**Reply to the Comments by Referee #1 for Manuscript gmdd-8-3197-2015**

**General comments:** The paper "Representation of vegetation effects on the snow-covered albedo in the Noah land surface model with multiple physics options", by S. Park and S. K. Park, addresses relevant scientific modelling questions, in my opinion, within the scope of GMD. The topic of the paper is the improvement of the parameterization of snow albedo over vegetated areas in the Noah-MP model, which is one of the land surface model more used and popular, and is also included in some mesoscale meteorological models, such as WRF. The question is important, as snow albedo strongly affects energy budget, and an erroneous evaluation can affect also hydrological components. The results obtained represent advances in modelling science suitable for addressing relevant scientific questions within the scope of EGU. To my knowledge, the method proposed and the results obtained are novel and represent a sufficiently substantial advance in modelling science; the authors have also clearly indicated their own original contribution. The methods and assumptions are valid and clearly outlined, but in some parts of the paper there are some sentences unclear and some details are missing. Nevertheless, the results are sufficient to support the interpretations and conclusions. The description of the methodology is sufficiently complete and precise to allow their reproduction by fellow scientists, but a few details should be specified better. The overall presentation is structured in a good way, despite some confusion in some technical passages. Regarding the language, in my opinion a thorough revision of English language is required.

⇒ *We appreciate the positive comments by the referee. The referee fully understands the major questions and results addressed in this study. We have improved the manuscript by making some unclear sentences clearer and by adding more details to some parts that details are missing. We also tried to avoid confusions in some technical passages in the revised manuscript. The revised manuscript went through a thorough language check.*

**Specific comments and technical corrections:** In the attached version of the manuscript, I have reported several notes, concerning some corrections, suggestions and requests.

⇒ *We do appreciate the detailed comments by the referee, which helped us improve the quality of the manuscript. We have faithfully revised the manuscript following the referees specific comments with some corrections, suggestions and requests. An item-by-item response to the referees specific comments in the supplement is provided below*

**Major points:**

Page 3198, line 11-12: "$\cdots$ the vegetation effect rarely exerts on the surface albedo in winter in East Asia with only these parameters." – This sentence is not very clear – please rephrase it.

⇒ *We have rewritten this part as "$\cdots$* ***leaf and stem in winter are not well represented with only these parameters.****"*

Page 3199, line 29: "In the Noah-MP, the formula for albedo includes a sum of leaf area index (LAI) and stem area index (SAI). The grid box values $\cdots$" – This study improves evaluation of albedo by modifying the value of LAI and SAI in Noah-MP. But it is not explicated how LAI an SAI depend on albedo. It is also useful to include the formula here.

⇒ *We have rewritten this part as "In the Noah-MP, the formula for albedo includes a sum of leaf area index (LAI) and stem area index (SAI).* ***The details on how LAI and SAI depend on albedo are explained in Sect. 3.2.1.*** *The grid box values ⋯"*

Page 3200, line 2-3: "The grid box values of LAI and SAI in winter **are set to the same minimum values over all vegetation types and are too low**." – How do you know this? No plot, no references ⋯.

⇒ *We plotted LAI and SAI, but have not shown. We have rewritten "The grid box values of LAI and SAI in winter are set to the same minimum values over all vegetation types* ***(i.e., $LAI_{min}$ = 0.05 and $SAI_{min}$ = 0.01) and are too low compared to Asner et al. (2003).****"*

Page 3200, line 5-6: "⋯ the model cannot simulate albedo accurately **due to a deficiency** in the effect of nonphotosynthetic vegetation structures. **They also cast a shadow on the snow-covered surface by the canopy, arising from the solar zenith angle (SZA).** Such a **deciency** can be a major cause of ⋯" – Not a deficiency: the problem is that they are not parameterized at all. Also rephrase the unclear sentence "They cast ⋯ the solar zenith angle (SZA)."

⇒ *We have rewritten this part as "⋯ the model cannot simulate albedo accurately* ***because nonphotosynthetic vegetation structures are not parameterized at all. In winter, these nonphotosynthetic parts are very important for surface albedo through shadowing. Such deficient parameterizations of nonphotosynthetic vegetation structures*** *can be a major cause of ⋯"*

Page 3200, line 9-10: "Therefore, we improve the model-calculated albedo through a clear understanding of vegetation effects on albedo." – Albedo will improve with a new parameterization; a clear understanding may improve the conceptual frame.

⇒ *We have rewritten this part more clearly as "Therefore, we improved the model-calculated albedo* ***with a new parameterization of vegetation parameters, based on an advanced conceptual frame*** *through a clear understanding of vegetation effects on* ***snow*** *albedo."*

Page 3200, line 19-22: "For this study, we have only changed ⋯" – Actually you have used both of them: see fig. 5 - explain better!

⇒ *We have changed this part to "For this study,* ***we have conducted experiments using the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al., 1993; Yang et al., 1997) as the option of snow surface albedo. We have also used the Canadian Land Surface Scheme (CLASS; Verseghy, 1991; Verseghy et al., 1993) with new vegetation parameters for testing model performance of albedo.****"*

Page 3202, before Section 3: How soil temperature and moisture has been initialized? Simulations are started on January 1st? How snow cover has been initialized?

⇒ *We have added the following sentences to the end of Section 2.1: "****Soil temperature and moisture, snow cover has been initialized by having a spin-up period of 6 months. Simulations started on 00:00 UTC 01 June.****"*

Page 3202, line 19-21: "leaves and stems are mostly shed $\cdots$ over the forest types" – Actually leaves disappear (fall down) for some vegetation (deciduous trees), and remain unchanged for others (coniferous) - while most of stems remain unchanged; it depends on vegetation type.

⇒ *We have rewritten this part and next sentence more clearly as "When the growing season is over,* ***leaves disappear for some vegetation (e.g., deciduous trees), and remain unchanged for others (e.g., evergreen trees) while most of stems remain unchanged – reaching the minimum values. Thus, this change at the end of the growing season and the amount of stems depend on vegetation types and make distinctions of albedos over the forest types in winter.****"*

Page 3202, line 23-24: "have little difference between forest and short vegetation (**not shown**)" – Why not shown? It is important!

⇒ *It is not feasible to directly compare albedos between observations and model results because snow cover fraction (SCF) is not verified. In Table 1 below, we compared albedos from the Noah-MP with that from MODIS under a 100 % SCF, which are averaged over each vegetation type during the years 2001-2010 within 40-60°N and 105-145°E. In the Noah-MP, albedos over all vegetation types are overestimated and the differences of albedos among different types are comparable. This table is added to the revised manuscript as Table 4.*

Page 3203: Since MODIS evaluates LAI, it could be interesting to compare MODIS LAI vs Noah-MP LAI and see if really data confirm your suspects.

⇒ *When we consider the effect of forest masking in winter, LAI is also important for evergreen trees. However, most trees in the region where snow falls moderately do not have broad leaves, thus SAI is more important than LAI to forest masking in winter. In addition, we have already shown the comparison between the Noah-MP LAI and the reference values of LAI in Table 3 (Table 5 in the revised manuscript).*

Page 3203, line 17-18: "These uncertainties are caused by their definition." – This sentence has no sense!

⇒ *We have rewritten this sentence as "$\cdots$ $LAI_{min}$.* ***These uncertainties are due to disregard of non-photosynthetic process in defining LAI in the model. Note that the observed LAI represents all leaves regardless of photosynthetic capacity. Hence, the observed LAI is higher than the model-evaluated LAI.*** *Actually, the structure $\cdots$."*

Page 3206, line 16-17: "The bias errors of albedo rarely decrease when SI reaches a certain value." – Please explain better.

⇒ *We have rewritten this part as "$\cdots$ (see Table 5).* ***The bias errors of albedo decrease very slowly after a certain value of SI; hence SI is considered to be optimized when the difference of bias between two consecutive SI is less than 0.005.*** *The other $\cdots$"*

Page 3206, line 20-22: You here only mention SI; in the table, there is also LI reported as "reference value": what means? Did you do a similar job also for evaluating LI? If not, how have you evaluated it? Also please say more clearly that, after having derived values of LI and SI for some vegetation types, you will use values in model simulations.

⇒ *We have added explanation for evaluating LI to line 5: "$\cdots$ for vegetation types in the East Asia region, in order to compare with the MODIS 16-day observations.* ***We have to priorly evaluate LI for drawing realistic SI effect because LI and SI are considered together for calculating albedo. Here we have assigned the observation values (Asner et al., 2003) to the LI values. Asner et al. (2003) collected more than 1,000 estimated LAI from literature and then made a global LAI dataset through a statistical analysis. The LAI dataset of forest types have been compiled from plenty of robust samples, thus they are sufficiently reliable to be used as the reference values of LI.*** *Figure 4 shows the bias errors of albedo between observations and model output $\cdots$"*

Page 3207, line 1: "Albedo with other radiation option is also overestimated" – Which options? You have to mention and describe each option you use. Otherwise nobody could understand the meaning of the figure.

⇒ *We have added the description of the radiation options and have rewritten this part as: "Albedo with other radiation options is also overestimated, due to underestimated LAI and SAI.* ***There are three radiation options in the Noah-MP for calculating energy fluxes: The first is MTSA, employed for parameterization in this study, that calculates canopy gaps from three-dimensional structure and solar zenith angle (OPT_RAD1). The second option is two-stream radiation option with no canopy gap that means leaves are evenly distributed within the grid-cell with a 100 % vegetation fraction (OPT_RAD2). The last is the tile approach that computes energy fluxes in vegetated fraction and bare fraction separately and then sum them up weighted by fraction (OPT_RAD3). The optimal LI and SI obtained through the MTSA had the similar improving effect on albedo when applied to the other options.*** *The RMSEs with the original $\cdots$"*

**Minor points:**

Page 3198, line 14-15: "We found that calculation of albedo without proper **reflection** of the vegetation effect $\cdots$" – **reflection**???

⇒ *We have rewritten this part as "We found that calculation of albedo without proper* ***representation*** *of the vegetation effect $\cdots$"*

Page 3198, line 23-25: "Vegetation influences both snow cover and albedo, **which** can be summarized in three points."

⇒ *We have rewritten this part as "Vegetation influences both snow cover and albedo* ***that*** *can be summarized in three points."*

Page 3199, line 6: "whose height is 10 m" → "10 m high"

⇒ *Done.*

Page 3199, line 6: "be accumulated more than 10 m" → "accumulate for more than 10 m"

⇒ *It is rewritten as "accumulate to more than 10 m".*

Page 3199, line 7: "the accumulated amount" → "an accumulated amount"

⇒ *Done.*

Page 3199, line 8: "off-nadir solar zenith angle"???

⇒ *We meant "**non-zero solar zenith angle**", and revised it in the text.*

Page 3199, line 11-12: "Although the air temperature is just below 0°C, there is no frost under trees and snow melts earlier." → "For instance, when the air temperature is just below 0°C, there is no frost and snow melts earlier under trees."

⇒ *Done.*

Page 3199, line 19: "a direct effect" → "a direct and quantifiable effect"

⇒ *Done.*

Page 3199, line 20: "a spatial" → "the spatial"

⇒ *Done.*

Page 3199, line 22: "or use **impractical** vegetation parameters" – **impractical**???

⇒ *We meant **unrealistic** vegetation parameters such as LAI and SAI in winter in the Noah-MP, and revised accordingly in the text.*

Page 3200, line 4-5: "With only photosynthetically active leaves and stems in winter" → "Being photosynthetically active leaves and stems absent in winter"

⇒ *Done.*

Page 3200, line 9: "we improve" → "we improved"

⇒ *Done.*

Page 3200, line 14: "to **expedite** physically based ensemble climate predictions ···" – **expedite**???

⇒ *We have rewritten this part as "to **accelerate physically-based** ensemble climate prediction **model runs** ···"*

Page 3200, line 16: "the model has been used in **an offline** mode" → "the model has been used in **offline** mode"

⇒ *Done.*

Page 3200, line 18: "We select" → "We have selected"

⇒ *Done.*

Page 3200, line 19: "in Yang et al. (2001)" → "by Yang et al. (2001)"

⇒ *Done.*

Page 3200, line 22-25: "In contrast to the **CLASS** which simply computes the overall snow albedo **with** fresh snow albedo and snow age, the **BATS** calculates snow albedo for direct and diffuse radiation in visible and near-infrared broadband accounting for several **aspects** such as **fresh snow albedo, snow age**, grain size growth, ···" → "In contrast to the **CLASS scheme** which simply computes the overall snow albedo **depending on** fresh snow albedo and snow age, the **BATS one** calculates snow albedo for direct and diffuse radiation in visible and near-infrared broadband accounting for several **additional parameters** such as grain size growth, ···"

⇒ *Done. However, to follow the comment by Referee #2, we have rewritten this part as "**In terms of the albedo options in the Noah-MP, the CLASS scheme simply computes** the overall snow albedo **depending on** fresh snow albedo and snow age while the **BATS one** calculates snow albedo for direct and diffuse radiation in visible and near-infrared broadband accounting for several **additional parameters** such as grain size growth, ⋯"*

Page 3201, line 3: "The computational domain covers" → "The computational domain **on which we have run the model** covers"

⇒ *Done.*

Page 3201, line 4-6: "However, most analyses **are conducted** in north of 40°N where snow falls moderately. The model **runs** during the years 2001-2010 with a spin-up time of 6 months." → "However, most analyses **have been performed** in north of 40°N**,** where snow falls moderately. The model **has run** during the years 2001-2010**,** with a spin-up time of 6 months."

⇒ *Done.*

Page 3201, line 9: "The atmospheric data is" → "The atmospheric data are"

⇒ *Done.*

Page 3201, line 11-13: "The atmospheric forcing fields can be obtained from the atmospheric data assimilation system (ADAS) component of a weather forecast and analysis system or from a reanalysis fields." – Which ones?

⇒ *We have rewritten this part as "The atmospheric forcing **data set is a combination of NOAA/GDAS atmospheric analysis field, spatially and temporally disaggregated NOAA Climate Prediction Center Merged Analysis of Precipitation (CAMP) fields, and observation-based downward shortwave and longwave radiation fields derived using the method of the Air Force Weather Agencys AGRicultural ME-Teorological modeling system (AGRMET).**"*

Page 3201, line 20: "(MCD43C3) is **produced** every 16 days" → "(MCD43C3)**, installed on both TERRA and AQUA polar satellites,** is **evaluated** every 16 days"

⇒ *Done.*

Page 3201, line 20: "in a level-3 data set" – What does it mean?

⇒ *A level-3 data set denotes global-gridded science products. There are categories of MODIS data products: Level 0 denotes raw spectral channel counts, Level 1B denotes calibrated and geolocated radiances, and Level 2 denotes orbital-swath science products.*

Page 3201, line 22-23: "(or bihemispherical reflectance under conditions of isotropic illumination)" → "(bihemispherical reflectance under conditions of isotropic illumination),"

⇒ *Done.*

Page 3201, line 24: "The albedo products ⋯" – MODIS? With which results? Are they reliable or not?

⇒ *We have rewritten this part as "**Cescatti et al. (2012) validated MODIS albedo retrievals against in situ measurements across 53 FLUXNET sites, and found a good agreement in mean yearly values between retrievals and measurements with a high correlation ($r^2$ = 0.82).**"*

Page 3202, line 2: "is" → "has been"

⇒ *Done.*

Page 3202, line 5-6: "Land cover types are grouped into 27 types according to the USGS classification (see Table 1)." – And you have used them?

⇒ *Yes, we have used them. To avoid any confusion, we have rewritten this part as "**In this study, land cover types are grouped into 27 types according to the USGS classification, as shown in Table 1.**"*

Page 3202, line 10: "within 40-60°N" – The interval of longitude?

⇒ *It is within* $40° - 60° N$ *and* $105° - 145° E$ *and the main text is modified accordingly.*

Page 3202, line 12: "we have averaged the white-sky albedo" – Data from MODIS or model Noah-MP?

⇒ *Data from MODIS. We have rewritten as "we have averaged the **MODIS** white-sky albedo"*

Page 3202, line 14: The number of days are comparable?

⇒ *Yes, the number of days is in the table below. It means the day when snow cover fraction equals 100 % for 2001-2010 in each area. We have added a sentence "**The number of days in each area with a 100 % SCF is sufficient for comparison, as shown in Table 3.**"*

| area 1 | area 2 | area 3 | area 4 | area 5 | area 6 | area 7 | area 8 | area 9 | area 10 |
|---|---|---|---|---|---|---|---|---|---|
| 1483 | 6159 | 13235 | 12391 | 4033 | 8201 | 328 | 9318 | 7973 | 248 |

Page 3203, line 4: "the leaf (stem) mass" → "the leaf (stem) mass per unit of surface"

⇒ *We changed it to "the leaf (stem) mass **per unit area**"*

Page 3203, line 6: "The default value of $LAI_{min}$ and $SAI_{min}$ is 0.05 and 0.01 $m^2m^{-2}$, respectively, and the effect of different vegetation types is not considered." → "The default values of $LAI_{min}$ and $SAI_{min}$ are 0.05 and 0.01 $m^2m^{-2}$, respectively, for all vegetation types."

⇒ *Done.*

Page 3203, line 8: "**are set** to **the** minimum values" → "**remain equal** to **their** minimum values"

⇒ *Done.*

Page 3203, line 12-13: "it might be inadequate for the model to treat LAI and SAI **the same** in the albedo parameterization" → "it might be inadequate for the model to treat LAI and SAI **in the same way** in the albedo parameterization"

⇒ *Done.*

Page 3203, line 17: "much" → "even"

⇒ *Done.*

Page 3203, line 19-20: "regardless of **the** ability to express photosynthesis; hence it is higher than the **model calculation**." → "regardless of **their** ability to express photosynthesis; hence it is higher than the **one evaluated by the model, which is related to photosynthesis**."

⇒ *Done.*

Page 3203, line 23: "We **introduce** new parameters" → "We **have introduced** new parameters **in the model**"

⇒ *Done.*

Page 3203, line 25-26: "We **substitute** LI with the reference minimum values (see Asner et al., 2003) for four forest types as **given** in Table 3 in Sect. 3.2.2 in order to draw" → "We **have substituted** LI with the reference minimum values (see Asner et al., 2003) for four forest types**,** as **shown** in Table 3 in Sect. 3.2.2**,** in order to draw"

⇒ *Done.*

Page 3204, line 3: "$\cdots$ in the Noah-MP and" → "$\cdots$ in the Noah-MP, and"

⇒ *Done.*

Page 3204, line 6: "We focus on the snow-covered albedo treatments rather than running the model with full physics in idealized cases." – Sentence not clear.

⇒ *We have changed the sentence to make it clear as "**We have focused on testing the albedo scheme in idealized cases.**"*

Page 3204, line 8: "we **assume**" → "we **have assumed**"

⇒ *Done.*

Page 3204, line 9: "the wetted fraction" – Why not the dry one?

⇒ *The wetted fraction is related to the intercepted snow. We controlled the model with a 100 % snow cover."*

Page 3204, line 9: "snow depth to 1 m" – Why 1 m and not 10 m or 10 cm?

⇒ *We wanted to show the shading effect when canopy of a tree is fully or almost covered by snow; thus 10 m is unrealistically high for snow accumulation while 1 cm is too short for trees and snow depth to discuss the vegetation effect on snow albedo. Of course, grass is already covered.*

Page 3204, line 9-10: "**SI varies** from 0.1 to 10.0 with an interval of 0.1 **having a SZA of** 0, 30, 45, 60 and 75°." → "**We have imposed SI to vary** from 0.1 to 10.0 with an interval of 0.1**, as well as SZA** 0, 30, 45, 60 and 75°."

⇒ *Done.*

Page 3205, line 3: "vegetation **fraction ranged** from" → "vegetation fraction**, and ranges** from"

⇒ *Done.*

Page 3205, line 6: "the Noah-MP to **SI averaged**" → "the Noah-MP to **SI, averaged**"

⇒ *Done.*

Page 3205, line 7: "Total albedo by vegetation and ground, $f_{re}$, **is**" → "Total albedo by vegetation and ground, $f_{re}$, **is evaluated as:**"

⇒ *Done.*

Page 3205, line 9-11: "where $\alpha_d$ and $\alpha_{dc}$ **is** the direct albedo of the underlying surface and canopy, respectively, and $\alpha_i$ and $\alpha_{ic}$ **is** the diffuse albedo of the underlying surface and canopy, respectively. **How to calculate** canopy albedo $\cdots$" → "where $\alpha_d$ and $\alpha_{dc}$ **are** the direct albedo of the underlying surface and canopy, respectively, and $\alpha_i$ and $\alpha_{ic}$ **are** the diffuse albedo of the underlying surface and canopy, respectively. **The parameterization of** canopy albedo $\cdots$"

⇒ *Done.*

Page 3205, line 12: "$\cdots$ for diffuse **radiation. Here** $K_{open}$ **is** set to 0.05." → "$\cdots$ for diffuse **radiation, and here it has been** set to 0.05."

⇒ *Done.*

Page 3205, line 13: "$\cdots$ decreases **with SI** because" → "$\cdots$ decreases **with increasing SI** because"

⇒ *Done.*

Page 3205, line 24-25: "$\cdots$ we **compare** the Noah-MP albedo with **observation**. We **performed** model runs **repeatedly by** changing $\cdots$" → "$\cdots$ we **have compared** the Noah-MP albedo with **observations**. We **have performed** model runs **by repeatedly** changing $\cdots$"

⇒ *Done.*

Page 3206, line 1-3: "$\cdots$ the optimal SI for each forest type **that reduce a** bias of albedo between observation and model output. LAI and SAI were used to calculate **carbon flux as well as radiation** during the growing season." → "$\cdots$ the optimal SI for each forest type **that is able to reduce the** bias of albedo between observation and model output. LAI and SAI were used to calculate **fluxes of carbon, radiation, turbulent heat, etc.,** during the growing season."

⇒ *Done.*

Page 3206, line 4: "Albedo **is** averaged $\cdots$" → "Albedo **has then been** averaged $\cdots$"

⇒ *Done.*

Page 3206, line 4-5: "in specific winter days (i.e. 337, 353, and 1, 17, and 33 as Julian day)" – Why?

⇒ *It is to compare with the MODIS 16-day observations, and the winter days are from December to February in the next year. We modified the sentence as "$\cdots$ in the East Asia region,* ***in order to compare with the MODIS 16-day observations****."*

Page 3206, line 6: "between **observation** and" → "between **observations** and"

⇒ *Done.*

Page 3206, line 12-13: "**It does not make sense that** short vegetation **has high SI; therefore modification** of $\cdots$" → "**Since** short vegetation **does not have high SI in winter, modification** of $\cdots$"

⇒ *Done.*

Page 3206, line 23: "$\cdots$ the new LI and SI **is described** by calculating the root" → "$\cdots$ the new LI and SI **has been evaluated** by calculating the root"

⇒ *Done.*

Page 3206, line 25: "$\cdots$ RMSE **is** reduced" → "$\cdots$ RMSE **has been** reduced"

⇒ *Done.*

Page 3207, line 4: "$\cdots$ (e.g., the 17th Julian day) **and** decrease" → "$\cdots$ (e.g., the 17th Julian day)**, and** decrease"

⇒ *Done.*

Page 3214, Figure 1: Explain what are the blue areas.

⇒ *We have rewritten the figure caption as "Figure 1. Geographical locations of the study domain.* ***Each blue area has a dominant vegetation type as explained in Table 2.****"*

Page 3215, Figure 2: Please move the legends within the plot, and mention in the caption that the areas are those of Fig. 1.

⇒ *We have moved the legends within the plot and have rewritten the figure caption as "Figure 2. The white-sky albedo for total shortwave broadband averaged for winter time in 2001-2010 (dots) and corresponding SD (bars) when SCF equals 100 %.* ***Descriptions for the areas are shown in Fig. 1 and Table 2.****"*

Page 3216, Figure 3: Figures are small and the legend is almost invisible – please enlarge them!

⇒ *We have enlarged Fig. 3 in the revised manuscript.*

Page 3217, Figure 4: Please indicate with a larger point the "optimized value" selected.

⇒ *Figure 4 is modified by including larger points to represent the optimized values and is depicted with solid lines of different colors to make the lines better discernible. The figure caption is also modified accordingly as "Figure 4. Sensitivity of the winter-averaged albedo to SI over four forest types and three short vegetation types in the Noah-MP for 2001-2010.* ***The optimized value for each forest type is indicated with a larger symbol.****"*

Page 3218, Figure 5: As I have said in the text, you need to describe the options used.

⇒ *We have redrawn Fig. 5 and modified the figure caption as: "Figure 5. Comparison of RMSE values of albedo with the original minimum value of LAI and SAI (dashed lines) vs. new LI and SI (solid lines) for three radiation options for (a) BATS and (b) CLASS* ***radiation schemes. OPT_RAD1 is MTSA, OPT_RAD2 is two-stream radiation option with no canopy gap, and OPT_RAD3 is the scheme that calculate the gap from vegetation fraction.****"*

Table 1: The values of mean and standard deviation (SD) of snow albedo from the MODIS observation and the Noah-MP results for the shortwave broadband for different categories of the MODIS land cover. The data are averaged for winter time in 2001-2010 over each vegetation type within $40^\circ - 60^\circ$N and $105^\circ - 145^\circ$E with corresponding SD when SCF equals 100 % and other snow conditions are the same.

| MODIS land cover | MODIS | | Noah-MP | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Dryland Cropland and Pasture | **0.515** | 0.088 | **0.795** | 0.012 |
| Grassland | **0.595** | 0.080 | **0.787** | 0.020 |
| Shrubland | **0.432** | 0.079 | **0.805** | 0.029 |
| Mixed Shrubland/Grassland | **0.474** | 0.085 | **0.806** | 0.026 |
| Deciduous Broadleaf Forest | **0.428** | 0.076 | **0.748** | 0.075 |
| Deciduous Needleleaf Forest | **0.346** | 0.080 | **0.678** | 0.134 |
| Evergreen Needleleaf Forest | **0.296** | 0.097 | **0.761** | 0.069 |
| Mixed Forest | **0.334** | 0.093 | **0.721** | 0.115 |

## Reply to the Comments by Referee #2 for Manuscript gmdd-8-3197-2015

**General comments:** Park and Park discuss simulations of albedo for vegetation with snow cover in the Noah-MP model. I have speculated (Essery 2013) that some current models use unrealistic parameter values in their representations of masking of snow albedo by forests, so I am interested to see a specific demonstration of this problem. However, I think that the manuscript requires some clarifications. The English is good for non-native writers, but will need editing for correct usage.

⇒ *The authors appreciate the positive comments by the referee. We agree with the referee's speculation that some current models use unrealistic parameter values in representing the forest-masking effect of the snow albedo. We have included Essery (2013) in the References and cited appropriately in the text, along with other references suggested by the referee. Some parts of the manuscript are explained more clearly following the referee's suggestions. The revised manuscript went through a language editing check. In the following, we made an item-by-item response to the specific comments by the referee. We believe that the referee's comments helped us improve the quality of the manuscript.*

**Specific comments and technical corrections:**

It needs to be pointed out that the minimum leaf and stem area indices quoted are only used by the dynamic vegetation option in Noah-MP. Otherwise, monthly indices are read from tables which could contain more realistic values.

⇒ *We agree with the referee and have added a sentence to page 3200, line 19: "··· Yang et al. (2011).* ***The dynamic vegetation option is employed to assess the minimum leaf and stem area indices.*** *For this study, ···"*

Page 3198, line 5: "Snow albedo of forest is typically lower than that of short vegetation" – that, indeed, can be the case due to litter in snow beneath trees (Hardy et al. 2000), but what is meant here is that the albedo of forests with snow cover is typically lower than that of short vegetation with snow cover.

⇒ *We have rewritten this part as "****For the snow-covered surface condition, albedo of forest is typically lower than that of short vegetation****"*

Page 3200, line 23: The CLASS albedo option in Noah-MP may compute an overall snow albedo, but CLASS itself computes albedos for direct and diffuse radiation in visible and nearinfrared bands (Verseghy et al. 1993).

⇒ *We have rewritten this part as "****In terms of the albedo options in the Noah-MP, the CLASS scheme simply computes*** *the overall snow albedo* ***depending on*** *fresh snow albedo and snow age* ***while the BATS one*** *calculates snow albedo for direct and diffuse radiation in visible and near-infrared broadband accounting for several* ***additional parameters*** *such as grain size growth, ···"*

Page 3202, line 24: Why not show Noah-MP snow-covered albedos in Fig. 2? The difference between these and observations is the main point being made.

⇒ *It is not feasible to directly compare albedos between observations and model results because snow cover fraction (SCF) is not verified. In Table 1 below, we compared albedos from the Noah-MP with that from MODIS under a 100 % SCF, which are averaged over each vegetation type during the years 2001-2010 within 40-60° N and 105-145° E. In the Noah-MP, albedos over all vegetation types are overestimated and the differences of albedos among different types are comparable. This table is added to the revised manuscript as Table 4.*

Page 3203: A brief discussion of how Noah-MP predicts leaf and stem indices would be useful. A large seasonal cycle in forest stem area does not seem like an intended behaviour.

⇒ *The equations for computing LAI and SAI from Noah-MP are given in Eqs. (1) and (2), respectively. We also added new figures showing the behaviour of LAI and SAI from Noah-MP. Figure 1 below shows a monthly averaged LAI, calculated from Noah-MP, during the period of 2001-2010 for deciduous broadleaf forest (Fig. 1a), deciduous needleleaf forest (Fig. 1b), and evergreen needleleaf forest and mixed forest (Fig. 1c). The red lines represent the minimum, mean and maximum LAI of the reference values from Asner et al. (2003) for each vegetation type. In Fig. 1c, the reference LAI values are shown for only evergreen needleleaf forest. It is notable that the model-evaluated LAI values are much smaller than the reference values for all vegetation types in winter. In Fig. 2 below, the forest SAI has a seasonal cycle in the Noah-MP, but the magnitude is negligibly small. In defining the new stem index (SI), we assumed that trees were mature and focused on winter when the growing season is over; thus SI having no seasonal cycle. These figures are added to the revised manuscript as Figs. 3 and 4, respectively.*

Page 3205, line 7: How were the four radiation components weighted to calculate the total albedo in Figure 3?

⇒ *First, the downward solar radiation (SWDOWN; W/m$^2$) is divided into four parts, direct visible (SOLAD(1)) and diffuse visible (SOLAI(1)) radiation and direct near-infrared (SOLAD(2)) and diffuse near-infrared (SOLAI(2)) radiation, through equations below:*

```
SOLAD(1) = SWDOWN*0.7*0.5      ! direct vis
SOLAD(2) = SWDOWN*0.7*0.5      ! direct nir
SOLAI(1) = SWDOWN*0.3*0.5      ! diffuse vis
SOLAI(2) = SWDOWN*0.3*0.5      ! diffuse nir
```

*Second, four albedo components are weighted to calculate the total radiaton as follows:*

```
RVIS = ALBD(1)*SOLAD(1) + ALBI(1)*SOLAI(1)
RNIR = ALBD(2)*SOLAD(2) + ALBI(2)*SOLAI(2)
FSR = RVIS + RNIR
```

*where ALBD(1) and ALBD(2) are albedos from direct visible bands and direct near-infrared bands, respectively. ALBI(1) and ALBI(2) are albedos from diffuse visible bands and diffuse near-infrared bands, respectively. RVIS and RNIR are reflected radiative fluxes from visible bands and near-infrared bands, respectively. FSR is total reflected radiative flux. Finally, you can get the albedo value through the formula below,*

```
ALBEDO = FSR/SWDOWN.
```

*This explanation is included in the revised manuscript as Appendix A.*

Page 3205, line 12: Why is K_open set to 0.05? It should also vary with vegetation cover. If the comparison is with MODIS white-sky albedo, only the model diffuse albedo should be used.

⇒ *In the Noah-MP, $K_{open}$ is considered as a constant and set to 0.05. For the accurate comparison, we should have the same condition between the model and the observation, but in the model each part of albedo, such as direct or diffuse albedo and visible or near-infrared albedo is much simply calculated, as shown above. In addition, the difference between the black-sky albedo and the white-sky albedo of MODIS is small, thus the weighted average albedo using the aerosol optical depth may have similar value to each of the MODIS albedo. Therefore, we compared the total albedo of the Noah-MP with the MODIS white-sky albedo and thought that such comparison is within the observation error range.*

Page 3205, line 16: Please consider doi:10.1029/2010EO450004.

⇒ *We thank the referee for recommending this reference. We have rewritten the sentence as: "**At a fixed SI, albedo represents different patterns for different SZA – with increasing SZA, albedo decreases at relatively low SI while it increases at relatively high SI.**"*

Page 3206, line 20: Because the influence of the SI in Figure 4 saturates at positive bias values, it is not just possible but in fact clear that snow cover fraction is too high, forest fraction is too low or snow-covered forest albedos are too high to match the observations.

⇒ *Please note that the bias errors in Fig. 4 are represented in the absolute values (i.e., absolute values of model minus observation), as we clearly mentioned in the text. So the argument made by the referee is partly true, but not always.*

Page 3206, line 27: If showing results from the other radiative transfer options, brief descriptions of them are required.

⇒ *We have added the description of the radiation options: "Albedo with other radiation options is also overestimated, due to underestimated LAI and SAI. **There are three radiation options in the Noah-MP for calculating energy fluxes: The first is MTSA, employed for parameterization in this study, that calculates canopy gaps from three-dimensional structure and solar zenith angle (OPT_RAD1). The second option is two-stream radiation option with no canopy gap that means leaves are evenly distributed within the grid-cell with a 100 % vegetation fraction (OPT_RAD2). The last is the tile approach that computes energy fluxes in vegetated fraction and bare fraction separately and then sum them up weighted by fraction (OPT_RAD3). The optimal LI and SI obtained through the MTSA had the similar improving effect on albedo when applied to the other options.** The RMSEs with the original ···"*

Page 3213: Please comment on why the optimized LI turns out larger for deciduous than evergreen forest.

⇒ *We believe that the deciduous broadleaf forest has a higher minimum value of LAI than the evergreen needleleaf forest due to the larger leaf area. Actually, in winter, deciduous forest does not have any leaf and LAI might be 0 theoretically. However, field measurements of LAI of deciduous forests have some value in winter, especially when the grid box size is as large as 25 km × 25 km. In this coarse grid box, vegetation is not fully homogeneous. Therefore, we have regarded that deciduous broadleaf forest has the minimum LAI with low spatial resolution due to heterogeneous vegetation types.*

Page 3215: Figure 2 caption should state that these are from observations.

⇒ *We have rewritten the caption as "**Figure 2. The MODIS white-sky albedo for total shortwave broadband averaged for winter time in 2001−2010 (dots) and corresponding standard deviation (bars) when snow cover fraction equals 100 %. Descriptions on the areas are provided in Fig. 1 and Table 2.**"*

Page 3218: Note that OPT_RAD1 in Figure 5 is MTSA in the text. Explain why OPT_RAD3 (new) differs from the other options much more with the BATS snow albedo than with CLASS.

⇒ *Compared to other options, OPT_RAD3 simply calculates the vegetation fraction. OPT_RAD1 calculates the vegetation fraction by considering 3-D structures and solar zenith angle; thus it specifically considers the vegetation effects. Because OPT_RAD2 calculates the grid cell with a 100 % vegetation fraction, the vegetation effects is maximized. Therefore, albedo with OPT_RAD3 is relatively less sensitive to vegetation parameters. In fact, while we examined Fig. 5 to reply to the referee's comment, we found a minor error in producing the results in Fig. 5. We have recalculated and redrawn Fig. 5 with new results in the revised manuscript (Fig. 7 now), in which OPT_RAD3 shows similar results in both the BATS and CLASS schemes. With this new calculation, we found that the improvement in the RMSE was approximately 69 % rather than 73 %. We have corrected in the abstract and main text accordingly.*

Essery, R (2013). Large-scale simulations of snow albedo masking by forests. Geophysical Research Letters, 40, 5521-5525, doi:10.1002/grl.51008.
Hardy, JP, R Melloh, P Robinson and R Jordan (2000). Incorporating effects of forest litter in a snow process model. Hydrological Processes, 14, 3227-3237.
Verseghy, D, NA McFarlane and M Lazare (1993). CLASS: A Canadian Land Surface Scheme for GCMs. II. Vegetation model and coupled runs. International Journal of Climatology, 13, 347-370.

⇒ *We thank the referee for suggesting these articles. We have added them to the References section and cited appropriately in the text.*

Table 1: The values of mean and standard deviation (SD) of snow albedo from the MODIS observation and the Noah-MP results for the shortwave broadband for different categories of the MODIS land cover. The data are averaged for winter time in 2001-2010 over each vegetation type within $40^\circ - 60^\circ$N and $105^\circ - 145^\circ$E with corresponding SD when SCF equals 100 % and other snow conditions are the same.

| MODIS land cover | MODIS | | Noah-MP | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Dryland Cropland and Pasture | **0.515** | 0.088 | **0.795** | 0.012 |
| Grassland | **0.595** | 0.080 | **0.787** | 0.020 |
| Shrubland | **0.432** | 0.079 | **0.805** | 0.029 |
| Mixed Shrubland/Grassland | **0.474** | 0.085 | **0.806** | 0.026 |
| Deciduous Broadleaf Forest | **0.428** | 0.076 | **0.748** | 0.075 |
| Deciduous Needleleaf Forest | **0.346** | 0.080 | **0.678** | 0.134 |
| Evergreen Needleleaf Forest | **0.296** | 0.097 | **0.761** | 0.069 |
| Mixed Forest | **0.334** | 0.093 | **0.721** | 0.115 |

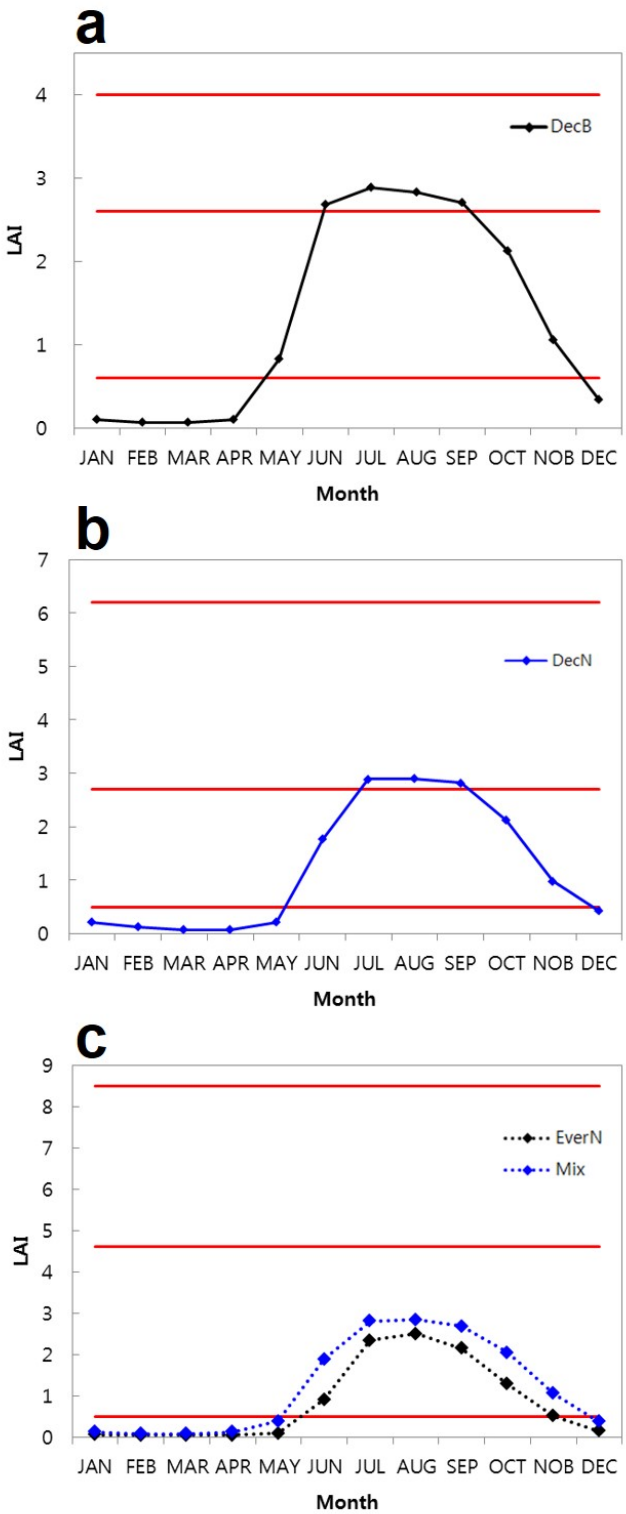


Figure 1: Monthly averaged LAI in the Noah-MP during the period of 2001−2010 for (a) deciduous broadleaf forest (DecB), (b) deciduous needleleaf forest (DecN), (c) evergreen needleleaf forest (EverN) and mixed forest (Mix). The red lines represent the minimum, mean and maximum LAI of the reference values. In (c), the reference values are shown only for EverN.

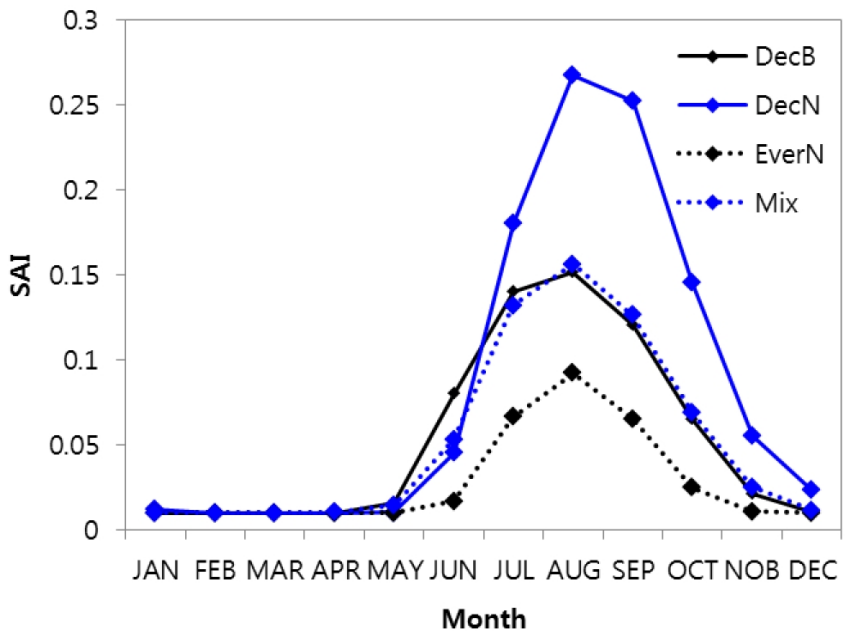


Figure 2: Monthly averaged SAI in the Noah-MP during the period of 2001−2010 for deciduous broadleaf forest (DecB), deciduous needleleaf forest (DecN), evergreen needleleaf forest (EverN) and mixed forest (Mix).

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# ~~Representation~~ Parameterization of ~~vegetation effects on~~ the snow-covered surface albedo in the ~~Noah land surface model with multiple physics options~~Noah-MP Version 1.0 by implementing vegetation effects

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**Abstract.** ~~Snow albedo plays a critical role in calculating the energy budget, but parameterization of the snow surface albedo is still under great uncertainty. It varies with~~ The snow-covered surface albedo varies with many factors, including snow grain size, snow cover thickness, snow age, forest shading factor~~and other variables. Snow~~ , etc., and its parameterization is still under great uncertainty. For the snow-covered surface condition, albedo of forest is typically lower than that of short vegetation; thus snow albedo is dependent on the spatial distributions of characteristic land cover and on the canopy density and structure. In the Noah land surface model with multiple physics options (Noah-MP), almost all vegetation types in East Asia during winter have the minimum values of leaf area index (LAI) and stem area index (SAI), which are too low and do not consider the vegetation types. Because LAI and SAI are represented in terms of photosynthetic activeness, ~~the vegetation effect rarely exerts on the surface albedo in winter in East Asia~~ leaf and stem in winter are not well represented with only these parameters. ~~Thus, we investigated the vegetation effects on the snow-covered albedo from observations and evaluated the model improvement by considering such effect.~~ We found that ~~calculation of albedo without proper reflection of~~ such inadequate representation of the vegetation effect is mainly responsible for the large positive bias in ~~winter. Therefore, we~~ calculating the winter surface albedo in the Noah-MP. In this study, we investigated the vegetation effect on the snow-covered surface albedo from observations and improved the model performance by implementing a new parameterization scheme. We developed new parameters, called leaf index (LI) and stem index (SI), which properly manage the effect of vegetation structure on the ~~winter~~ snow-covered surface

albedo. As a result, the Noah-MP's performance in ~~albedo has been~~ the winter surface albedo has significantly improved – ~~RMSE~~ the root mean square error is reduced by approximately ~~73~~69 %.

## 1 Introduction

Snow albedo is very important ~~when it comes to~~ in calculating the energy budget at the land surface, but the vegetation effects on adequate parameterization of the snow surface albedo are still under great uncertainty. Vegetation influences both snow cover and albedo ~~, which~~ that can be summarized in three points. First, the canopy changes snow depth because leaves and branches can intercept part of the snow. Second, vegetation generally has a larger roughness than bare soil. Normally just a small amount of snow is sufficient to cover a bare soil, resulting in high albedo. However, the same snow amount above a grass field cannot cover all the grass because some individual elements of grass can be higher than snow depth. Thus, in case of snow, total albedo over a grass is lower than that over a bare soil. With the same amount of snow, total albedo becomes much lower over a forest. This can be the case due to litter in snow beneath trees (Hardy et al., 2000); however, it is mostly related to snow depth to cover vegetation. For example, in order to fully cover a tree ~~whose height is~~ 10 m high, snow should ~~be accumulated~~ accumulate to more than 10 m. Although the tree top can be intercepted by snow with ~~the~~ an accumulated amount lower than 10 m, the shading effect of tree through its structure still remains at ~~off-nadir~~ non-zero solar zenith angle. Lastly, vegetation can change heat flux with different temperature from a bare soil. Moreover, vegetation changes the longwave radiation as a tree re-emits radiation downwards. ~~Although~~ For instance, when the air temperature is just below 0 °C, there is no frost ~~under trees~~ and snow melts earlier under trees.

Previous studies have addressed the apparent relationship between snow cover over different vegetation types and the snow surface albedo through field measurements and satellite observations as well (Henderson-Sellers and Wilson, 1983; Jin et al., 2002; Gao et al., 2005). Gao et al. (2005) found that the maximum snow-covered albedos of non-forest types are typically higher than those of forest types, showing the shading effect of the density and vertical structure of canopy on snow cover. Forest shading is caused by leaves, stems, branches and trunks, and has a direct and quantifiable effect on albedo. Despite ~~a~~the spatial distribution of albedo generally follows the patterns of land cover type (Jin et al., 2002), many land surface models (LSMs) do not consider the vegetation effect on snow albedo or use ~~impractical vegetation parameters~~unrealistic vegetation parameters; thus resulting in no significant differences in snow-covered albedo over different land surface (Essery, 2013). In numerical models, albedo under snow condition is usually parameterized through separate treatments for different surfaces (i.e., snow-covered vs. snow-free), which are weighted by the snow cover fraction. Thus, the snow cover fraction is also important for accurate calculation of albedo.

In this study, we examine how vegetation effects can be adequately considered for computation of albedo during winter in the Noah land surface model with multiple physics options (Noah-MP)

version 1.0 (Niu et al., 2011; Yang et al., 2011). In the Noah-MP, the formula for albedo includes a sum of leaf area index (LAI) and stem area index (SAI). The details on how LAI and SAI depend on albedo are explained in Sect. 3.2.1. In most cases, the grid box values of LAI and SAI in winter are set to the same minimum values over all vegetation types ~~and~~ (i.e., $LAI_{min}$ = 0.05 and $SAI_{min}$ = 0.01) and are too low ~~.~~ compared to Asner et al. (2003). The crucial point to note is that both LAI and SAI are represented as photosynthetically active structures in the Noah-MP. ~~With only~~ Being photosynthetically active leaves and stems absent in winter, the model cannot simulate albedo accurately ~~due to a deficiency in the effect of~~ because nonphotosynthetic vegetation structures ~~. They also cast a shadow on the snow-covered surface by the canopy, arising from the solar zenith angle (SZA). Such a deficiency~~ are not parameterized at all. In winter, these nonphotosynthetic parts are very important for surface albedo through shadowing. Such deficient parameterizations of nonphotosynthetic vegetation structures can be a major cause of the large positive bias errors of albedo in the Noah-MP. Therefore, we ~~improve~~ improved the model-calculated albedo with a new parameterization of vegetation parameters, based on an advanced conceptual frame through a clear understanding of vegetation effects on snow albedo.

## 2 Model and data description

### 2.1 The Noah-MP

The Noah-MP has evolved from the Noah land surface model and has a variety of potentials to ~~expedite physically based ensemble climate predictions~~ accelerate physically-based ensemble climate prediction model runs and identification of both the optimal scheme combinations and the critical processes controlling the coupling strength (Niu et al., 2011). In this study, the model has been used in ~~an~~ offline mode, simulating the land surface processes with atmospheric forcing. The Noah-MP has 12 different scheme sets representing various physical processes. We ~~select~~ have selected the default options that were verified for the global river basins ~~in~~ by Yang et al. (2011). The dynamic vegetation option is employed to assess the minimum leaf and stem area indices. For this study, we have ~~only changed the~~ conducted experiments using the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al., 1993; Yang et al., 1997) as the option of snow surface albedo~~scheme from~~. We have also used the Canadian Land Surface Scheme (CLASS; Verseghy, 1991~~) to the Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et~~ ; Verseghy et al., 1993~~;~~ ~~Yang et al., 1997) . In contrast to the CLASS which~~ ) with new vegetation parameters for testing model performance of albedo. In terms of the albedo options in the Noah-MP, the CLASS scheme simply computes the overall snow albedo ~~with~~ depending on fresh snow albedo and snow age ~~, the BATS~~ while the BATS one calculates snow albedo for direct and diffuse radiation in visible and near-infrared broadband accounting for several ~~aspects such as fresh snow albedo, snow age,~~ additional

parameters such as grain size growth, impurity, and especially solar zenith angle (SZA) (Niu et al., 2011).

The computational domain on which we have run the model covers 4000 km × 4000 km, with a grid size of approximately 30 km, in the East Asia region (105−145° E, 20−60° N). However, most analyses ~~are conducted in~~ have been performed over north of 40° N, where snow falls moderately. The model ~~runs~~ has run during the years 2001–2010, with a spin-up time of 6 months. Soil temperature and moisture, snow cover has been initialized by having a spin-up period of 6 months. Simulations started on 00:00 UTC 01 June.

### 2.2 Data sets

#### 2.2.1 Atmospheric forcing

The atmospheric data ~~is~~ are required to force the land surface processes in LSMs. For the Noah-MP, the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) data have been used to drive the model during the period 2001–2010. The atmospheric forcing ~~fields can be obtained from the atmospheric data assimilation system (ADAS) component of a weather forecast and analysis system or from a reanalysis fields~~ data set is a combination of NOAA/GDAS atmospheric analysis field, spatially and temporally disaggregated NOAA Climate Prediction Center Merged Analysis of Precipitation (CAMP) fields, and observation-based downward shortwave and longwave radiation fields derived using the method of the Air Force Weather Agencys AGRicultural METeorological modeling system (AGRMET). The data consist of 8 forcing fields: precipitation, downward shortwave and longwave radiation, near-surface air temperature, near-surface specific humidity, near-surface zonal and meridional wind, and surface pressure. The temporal resolution is 3 h and the spatial resolution is 0.25°.

#### 2.2.2 MODIS albedo

The MODerate-resolution Imaging Spectroradiometer (MODIS) albedo product (MCD43C3)~~is produced~~, installed on both TERRA and AQUA polar satellites, is evaluated every 16 days in a ~~level-3~~ Level 3 data set, projected to a 0.05 latitude/longitude Climate Modelling Grid (CMG) (Schaaf et al., 2002). We use total shortwave broadband for white-sky albedo (~~or~~ bihemispherical reflectance under conditions of isotropic illumination), and quality flags that include the percentage of snow and the percentage contribution of fine resolution data. ~~The albedo products were evaluated by in situ measurement (Cescatti et al.,~~ Cescatti et al. (2012) validated MODIS albedo retrievals against in situ measurements across 53 FLUXNET sites, and found a good agreement in mean yearly values between retrievals and measurements with a high correlation ($r^2$ = 0.82).

### 2.2.3 USGS land use and land cover

The yearly MODIS land cover and land use data within the International Geosphere–Biosphere Programme (IGBP) global vegetation classification scheme ~~is~~ has been slightly modified to fit into the land cover classification of the U.S. Geological Survey (USGS) (Anderson et al., 1976). ~~Land~~ In this study, land cover types are grouped into 27 types according to the USGS classification~~(see Table 1).~~ , as shown in Table 1.

## 3 Results

### 3.1 Physical properties of snow-covered vegetation

For figuring out the difference of albedo among various vegetation types, we select 10 areas within 40−60° N and 105−145° E (Fig. 1) where a single type or similar two types of vegetation occupies more than 70 % in each area (Table 2). In order to minimize the effects of snow cover change, we have averaged the MODIS white-sky albedo over dominating vegetation type in each area for winter time (i.e., 273–129 as Julian day) in total shortwave broadband during 10 years (2001–2010) with a 100 % snow cover fraction (SCF) (see Fig. 2). The number of days in each area with a 100 % SCF is sufficient for comparison, as shown in Table 3. It is evident that the snow-covered albedo values are distributed over a wide range and relatively low for various forest types. The snow-covered surface albedo is different when the snow is over the ground surface vs. over the canopy, mainly due to an uneven structure of the canopy and the forest shading effect. When the growing season is over, leaves ~~and stems are mostly shed and their amount remains~~ disappear for some vegetation (e.g., deciduous trees) and remain unchanged for others (e.g., evergreen trees), while most of stems remain unchanged – reaching the minimum values. ~~These values may be different according to vegetation type, thus making~~ Thus, this change at the end of the growing season and the amount of stems depend on vegetation types and make distinctions of albedos over the forest types in winter.

Compared to the ~~observation as shown in Fig. 2~~MODIS observation, the Noah-MP snow-covered albedos are overestimated over all vegetation types in winter and have little difference between forest and short vegetation (~~not shown~~see Table 4). This is mainly due to the use of LAI and SAI, which are not able to quantify leaves and stems representing the forest masking in winter. In the Noah-MP, LAI and SAI are computed as follows:

$$\mathrm{LAI} = \max(m_{\mathrm{leaf}} \times \cdot \mathrm{LAPM}, \mathrm{LAI}_{\mathrm{min}}) \quad (1)$$

$$\mathrm{SAI} = \max(m_{\mathrm{stem}} \times \cdot \mathrm{SAPM}, \mathrm{SAI}_{\mathrm{min}}) \quad (2)$$

where $m_{\mathrm{leaf}}$ ($m_{\mathrm{stem}}$) is the leaf (stem) mass per unit area (in $\mathrm{g\,m^{-2}}$) and LAPM (SAPM) is the leaf (stem) area per unit mass (in $\mathrm{m^2\,g^{-1}}$). The subscript ~~"min "~~ min implies the minimum value. The default ~~value~~ values of $\mathrm{LAI}_{\mathrm{min}}$ and $\mathrm{SAI}_{\mathrm{min}}$ ~~is~~ are 0.05 and 0.01 $\mathrm{m^2\,m^{-2}}$, respectively, ~~and the effect of different vegetation typesis not considered~~for all vegetation types. During most of the winter

period, both LAI and SAI ~~are set to the~~ remain equal to their minimum values (i.e., $LAI_{min}$ and $SAI_{min}$). Tian et al. (2004) indicated that discrepancies in the winter albedos between the MODIS observation and LSMs were related to the uncertainty in quantifying LAI and SAI in the model. They also mentioned that stems would have different single-scattering albedo than green leaves, and hence it might be inadequate for the model to treat LAI and SAI the same way in the albedo parameterization.

Figure 3 shows a monthly averaged LAI, calculated from Noah-MP, during the period of 2001-2010 for deciduous broadleaf forest (Fig. 3a), deciduous needleleaf forest (Fig. 3b), and evergreen needleleaf forest and mixed forest (Fig. 3c). The red lines represent the minimum, mean and maximum LAI of the reference values from Asner et al. (2003) for each vegetation type. It is notable that the model-evaluated LAI values are much smaller than the reference values for all vegetation types in winter. In Fig. 4, the forest SAI has a seasonal cycle in the Noah-MP, but the magnitude is negligibly small.

As previously stated, both LAI and SAI are linked to photosynthetic activeness in the Noah-MP. Compared to the reference value of $LAI_{min}$ (e.g., Asner et al., 2003), the model-calculated $LAI_{min}$ is highly underestimated for all forest types during a winter season, and $SAI_{min}$ is ~~much~~ even lower than $LAI_{min}$. These uncertainties are ~~caused by their definition.~~ due to disregard of nonphotosynthetic process in defining LAI in the model. Note that the observed LAI represents all leaves regardless of photosynthetic capacity. Hence, the observed LAI is higher than the model-evaluated LAI. Actually, the structure and density of all leaves and stems have effects on albedo. ~~Observed LAI includes all leaves, regardless of the ability to express photosynthesis; hence it is higher than the model calculation.~~ Therefore, it is necessary to properly parameterize the vegetation effects on the snow-covered albedo.

### 3.2 Parameterization of the vegetation effects on the snow surface albedo

We ~~introduce new parameters~~ have introduced new parameters in the model – leaf index (LI) and stem index (SI). LI represents a sum of LAI defined in the Noah-MP (i.e., photosynthetic leaves) and LAI of nonphotosynthetic leaves. We ~~substitute~~ have substituted LI with the reference minimum values (see Asner et al., 2003) for four forest types~~as given~~ , as shown in Table ~~3~~ 5 in Sect. 3.2.2, in order to draw realistic SI effect. SI represents a sum of SAI defined in the model (i.e., photosynthetic stems) and SAI of nonphotosynthetic stems. In defining SI, we assumed that trees were mature and focused on winter when the growing season is over; thus SI having no seasonal cycle. To figure out how albedo responses to stems, we examine the sensitivity of winter albedo to SI over forest types in the Noah-MP, and then validate albedo with the optimal SI value.

### 3.2.1 Sensitivity of the snow-covered albedo to SI

We ~~focus on the snow-covered albedo treatments rather than running the model with full physics~~ have focused on testing the albedo scheme in idealized cases. To avoid the effects of other parameters such as snow cover fraction and snow age, we ~~assume~~ have assumed a fresh snow with the snow cover fraction set to 1, the wetted fraction of both LI and SI to 1, and snow depth to 1 m. ~~SI varies~~ We have imposed SI to vary from 0.1 to 10.0 with an interval of 0.1~~having a SZA of~~, as well as SZA 0, 30, 45, 60 and 75°. In the Noah-MP, options for two-stream radiation transfer decide the values of canopy gap probability for direct and diffuse beam. Here the canopy gap probability is defined as the chance that a photon penetrates through the vegetation without being intercepted by any crowns (Niu and Yang, 2004). The modified two-stream approximation (MTSA), which is the first option of the two-stream radiation transfer scheme, explicitly includes the three-dimensional structure of the vegetation canopy by calculating the total canopy gap probability for direct beam, $P_{\mathrm{c}}$. It equals to the sum of the between-crown gap probability, $P_{\mathrm{bc}}$, which is a function of crown geometric properties and the SZA, and the within-crown gap probability, $P_{\mathrm{wc}}$, which is parameterized on the basis of a modified version of Beer's law:

$$P_{\mathrm{bc}} = e^{-\rho_{\mathrm{t}}\pi R^2/\cos(\theta')} \tag{3}$$

$$P_{\mathrm{wc}} = (1-P_{\mathrm{bc}})e^{-0.5F_{\mathrm{a}}H_{\mathrm{d}}/\cos\theta} \tag{4}$$

$$P_{\mathrm{c}} = \min(1-f_{\mathrm{veg}}, P_{\mathrm{bc}}+P_{\mathrm{wc}}) \tag{5}$$

where $\rho_{\mathrm{t}}$ is the crown density (stems $\mathrm{m}^{-2}$), $R$ is the horizontal crown radius, $\theta$ is the solar zenith angle, $\theta' = \tan^{-1}[(b/R)\tan\theta]$, and $b$ is the vertical crown radius. $F_{\mathrm{a}}$ is the foliage area volume density ($\mathrm{m}^{-1}$) and is equal to LSAI/$(\frac{4}{3}\pi R^2 b\rho_{\mathrm{t}})$, where LSAI is the effective leaf and stem area index, through which the effect of clumping of needles into shoots is included (Chen et al., 1991; Niu and Yang, 2004). $H_{\mathrm{d}}$ is the crown depth. $f_{\mathrm{veg}}$ is the green vegetation fraction~~ranged~~, and ranges from zero to 1. Therefore, if we apply new LI and SI, LSAI is changed and then the canopy gap probability is changed.

Figure ~~3~~ 5 depicts the sensitivity of the snow-covered surface albedo and each term in albedo equation in the Noah-MP to SI, averaged over four forest types for different SZA. Total albedo by vegetation and ground, $f_{\mathrm{re}}$, is evaluated as:

$$f_{\mathrm{re}} = \begin{cases} \alpha_{\mathrm{dc}}(1-P_{\mathrm{c}}) + \alpha_{\mathrm{d}}P_{\mathrm{c}} & \text{(for direct beam)} \\ \alpha_{\mathrm{ic}}(1-K_{\mathrm{open}}) + \alpha_{\mathrm{i}}K_{\mathrm{open}} & \text{(for diffuse beam)} \end{cases} \tag{6}$$

where $\alpha_{\mathrm{d}}$ and $\alpha_{\mathrm{dc}}$ ~~is~~ are the direct albedo of the underlying surface and canopy, respectively, and $\alpha_{\mathrm{i}}$ and $\alpha_{\mathrm{ic}}$ ~~is~~ are the diffuse albedo of the underlying surface and canopy, respectively. ~~How to calculate~~ The parameterization of canopy albedo is explained in detail in Sellers (1985). $K_{\mathrm{open}}$ is the between-crown gap probability for diffuse radiation~~. Here, $K_{\mathrm{open}}$ is~~, and here it has been set to 0.05. Calculation of the total albedo based on the four radiation components, shown in Fig. 5 (i.e., direct

vs. diffuse albedo for visible and direct vs. diffuse albedo for near-infrared broadband), is explained in detail in Appendix A.

As expected, total albedo over four forest types generally decreases with increasing SI because snow albedo over the vegetated surface is lower than that over the bare soil surface (Fig. ~~3a~~5a). At a fixed SI, albedo represents different patterns for different SZA – ~~albedo increases (decreases)~~ with increasing SZA~~at relatively high (low ) SI~~, albedo decreases at relatively low SI while it increases at relatively high SI. Note that there is sufficient ground surface at relatively low SI that can be shaded by the vegetative canopy as SZA increases (Fig. ~~3b~~5b). Thus, at low SI, albedo is highest when the shadow area of underlying snow-covered surface is the smallest, that is, at local noon. Wang and Zeng (2010) also pointed out this feature using the Community Land Model 3.0. Canopy albedo also decreases with SI due to the increasing optical depth of direct and diffuse beam through leaf and stem area (Fig. ~~3c–f~~5c–f).

### 3.2.2 Validation of surface albedo with the optimal SI value

For quantifying the forest shading effect through SI in winter, we ~~compare~~ have compared the Noah-MP albedo with ~~observation. We~~ observations. We have performed model runs ~~repeatedly by~~ by repeatedly changing SI from 0.0 to 3.0 in order to find the optimal SI for each forest type that ~~reduce a~~ is able to reduce the bias of albedo between observation and model output. LAI and SAI were used to calculate ~~carbon flux as well as radiation~~fluxes of carbon, radiation, turbulent heat, etc., during the growing season. Hence, we have applied LI and SI when the growing season index was off. Albedo ~~is~~ has then been averaged for 10 years in specific winter days (i.e., 337, 353, and 1, 17, and 33 as Julian day) for vegetation types in the East Asia region~~. Figure 4~~, in order to compare with the MODIS 16-day observations. We have to priorly evaluate LI for drawing realistic SI effect because LI and SI are considered together for calculating albedo. Here we have assigned the observation values (Asner et al., 2003) to the LI values. Asner et al. (2003) collected more than 1,000 estimated LAI from literature and then made a global LAI dataset through a statistical analysis. The LAI dataset of forest types have been compiled from plenty of robust samples, thus they are sufficiently reliable to be used as the reference values of LI.

Figure 6 shows the bias errors of albedo between ~~observation~~ observations and model output (i.e., absolute values of model minus observation) with SI values for four forest types (i.e., deciduous broadleaf, deciduous needleleaf, evergreen needleleaf and mixed forest) and three short vegetation types (i.e., grassland, shrubland and mixed shrubland/grassland). In case of forest types, the bias errors of albedo decrease with increasing SI. On the contrary, the bias errors of albedo for short vegetation types decrease slightly or even increase with increasing SI. ~~It does not make sense that short vegetation has high SI ; therefore~~ Since short vegetation does not have high SI in winter, modification of albedo over short vegetation by increasing SI is meaningless. The optimized SI values, effective for reduction of bias errors in albedo, are 1.3 for deciduous broadleaf forest, 1.5 for decid-

uous needleleaf forest, 2.3 for evergreen needleleaf forest, and 2.0 for mixed forest (see Table ~~3~~5). The bias errors of albedo ~~rarely decrease when SI reaches a certain value . Therefore,~~ decrease very slowly after a certain value of SI; hence SI is considered to be optimized when the difference of bias between two consecutive SI is ~~below~~ less than 0.005~~, SI is considered to be optimized~~. The other land cover types are not optimized and the default values of $SAI_{min}$ are used. The reason why the errors do not decrease below a certain level is possibly due to other parameters such as snow age, fresh snow albedo, and snow cover fraction that are not validated in the model.

The model performance with the new LI and SI ~~is described~~ has been evaluated by calculating the root mean square errors (RMSEs) of albedo with observation as shown in Fig. ~~5.~~ 7. The performance of the Noah-MP in calculating albedo has greatly improved – RMSE ~~is~~ has been reduced by approximately ~~73~~69 %. Although we optimized SI with the MTSA, Fig. ~~5~~ 7 shows how the parameterization affects albedo with other options as well. The simulations of albedo are improved for all two-stream radiation transfer and snow surface albedo schemes – BATS (Fig. ~~5a~~7a) and CLASS (Fig. ~~5b~~7b) with RMSEs reduced by approximately 70 % on the average. Albedo with other radiation ~~option~~ options is also overestimated~~due to unrealistic leaf and stem effect. Thus, the~~ , due to underestimated LAI and SAI.

There are three radiation options in the Noah-MP for calculating energy fluxes (see Fig. 7): The first is MTSA, employed for parameterization in this study, that calculates canopy gaps from three-dimensional structure and solar zenith angle (OPT_RAD1). The second option is two-stream radiation option with no canopy gap that means leaves are evenly distributed within the grid-cell with a 100 % vegetation fraction (OPT_RAD2). The last is the tile approach that computes energy fluxes in vegetated fraction and bare fraction separately and then sum them up weighted by fraction (OPT_RAD3). The optimal LI and SI ~~with the MTSA have the similar~~ obtained through the MTSA had the similar improving effect on albedo ~~calculated with~~ when applied to the other options. The RMSEs with the original minimum values of LAI and SAI increase until ~~the mid winter~~ mid-winter (e.g., the 17th Julian day), and decrease after that. During the winter, albedo is dominantly influenced by the snow cover and forest masking (Bonan, 2008; Essery et al., 2009; Brovkin et al., 2013). The Noah-MP overestimates snow cover fraction and underestimates vegetation parameters (i.e., LAI and SAI) related to albedo, therefore it makes albedo be greatly overestimated. This error is significantly reduced by applying new parameters that consider all the forest structure effect with realistic values.

## 4 Conclusions

In winter, albedo has a large variation due to snow cover; however, in the forest region, the snow-covered albedo remains low because of two reasons. First, when the snow covers a forest canopy, the incident radiation is diffused rather than reflected due to irregular surfaces. Second, vegetation

shields the snow-covered surfaces. In addition, under the forest, temperature is relatively high and snow tends to melt earlier. This effect reduces albedo further, causing more radiation to be absorbed by the ground; thus resulting in a strong positive feedback (Qu and Hall, 2007). Therefore, accurate calculation of albedo is very influential in the land surface processes. We have addressed the noticeable relationship between the vegetation types and the snow surface albedo through satellite observations. Nevertheless, in the Noah land surface model with multiple physics options (Noah-MP) as well as many land surface models, albedo was calculated without considering the vegetation effects properly. In order to apply the vegetation effect on the snow-covered albedo, we have introduced new parameters, called leaf index (LI) and stem index (SI). We focused on the SI effect because stems are more critical than leaves in the winter albedo. The performance of the Noah-MP in calculating albedo has remarkably improved with simple parameterization for all radiation options and snow surface albedo schemes. However, there is a limitation to enhancing the accuracy of albedo by changing only vegetation indices. Thus, it is required to assess the other parameters, too, such as snow cover fraction and fresh snow albedo, which are not validated against observations.

## Appendix A: Calculation of total albedo and weights by the radiation components

We here discuss how the radiation components in Fig. 5 are weighted to calculate the total albedo. First, the downward solar radiation (`SWDOWN`; W/m$^2$) is divided into four parts – direct visible (`SOLAD(1)`) and diffuse visible (`SOLAI(1)`) radiation, and direct near-infrared (`SOLAD(2)`) and diffuse near-infrared (`SOLAI(2)`) radiation, as shown in the following equations:

```
SOLAD(1) = SWDOWN*0.7*0.5        ! direct vis
SOLAD(2) = SWDOWN*0.7*0.5        ! direct nir
SOLAI(1) = SWDOWN*0.3*0.5        ! diffuse vis
SOLAI(2) = SWDOWN*0.3*0.5        ! diffuse nir
```

Second, four albedo components are weighted to calculate the total radiaton as follows:

```
RVIS = ALBD(1)*SOLAD(1) + ALBI(1)*SOLAI(1)
RNIR = ALBD(2)*SOLAD(2) + ALBI(2)*SOLAI(2)
FSR = RVIS + RNIR
```

where `ALBD(1)` and `ALBD(2)` are albedos from direct visible bands and direct near-infrared bands, respectively, and `ALBI(1)` and `ALBI(2)` are albedos from diffuse visible bands and diffuse near-infrared bands, respectively. `RVIS` and `RNIR` are reflected radiative fluxes from visible bands and near-infrared bands, respectively, and `FSR` is total reflected radiative flux. Finally, the total albedo is obtained through the formula:

```
ALBEDO = FSR/SWDOWN,
```

as the ratio of total reflected radiative flux to the downward solar radiation.

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**Table 1.** The USGS land cover classification.

| | |
|---|---|
| ~~USGS land cover type~~ 1-Urban and Built-up Land | 15-Mixed Forest |
| 2-Dryland Cropland and Pasture | 16-Water bodies |
| 3-Irrigated Cropland and Pasture | 17-Herbaceous Wetland |
| 4-Mixed Dryland/Irrigated Cropland and Pasture | 18-Wooded Wetland |
| 5-Cropland/Grassland Mosaic | 19-Barren or Sparsely Vegetated |
| 6-Cropland/Woodland Mosaic | 20-Herbaceous Tundra |
| 7-Grassland | 21-Wooded Tundra |
| 8-Shrubland | 22-Mixed Tundra |
| 9-Mixed Shrubland/Grassland | 23-Bare Ground Tundra |
| 10-Savanna | 24-Snow or Ice |
| 11-Deciduous Broadleaf Forest | 25-Playa |
| 12-Deciduous Needleleaf Forest | 26-Lava |
| 13-Evergreen Broadleaf Forest | 27-White Sand |
| 14-Evergreen Needleleaf Forest | |

**Table 2.** Geographic location, vegetation type and percentage of dominant vegetation type for selected areas.

| Area | Longitude | Latitude | Vegetation type | Percentage |
|---|---|---|---|---|
| ~~(1)~~ | 105.00–107.25° E | 56.50–58.25° N | Mixed Forest | 71.4 |
| ~~(2)~~ | 116.25–120.00° E | 55.50–57.75° N | Shrubland | 80.0 |
| | | | Mixed Shrubland/Grassland | |
| ~~(3)~~ | 122.50–127.75° E | 57.50–60.00° N | Deciduous Needleleaf Forest | 85.7 |
| ~~(4)~~ | 133.75–136.50° E | 55.75–60.00° N | Deciduous Needleleaf Forest | 90.4 |
| ~~(5)~~ | 138.50–140.75° E | 56.25–60.00° N | Shrubland | 82.6 |
| | | | Mixed Shrubland/Grassland | |
| ~~(6)~~ | 121.25–126.50° E | 53.75–55.75° N | Deciduous Needleleaf Forest | 93.5 |
| ~~(7)~~ | 107.75–111.50° E | 49.00–51.00° N | Mixed Forest | 81.7 |
| ~~(8)~~ | 113.75–117.75° E | 45.00–49.00° N | Grassland | 97.2 |
| ~~(9)~~ | 123.75–127.75° E | 46.75–50.25° N | Dryland Cropland and Pasture | 77.2 |
| ~~(10)~~ | 135.00–137.75° E | 45.00–47.74° N | Mixed Forest | 93.8 |

**Table 3.** ~~Minimum value~~ Number of ~~LAI, reference values (LI), the default minimum value of SAI, and optimized SI values for selected USGS land~~ days with a 100 % snow cover ~~type~~ fraction (~~forest~~SCF) ~~. The optimized values are based on~~ in each area in the ~~sensitivity test.~~period of 2001−2010.

| Area | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| No. of days | 1483 | 6159 | 13235 | 12391 | 4033 | 8201 | 328 | 9318 | 7973 | 248 |

**Table 4.** The values of mean and standard deviation (SD) of snow albedo from the MODIS observation and the Noah-MP results for the shortwave broadband for different categories of the MODIS land cover. The data are averaged for winter time in 2001-2010 over each vegetation type within 40−60° N and 105−145° E with corresponding SD when SCF equals 100 % and other snow conditions are the same.

| MODIS land cover | MODIS | | Noah-MP | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Dryland Cropland and Pasture | **0.515** | 0.088 | **0.795** | 0.012 |
| Grassland | **0.595** | 0.080 | **0.787** | 0.020 |
| Shrubland | **0.432** | 0.079 | **0.805** | 0.029 |
| Mixed Shrubland/Grassland | **0.474** | 0.085 | **0.806** | 0.026 |
| Deciduous Broadleaf Forest | **0.428** | 0.076 | **0.748** | 0.075 |
| Deciduous Needleleaf Forest | **0.346** | 0.080 | **0.678** | 0.134 |
| Evergreen Needleleaf Forest | **0.296** | 0.097 | **0.761** | 0.069 |
| Mixed Forest | **0.334** | 0.093 | **0.721** | 0.115 |

**Table 5.** Minimum value of LAI, reference values (LI), the default minimum value of SAI, and optimized SI values for selected USGS land cover type (forest). The optimized values are based on the sensitivity test.

| USGS Land Cover type | Minimum of LAI (default) | LI (reference) | Minimum of SAI (default) | SI (optimized) |
|---|---|---|---|---|
| 11-Deciduous Broadleaf Forest | 0.05 | 0.6 | 0.01 | **1.3** |
| 12-Deciduous Needleleaf Forest | 0.05 | 0.5 | 0.01 | **1.5** |
| 14-Evergreen Needleleaf Forest | 0.05 | 0.5 | 0.01 | **2.3** |
| 15-Mixed Forest | 0.05 | 0.5 | 0.01 | **2.0** |

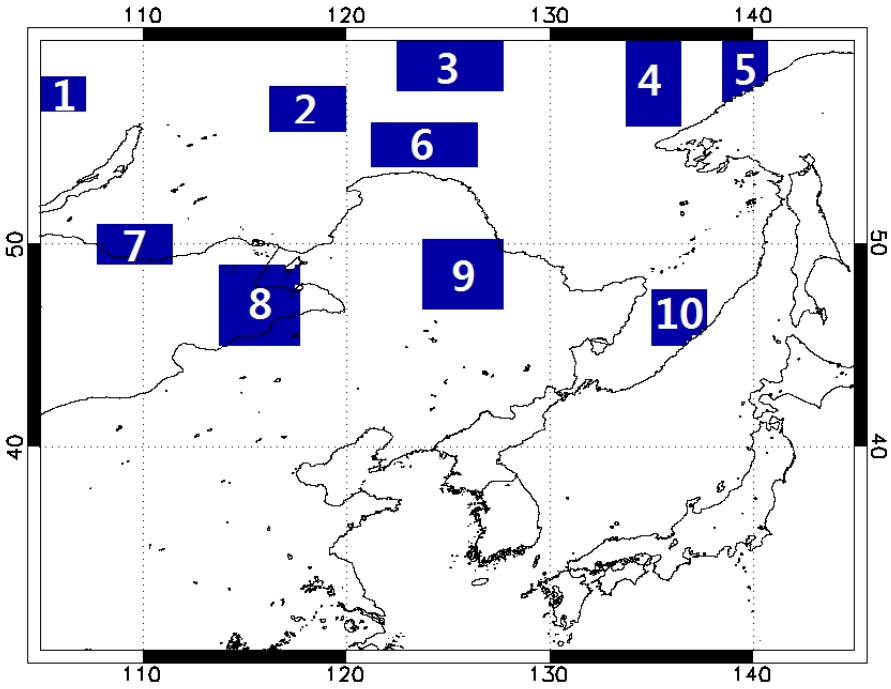


**Figure 1.** Geographical locations of the study domain. Each blue area has a dominant vegetation type as explained in Table 2.

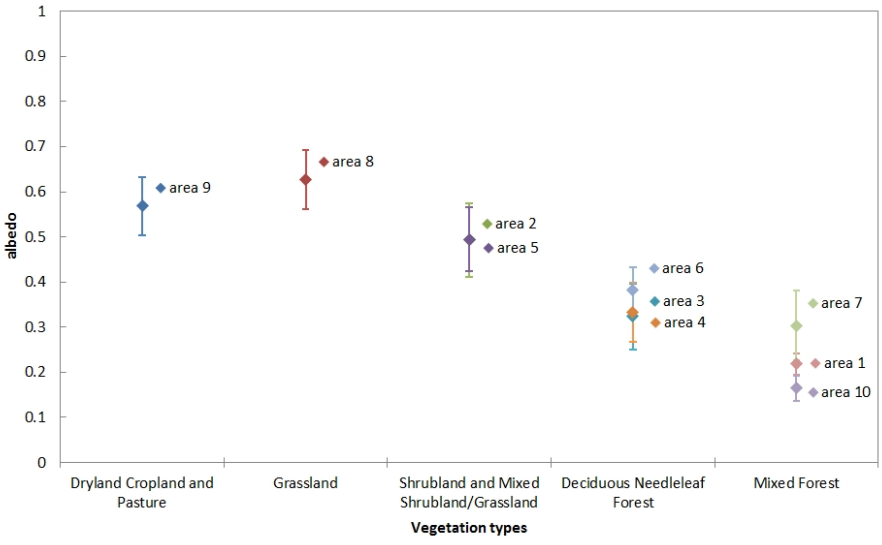


**Figure 2.** The MODIS white-sky albedo for total shortwave broadband averaged for winter time in ~~2001–2010~~ 2001–2010 (dots) and corresponding ~~SD~~ standard deviation (bars) when ~~SCF~~ snow cover fraction equals 100 %. Descriptions on the areas are provided in Fig. 1 and Table 2.

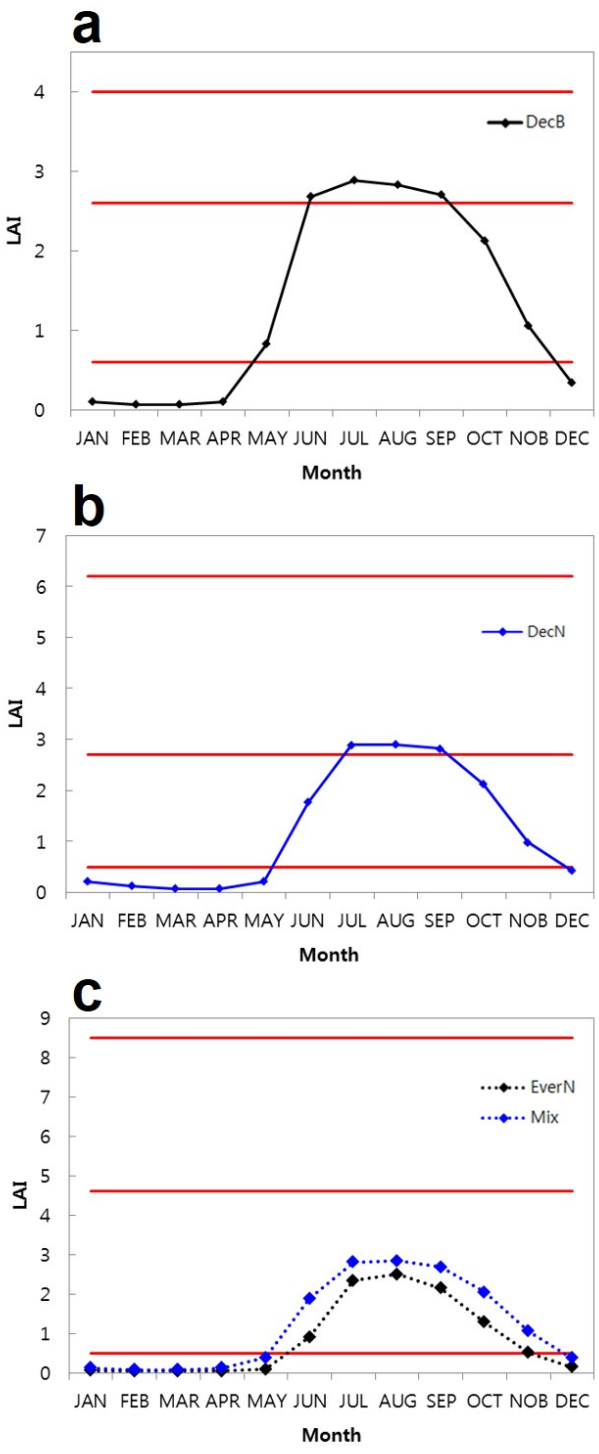


**Figure 3.** Monthly averaged LAI in the Noah-MP during the period of 2001–2010 for (a) deciduous broadleaf forest (DecB), (b) deciduous needleleaf forest (DecN), (c) evergreen needleleaf forest (EverN) and mixed forest (Mix). The red lines represent the minimum, mean and maximum LAI of the reference values. In (c), the reference values are shown only for EverN.

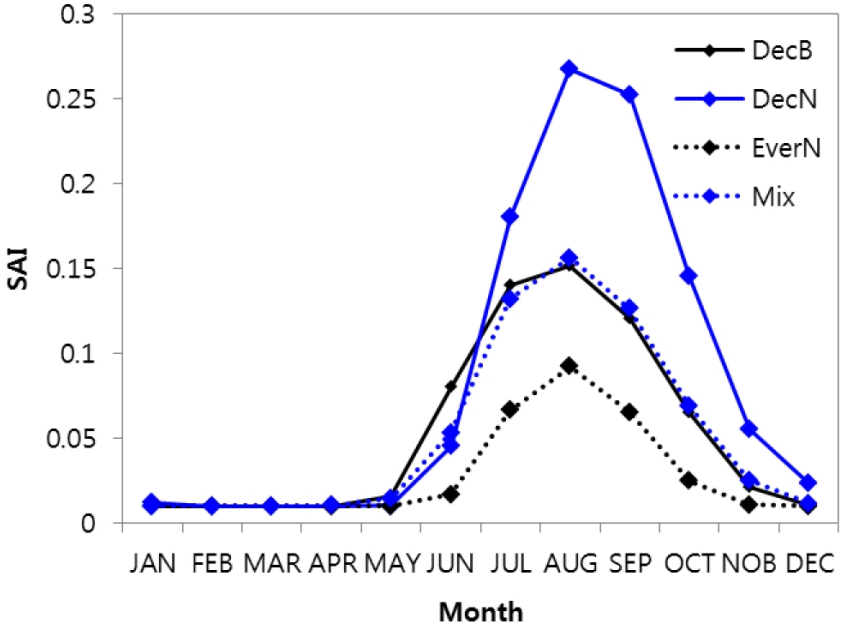


**Figure 4.** Monthly averaged SAI in the Noah-MP during the period of 2001−2010 for deciduous broadleaf forest (DecB), deciduous needleleaf forest (DecN), evergreen needleleaf forest (EverN) and mixed forest (Mix).

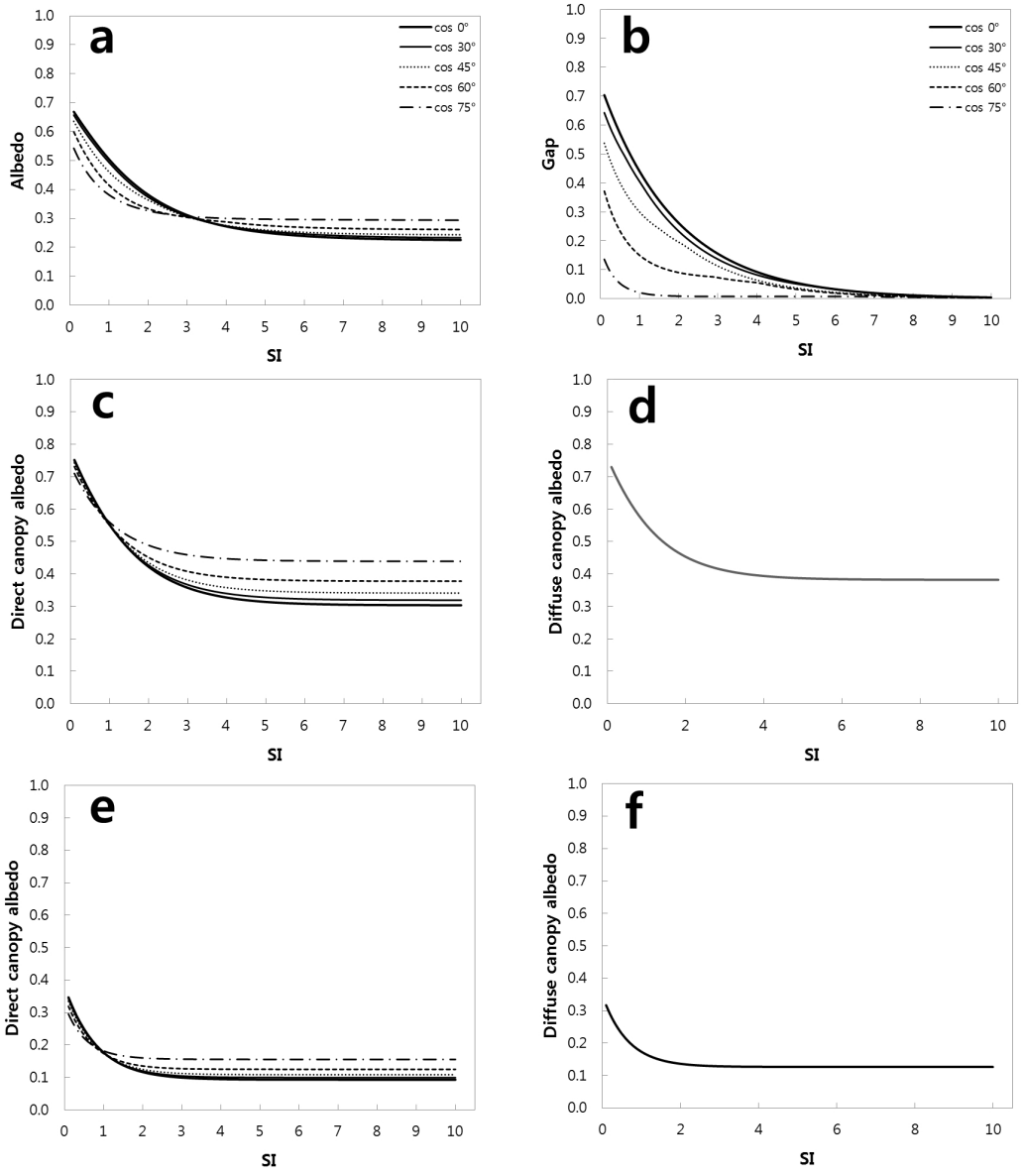


**Figure 5.** Sensitivity of the snow-covered surface albedo and each term in the albedo equation in the Noah-MP to SI averaged over four forest types: **(a)** total albedo, **(b)** canopy gap probability, **(c)** direct albedo and **(d)** diffuse albedo for visible broadband, and **(e)** direct albedo and **(f)** diffuse albedo for near-infrared broadband.

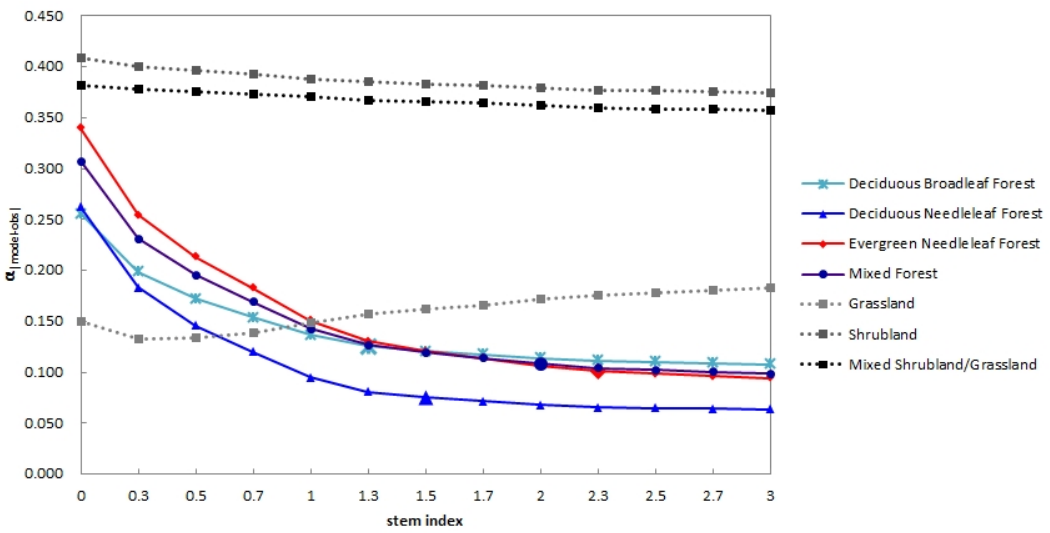


**Figure 6.** Sensitivity of the winter-averaged albedo to SI over four forest types and three short vegetation types in the Noah-MP for 2001–2010. The optimized value for each forest type is indicated with a larger symbol.

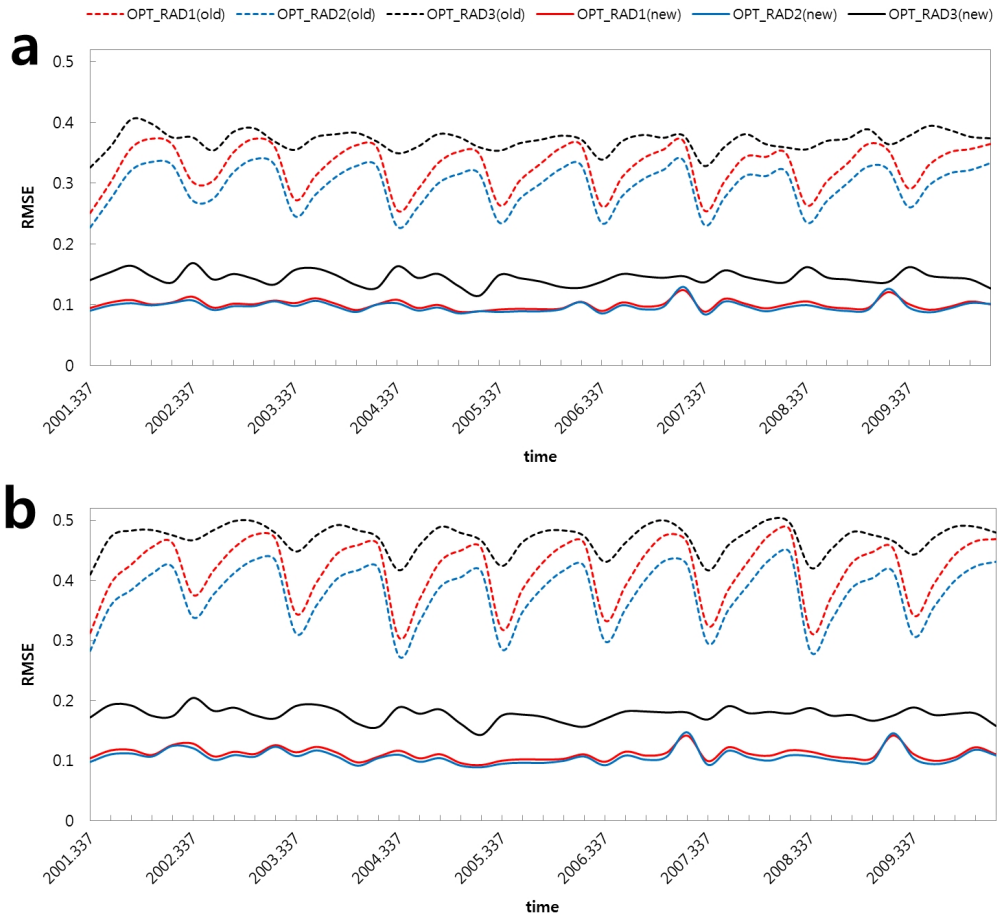


**Figure 7.** Comparison of RMSE values of albedo with the original minimum value of LAI and SAI (dashed lines) vs. new LI and SI (solid lines) for three radiation options for **(a)** BATS and **(b)** CLASS radiation schemes. OPT_RAD1 is MTSA, OPT_RAD2 is two-stream radiation option with no canopy gap, and OPT_RAD3 is the scheme that calculate the gap from vegetation fraction.