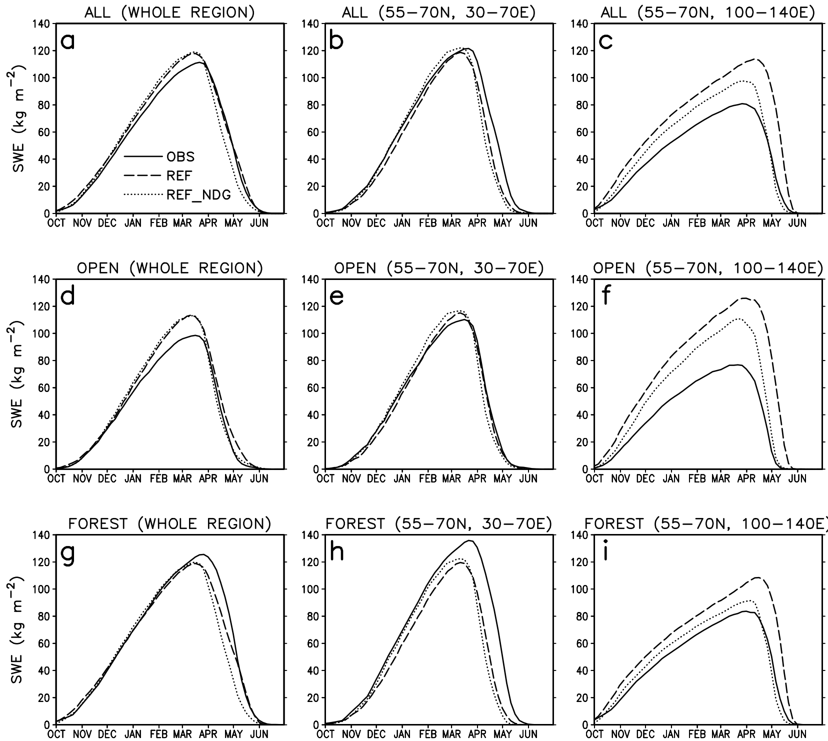

Figure 8. Mean annual cycle of SWE according to the snow course measurements (solid line), in the REF experiment (dashed line) and in the REF_NDG experiment (dotted line) for **(a)** all snow courses for the whole Northern Eurasian domain, **(b)** for Western Russia (55–70° N, 30–70° E) and **(c)** for Eastern Siberia (55–70° N, 100–140° E). **(d–f)**: as **(a–c)** but including only ~~field~~ open-terrain snow courses. **(g–i)**: as **(a–c)** but including only forest snow courses. Only those ECHAM5 grid cells with snow course data are included in the domain-mean values. For clarity, results for the ALB1, ALB2, ALB1_NDG and ALB2_NDG experiments are not shown. In general, albedo changes had little effect on SWE, except for the snow melt season.

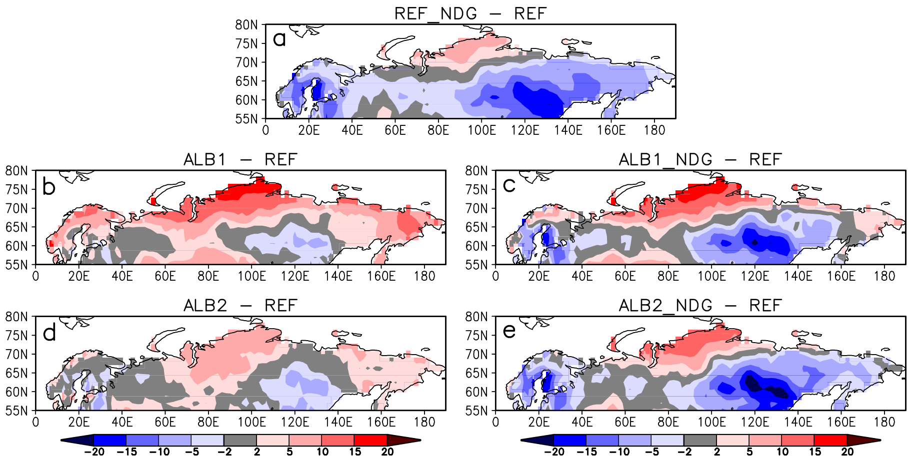

Figure 9. Differences in average snow-off date between the five sensitivity experiments (REF_NDG, ALB1, ALB1_NDG, ALB2 and ALB2_NDG) and the REF experiment.

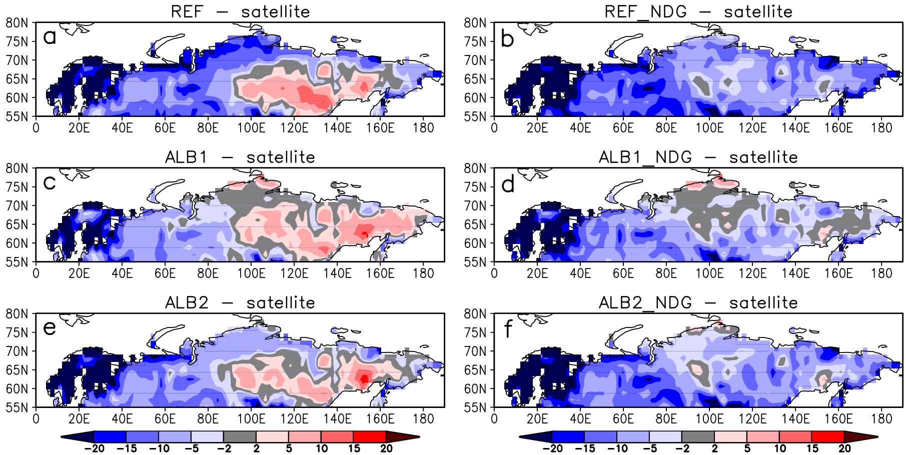

Figure 10. Differences in average snow-off date between the six ECHAM5 experiments and the satellite retrievals.

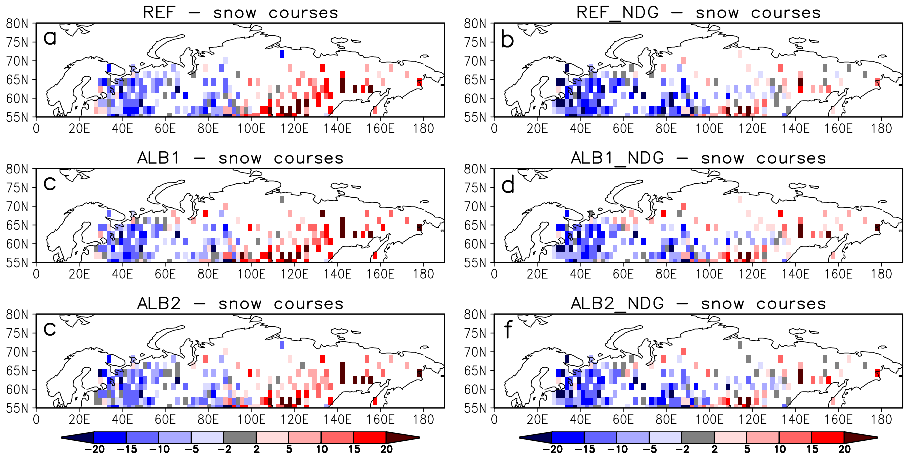

Figure 11. Differences in average snow-off date between the six ECHAM5 experiments and the Russian snow course data. Both ~~field~~ open-terrain and forest snow courses are included in the comparison.

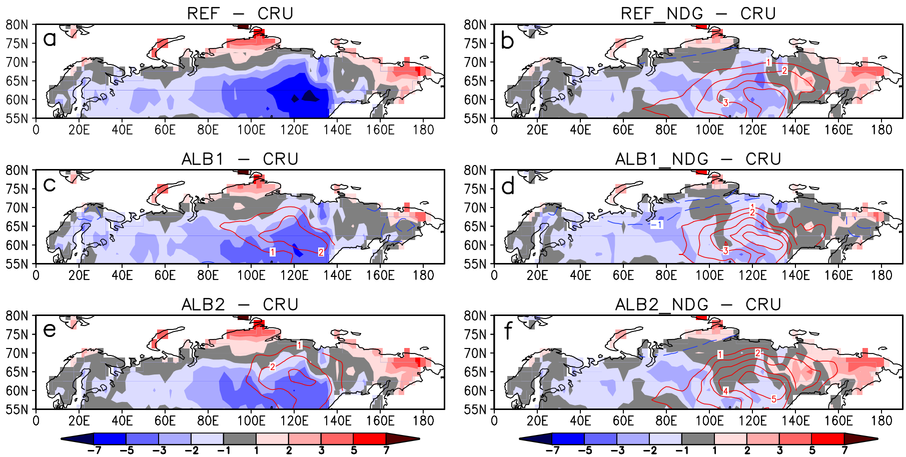

Figure 12. Differences in April–May mean 2 m air temperature between ECHAM5 and the CRUTEM3 dataset for the **(a)** REF, **(b)** REF_NDG, **(c)** ALB1, **(d)** ALB1_NDG, **(e)** ALB2 and **(f)** ALB2_NDG experiments. The contours in **(b–f)** indicate the difference from the REF experiment (contour interval 1 K; zero contour omitted).

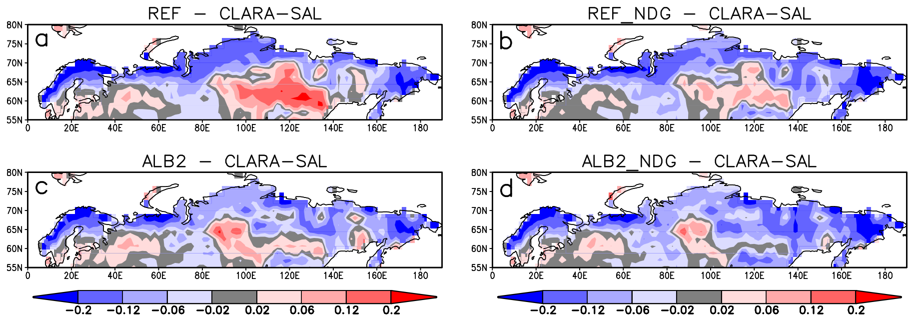

Figure 13. Differences in April–May mean albedo between ECHAM5 and the CLARA-SAL dataset for the **(a)** REF, **(b)** REF_NDG, **(c)** ALB2 and **(d)** ALB2_NDG experiments. In ALB1 and ~~ALB~~ALB1_NDG (not shown) the albedo values are, by construction, identical to the CLARA-SAL data.

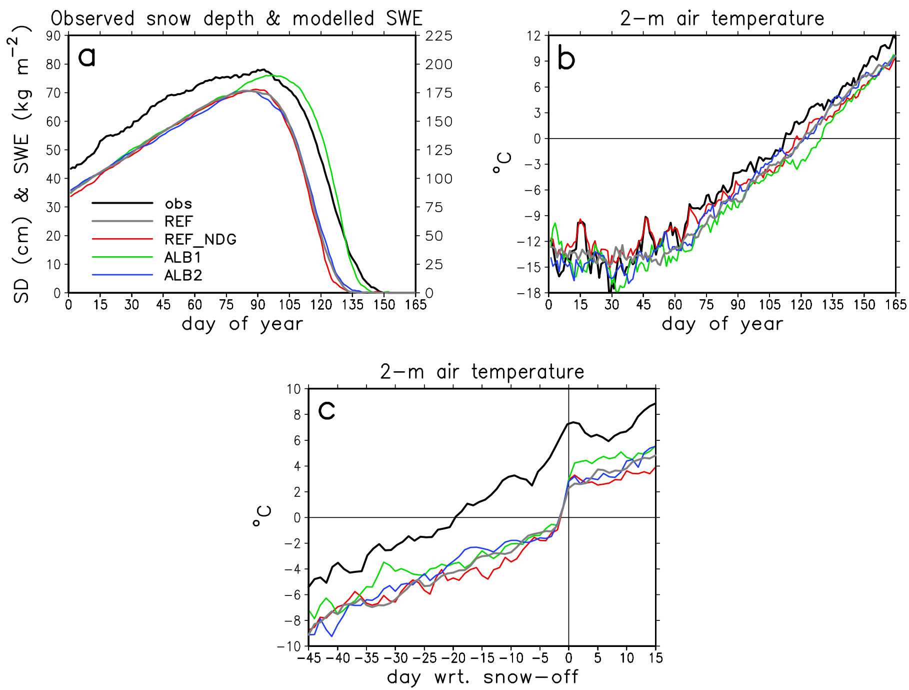

Figure 14. Comparison of ECHAM5 simulations with observations at Sodankylä (67.37° N, 26.63° E). **(a)** Mean seasonal cycle of observed snow depth (black line, scale on the left) and modelled SWE (four curves for different ECHAM5 experiments, scale on the right) in 1979–2006. **(b)** Mean seasonal cycle of 2 m air temperature. **(c)** Mean 2 m air temperature composited with respect to the snow-off date, "day 0" representing the first completely snow-free day. The ECHAM5 results are taken from the grid point nearest to the Sodankylä site (68.08° N, 26.25° E).