2010

Impact of revised and potential future albedo estimates on CCSM3 simulations of growing-season surface temperature fields for North America

Warren E. Heilman
USDA Forest Service, wheilman@fs.fed.us

David Y. Hollinger
USDA Forest Service

Xiuping Li
USDA Forest Service

Xindi Bian
USDA Forest Service

Shiyuan Zhong
USDA Forest Service

Heilman, Warren E.; Hollinger, David Y.; Li, Xiuping; Bian, Xindi; and Zhong, Shiyuan, "Impact of revised and potential future albedo estimates on CCSM3 simulations of growing-season surface temperature fields for North America" (2010). *USDA Forest Service / UNL Faculty Publications*. 144.
http://digitalcommons.unl.edu/usdafsfacpub/144

ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **11**: 319–326 (2010)

(wileyonlinelibrary.com) **DOI:** 10.1002/asl.301

RMetS
Royal Meteorological Society

Impact of revised and potential future albedo estimates on CCSM3 simulations of growing-season surface temperature fields for North America

Warren E. Heilman,[1]†* David Y. Hollinger,[2]† Xiuping Li,[3] Xindi Bian[1]† and Shiyuan Zhong[4]
[1] *USDA Forest Service, East Lansing, MI, USA*
[2] *USDA Forest Service, Durham, NH, USA*
[3] *College of Water Sciences, Beijing Normal University, Beijing, China*
[4] *Department of Geography, Michigan State University, East Lansing, MI, USA*

**Correspondence to:
Warren E. Heilman, USDA Forest Service, Northern Research Station, 1407 S. Harrison Road, Room 220, East Lansing, MI, USA.
E-mail: wheilman@fs.fed.us*

†The contributions of W. E. Heilman, D. Y. Hollinger, and X. Bian to this article were prepared as part of their official duties as United States Federal Government employees..

Received: 23 June 2010
Revised: 10 September 2010
Accepted: 10 September 2010

Abstract

Recently published albedo research has resulted in improved growing-season albedo estimates for forest and grassland vegetation. The impact of these improved estimates on the ability of climate models to simulate growing-season surface temperature patterns is unknown. We have developed a set of current-climate surface temperature scenarios for North America using the Community Climate System Model – Version 3 (CCSM3). Simulation results suggest that modifications to the default CCSM3 radiative parameters that are consistent with more recent accurate measurements of albedo values for grasslands and needle-leaf deciduous trees (NDTs) can reduce the overall growing-season surface temperature bias over North America in CCSM3 simulations. Copyright © 2010 Royal Meteorological Society

Keywords: albedo; CCSM3 simulations; surface temperatures; North America

1. Introduction

Climate researchers have modified the land surface model (LSM) component of several climate models to address potential climatic consequences of land-use strategies (e.g., afforestation) aimed at reducing atmospheric CO_2 levels (Betts, 2000; Gibbard *et al.*, 2005; Bala *et al.*, 2007). In these studies, it was found that in some regions decreases in shortwave radiation reflectivity (albedo) resulting from afforestation contributed to climatic warming that was greater than the cooling effects of reduced atmospheric CO_2 associated with forest growth. These results highlight the importance of albedo parameters used in LSMs, an area of relative neglect for the last 20 years. The LSMs of many climate models [e.g., community land model (CLM); Oleson *et al.*, 2004] utilize the same (or slightly modified) two-stream model of canopy radiation transport described by Sellers (1985) to calculate albedo on the basis of foliage optical characteristics, leaf area index, and plant stem area index (Dorman and Sellers, 1989).

Hollinger *et al.* (2010) recently compared tower-based measurements of growing-season albedo from sites in the AmeriFlux network with estimates from the two-stream canopy radiation transport model as implemented in the CLM (Oleson *et al.*, 2004). They found good agreement between measured and modeled albedos for several plant functional types (PFTs) including broadleaf deciduous trees, needle-leaf evergreen trees, and various crop species, but large and systematic biases for grassland and needle-leaf deciduous trees (NDTs). The summer two-stream model grassland albedo estimates were consistent with measurements from a dry climate (Mediterranean-type) grassland, but up to 50% too high for temperate grasslands. Similarly, the model albedo estimate for NDTs was only about two-thirds of the measured values. Because grassland and needle-leaf tree vegetation are regionally important land-cover types, errors in albedo for these PFTs may result in regional errors in predicted climate characteristics. The first objective of this study is to explore the consequences of updated grassland, needle-leaf, and deciduous tree/shrub albedo estimates (based on the albedo measurements of Hollinger *et al.* (2010)) on Community Climate System Model – Version 3 (CCSM3) (Collins *et al.*, 2006) 'current climate' (1990–1999) simulations of growing-season surface temperatures over North America.

Recent results (Ollinger *et al.*, 2008; Hollinger *et al.*, 2010) have also demonstrated a correlation between foliage nitrogen and canopy albedo. In a world where the nitrogen cycle continues to be widely perturbed (Vitousek *et al.*, 1997), one potential result of anthropogenic nitrogen deposition could be increases in vegetation albedo. The second objective of this study is to examine the sensitivity of CCSM3-predicted surface temperatures over North America to modest increases in albedo consistent with continued nitrogen eutrophication of the terrestrial biosphere. The regional focus on North America for both objectives is, in part, a response to the North American Forest Commission's recent recommendation that attention be paid to the role of forests in mitigating climate change (North American Forest Commission, 2008) and the availability of observational networks over North America that enhance the accuracy of reanalysis data sets for validating climate model simulations.

2. Model and experimental design

The CCSM3 is a coupled climate model for simulating the earth's past, present, and future climate states (Collins *et al.*, 2006). Within the land model component [Community Land Model – Version 3 (CLM3)] of the CCSM3, 16 vegetation or PFTs are specified. Each model grid cell consists of a mosaic of up to three PFTs as well as water and bare ground (Figure 1). For each PFT, default values have been assigned to radiative process parameters within CLM3 that characterize the vegetation effects on visible and near-infrared radiative transfer. These radiative process parameters include visible and near-infrared

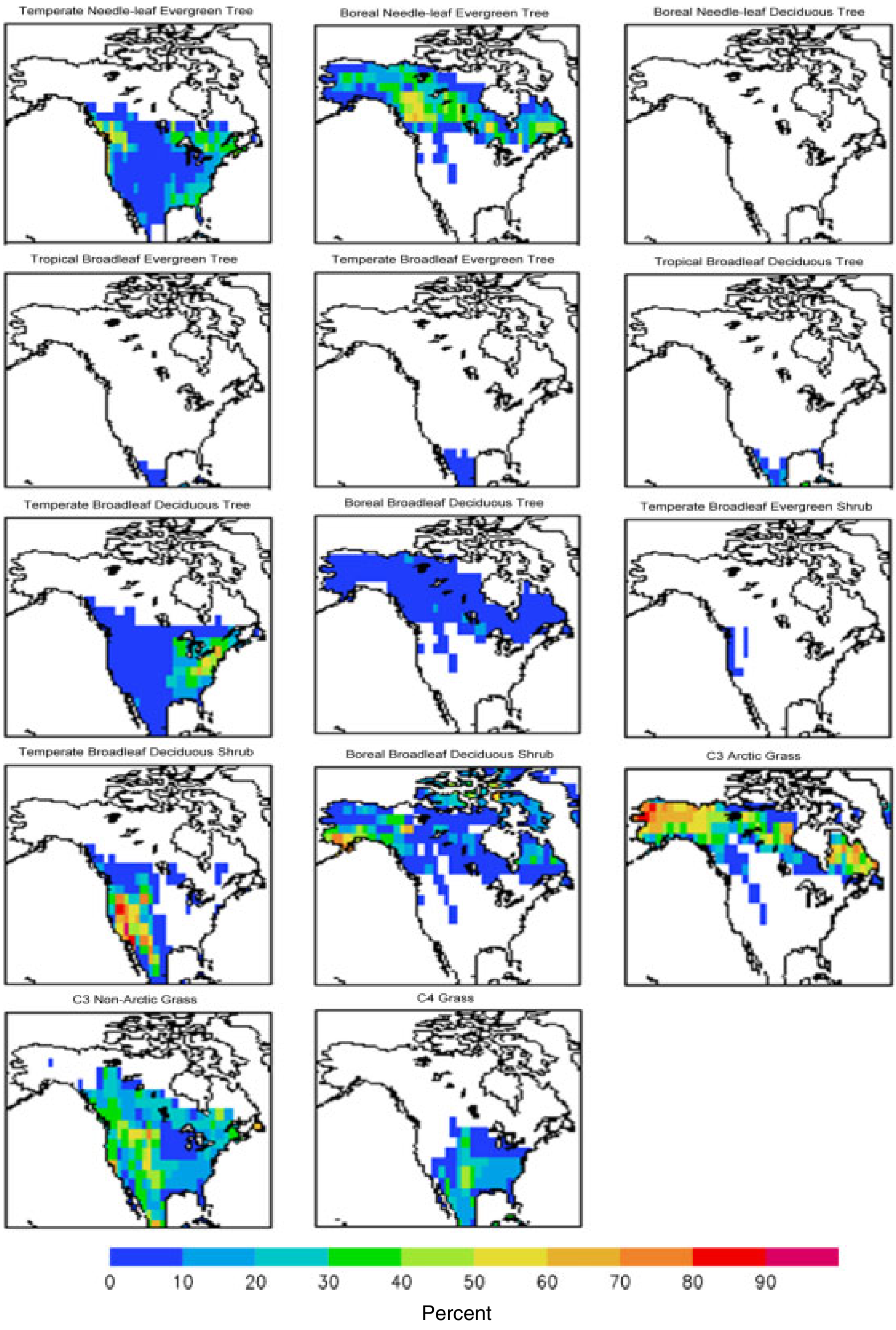

Figure 1. Percent distributions of the PFTs across the North American domain (excluding corn and wheat) that are used within the land model component of the CCSM3.

leaf and stem reflectance and transmittance parameters that are combined to generate scattering coefficients used to calculate surface albedo values via the Sellers (1985) two-stream radiative transfer scheme (Hollinger *et al.*, 2010). The CCSM3 default values for these parameters are identical to the leaf and stem reflectance and transmittance values published in Dorman and Sellers (1989) (Table I). Four numerical experiments were set up to test the sensitivity of CCSM3 predictions of growing-season surface temperatures under the 'current climate' to specific changes in the default CCSM3 visible and near-infrared reflectance and transmittance values. The CCSM3 numerical experiments included a baseline (BL) simulation of the 'current climate' that employed the default vegetation-related radiative parameter values and three case studies with modified parameter values.

The first case study (hereafter referred to as RA, signifying a 'revised albedo' test) addressed the recent findings of potential biases in the default albedo values for grassland and NDTs used in the CLM3 component of the CCSM3 (Hollinger *et al.*, 2010). In this study, values for near-infrared reflectance for grass leaves (0.58–0.50), visible reflectance (0.36–0.25) and transmittance (0.22–0.07) for grass stems, near-infrared transmittance (0.38–0.20) for grass stems, and visible (0.07–0.10) and near-infrared reflectance (0.35–0.45) for leaves on boreal NDTs were all modified as noted by red and blue text in Table I. These changes decreased the surface albedo of all grassland PFTs and increased the albedo of NDTs, bringing their values simulated by the CLM3 more into line with observations (Figure 2). We would argue that these modifications reflect true surface characteristics more accurately than the 'baseline' case radiative parameters and, therefore, results from the RA case should have less of a temperature bias than the default CCSM3 BL case. As shown in Figure 1, boreal NDTs are not common in the North American domain; they are generally found in the Siberian region of Russia, with coverage ranging from less than 10% to more than 50% of the land area in specific locations in this region of Russia. Nevertheless, the boreal NDT radiative parameter changes were incorporated into the RA case study to account for any potential large-scale impact on the climate system brought on by modified radiative processes in distant and nearby regions relative to North America.

We then carried out two subsequent case studies (N1 and N2) characterized by modest increases in the near-infrared reflectance and transmittance for all tree-dominated PFTs to test the sensitivity of CCSM3 climate predictions to increases in albedo values consistent with a more nitrogen-rich world arising from unintended human activities or a general warming of the climate (Ollinger *et al.*, 2008; Hollinger *et al.*, 2010). The resulting albedo changes were roughly equivalent to those that would be produced by replacing evergreen with deciduous tree species (midsummer albedo increases of ~0.03–0.04 and ~0.05–0.07 for most PFTs under scenarios N1 and N2). The optical properties of crop and grassland PFTs were not modified because the nitrogen state of these vegetation types is already routinely managed. In scenario N1, near-infrared leaf reflectance values were increased by 0.1 for the 11 tree- and shrub-related functional plant types with all other reflectance and transmittance values held at the default values (Table I). Scenario N2 used the modified near-infrared leaf reflectance values from simulation N1 and further increased the two-stream model scattering coefficient of the 11 tree and shrub PFTs by increasing foliage near-infrared transmittance by 0.05 (Table I).

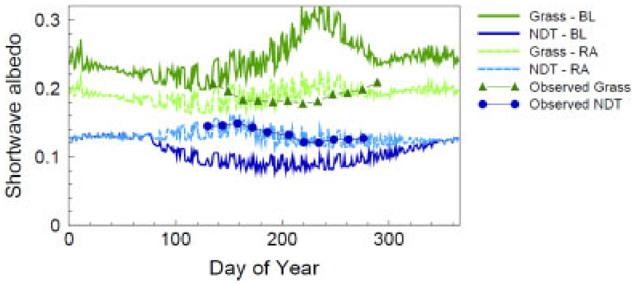

Figure 2. Time series of shortwave albedo for grass and NDT PFTs under the BL and RA simulations compared with observed albedo values from Hollinger *et al.* (2010). Table I summarizes radiative parameters used in the BL and RA simulations.

Ten-year simulations of the 'current climate' were carried out with the CCSM3 with a grid resolution of T42 (128 × 64 grid points, about 2.8° grid spacing) for the BL, RA, N1, and N2 case studies using 'current-climate' initialization fields. Monthly means of simulated surface temperatures during the growing season (March–November) were computed at each grid point within the North American subdomain (see Figure 3 for the spatial extent of the domain). The simulated surface temperatures were then compared with the corresponding surface temperature data over the North American sub-domain from the National Centers for Environmental Prediction (NCEP)/US Department of Energy (DOE) Global Reanalysis-2 (henceforth referred to as GR2) dataset (Kanamitsu *et al.*, 2002). The comparisons of the individual case study simulations with the NCEP/DOE GR2 data provide insight into the sensitivity of CCSM3 climate simulations to modified vegetation radiative parameters and associated albedo values, and the temporal and spatial patterns of the growing-season temperature biases that result from those simulations.

3. Results and discussion

Figure 3 shows the spatial patterns of the March–November surface temperature biases over North

Table I. Leaf and stem reflectance and transmittance values (unitless) used in CCSM3 for the BL, RA, N1, and N2 simulations of the 'current climate'.

	BL							
	Leaf reflectance		**Stem reflectance**		**Leaf transmittance**		**Stem transmittance**	
PFT	**VIS**	**NIR**	**VIS**	**NIR**	**VIS**	**NIR**	**VIS**	**NIR**
Temperate needle-leaf evergreen tree	0.07	0.35 0.45 (N1)	0.16	0.39	0.05	0.10 0.15 (N2)	0.001	0.001
Boreal needle-leaf evergreen tree	0.07	0.35 0.45 (N1)	0.16	0.39	0.05	0.10 0.15 (N2)	0.001	0.001
Boreal NDT	0.07 0.10 (RA)	0.35 0.45 (RA, N1, N2)	0.16	0.39	0.05	0.10 0.25 (RA) 0.15 (N2)	0.001	0.001
Tropical broadleaf evergreen tree	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Temperate broadleaf evergreen tree	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Tropical broadleaf deciduous tree	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Temperate broadleaf deciduous tree	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Boreal broadleaf deciduous tree	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Temperate broadleaf evergreen shrub	0.07	0.35 0.45 (N1, N2)	0.16	0.39	0.05	0.10 0.15 (N2)	0.001	0.001
Temperate broadleaf deciduous shrub	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Boreal broadleaf deciduous shrub	0.10	0.45 0.55 (N1, N2)	0.16	0.39	0.05	0.25 0.30 (N2)	0.001	0.001
Arctic C_3 grass	0.11	0.58 0.50 (RA)	0.36 0.25 (RA)	0.58	0.07	0.25	0.220 0.070 (RA)	0.380 0.200 (RA)
Non-arctic C_3 grass	0.11	0.58 0.50 (RA)	0.36 0.25 (RA)	0.58	0.07	0.25	0.220 0.070 (RA)	0.380 0.200 (RA)
C_4 grass	0.11	0.58 0.50 (RA)	0.36 0.25(RA)	0.58	0.07	0.25	0.220 0.070 (RA)	0.380 0.200 (RA)
Corn	0.11	0.58	0.36	0.58	0.07	0.25	0.220	0.380
Wheat	0.11	0.58	0.36	0.58	0.07	0.25	0.220	0.380

Abbreviations include VIS (visible spectral range) and NIR (near-infrared spectral range). Modifications to the BL default CCSM3 radiative parameters (black) for the RA, N1, and N2 simulations are shown in red (increase) and blue (decrease). The RA parameter modifications reflect revised and improved albedo estimates from observations while the N1 and N2 parameter modifications reflect potential future albedo changes associated with a more nitrogen-rich world from human activities or a warming of the climate

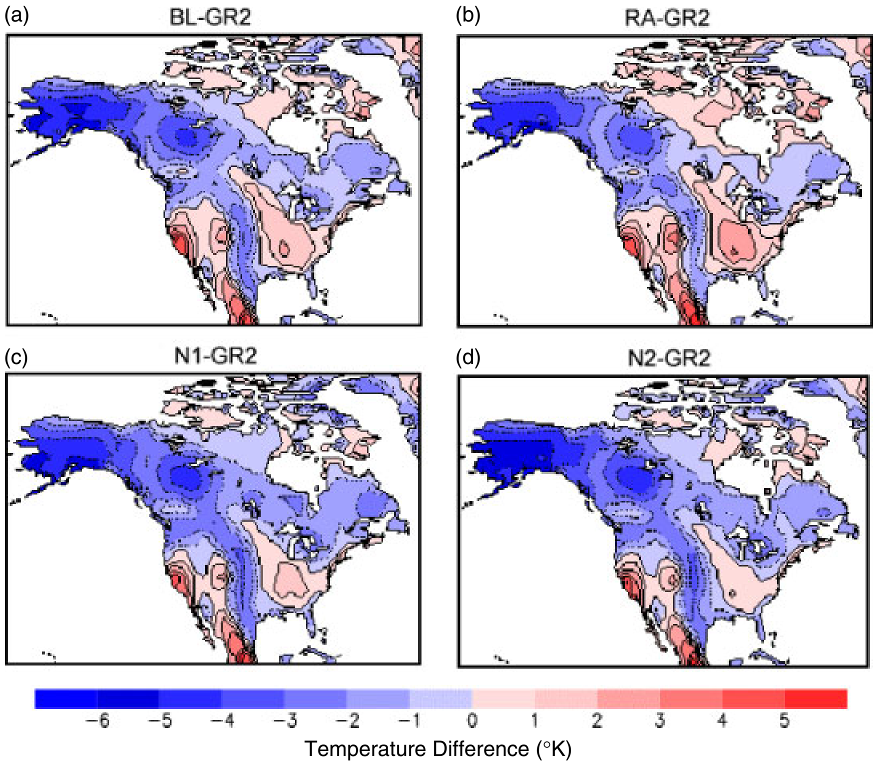

Figure 3. North American maps of the differences between CCSM3 simulations of the mean March–November 'current climate' surface temperatures for the (a) BL, (b) RA, (c) N1, and (d) N2 case studies and the corresponding mean surface temperature data derived from the GR2 data. Table I summarizes the radiative parameters used in the BL, RA, N1, and N2 simulations.

America for the CCSM3-based BL, RA, N1, and N2 case studies compared to the GR2 data. For the BL case study (Figure 3(a)), which utilized the default CCSM3 radiative parameters shown in Table I, the most significant growing-season mean surface temperature biases were found over Alaska, northwestern Canada, the southwestern region of the conterminous United States, and Mexico. The CCSM3 simulations resulted in a cold bias ranging from ~2–6 K below the GR2-based mean temperatures over Alaska and northwestern Canada for the same period to ~1–4 K lower over the central United States. A warm bias (~1–6 K) was prevalent over southwestern United States and Mexico. Somewhat smaller warm biases (~1–3 K) characterized the midwestern and southeastern regions of the United States. These March–November surface temperature bias patterns over the North American domain are generally consistent with the summertime (June–August) temperature bias patterns obtained from previous CCSM3 simulation comparisons with the GR surface temperature data for the current climate (available from NCAR: http://www.ccsm.ucar.edu/experiments/).

For the RA case study, which examined the effects of decreased surface albedo values for all grassland PFTs and increased albedo values for NDTs (Table I), an overall warming over the March–November period was observed. Compared to the default CCSM3 parameterizations, the magnitudes of the warm biases over the southeastern, Midwestern, and southwestern US regions increased somewhat, while the magnitudes of the cold biases over Alaska, northwestern Canada, and the central United States decreased (Figure 3(b)). Figure 4(a) and (b), which compares the RA case study results with the BL case study results, suggests that replacing the default (BL) CCSM3 radiative parameters with those used in the RA simulation leads to an overall albedo reduction ranging from 0.02 to 0.06 over North American, which, in turn, tends to increase the March–November surface temperatures over all of North America except over the northwestern region of the United States and the southwestern region of Canada. In our simulations, mean March–November temperature differences were largest (1.0–1.5 K) over the south central region of the United States and over the north central region of Canada. Mean March–November surface temperatures were 0–1 K lower over the northwestern and southwestern regions of the United States and Canada respectively. The reduced reflectance and transmittance values that led to reduced albedo for arctic and non-arctic grasses in the RA compared to BL case studies (albedo values supported by other work, Hope *et al*., 1991) clearly had a warming effect over much of North America. This is consistent with the substantial percentages of grass coverage over many areas in North America (Figure 1). The likely cooling effect associated with the imposed larger leaf reflectance and stem transmittance values (increased albedo) for boreal NDTs (found mostly in Siberia) in the RA case study (Table I) was not apparent over much of North America, which has little coverage

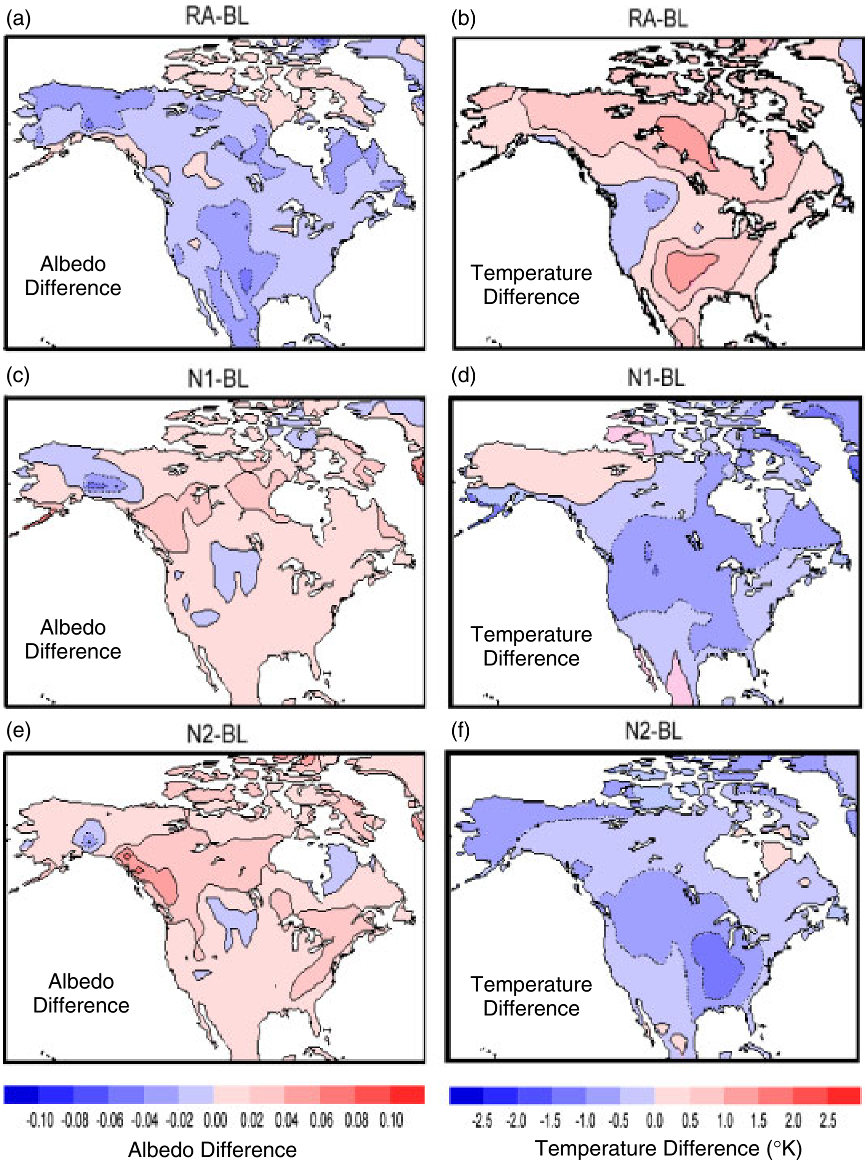

Figure 4. Simulated mean March–November 'current climate' albedo and surface temperature differences between the (a, b) RA, (c, d) N1, and (e, f) N2 case studies and the BL case study using CCSM3. Table I summarizes the radiative parameters used in the BL, RA, N1, and N2 simulations.

of this PFT. We believe that the surface albedo changes resulting from our modified grassland and deciduous needle-leaf tree parameterizations in the RA case represent a slight but important improvement in the default land-surface parameterization of CCSM3, yielding an average North American growing-season bias of −0.28 K instead of −0.65 K relative to the reanalysis data.

When just the CCSM3 near-infrared leaf reflectance values were increased by 0.1 for the tree and shrub vegetation types (Table I) in the N1 simulation (a test of model sensitivity to a slight increase in tree vegetation albedo associated with deposition of anthropogenic nitrogen or climate-warming-mediated nitrogen mineralization), surface temperatures generally dropped. We note that we do not include here other climate system effects of a perturbed nitrogen cycle (Gruber and Galloway, 2008). Compared to the BL simulation, albedo values generally increased (0.02–0.04) over North America (excluding parts of Alaska, parts of northwestern and south-central Canada, and parts of north-central and western United States), while temperatures cooled in most areas, except over northern Alaska and northwestern Canada (Figures 3(c) and 4(c) and (d)). In areas where the N1 simulation resulted in lower mean March–November surface temperatures than the BL simulation, temperature differences were on the order of 0 to −1.5 K (Figure 4(d)). Averaged over the growing season and across the entire North American domain, temperatures were ~0.3 K lower than the present (BL) model and ~0.77 K cooler than our recommended parameters. The trend toward lower March–November mean surface temperatures over most of North America in the N1 case study is consistent with the increased growing-season near-infrared leaf-reflectance values prescribed for the tree- and shrub-related PFTs, which have substantial coverage over much of Canada and the United States.

The effects of further increasing albedos by increasing both the default CCSM3 near-infrared leaf-reflectance values and the near-infrared leaf-transmittance values for the temperate and boreal tree vegetation types on the simulated 'current climate' March–November mean surface temperatures are shown in Figure 3(d) (N2 case study). Further cooling was observed with the increased albedo values (Figure 4(e)). The most prominent differences in surface temperatures between the N2 and BL simulations occurred over Alaska, northwestern Canada, and the area extending from the southeastern United States to southwestern Canada (Figure 4(f)). Temperature differences ranged from −0.5 to −1.5 K in these areas. Averaged across the entire North American domain for the March–November period, the radiative parameters used in the N2 case study generated surface temperatures that were slightly colder (∼0.05 K) than those in our N1 case study.

The differences between CCSM3-simulated North American surface temperatures and reanalysis data exhibit important monthly variations. Figure 5 shows the 'current climate' monthly mean surface temperature differences between the BL, RA, N1, and N2 CCSM3 simulations and the GR2 data, averaged over the North American domain for the March–November period. The BL, RA, N1, and N2 simulations all produced domain-averaged surface temperatures that were lower than the domain-averaged surface temperatures from the GR2 data for 7 of the 9 months. Only during the months of April and May did the BL and RA simulations result in an overall warm bias across the North American domain. For every month except April and June, our alternative BL case (RA) produced smaller biases than the BL case study. Domain-averaged monthly mean surface temperature differences ranged from 0.59 to −1.60 K in the BL case study, and 0.84 to −0.93 K for the improved CCSM foliage optical parameters in the RA case study. When averaged over the entire March–November period, North American temperature differences between the BL and RA simulations and the GR2 data were −0.65 and −0.28 K respectively. The radiative parameters used in the RA case study reduced the average surface temperature bias observed with the BL case study by about 56% over the March–November, North American growing season. This is a substantial improvement in the overall cold bias associated with the BL case study and suggests that the modified radiative parameters used for the RA case study may provide improved CCSM3 surface temperature predictions for the growing season when averaged over the entire North American domain.

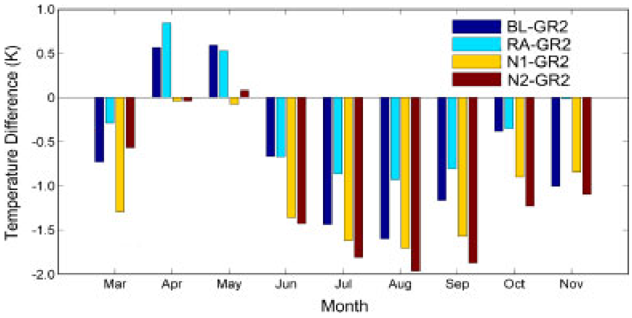

Figure 5. Differences in monthly mean surface temperatures between the BL, RA, N1, and N2 CCSM3 'current climate' simulations and the GR2 data over North America for the 1990–1999 period. Table 1 summarizes the radiative parameters used in the BL, RA, N1, and N2 simulations.

Figure 5 also shows that the increased forest albedo scenarios (N1 and N2 case studies) resulted in lower surface temperatures than the BL case study during the April–October period. Differences between the reanalysis data and model simulations ranged between −0.04 and −1.71 K for the N1 case study, and 0.08 and −1.96 K for the N2 case study. Averaging over the entire March–November period, the modest increases in forest albedo introduced in the N1 and N2 case studies resulted in an average surface temperature reduction of ∼1 K over the entire North American domain (−1.05 K for case study N1; −1.10 K for case study N2). This is similar to the regional summer temperature decrease of up to 1 K predicted in simulations from the Hadley Centre Coupled Model – Version 3 (HadCM3) utilizing a 0.04 increase in cropland albedo (Ridgwell *et al.*, 2009). The increased cooling associated with the higher vegetation albedo values in case studies N1 and N2 is in contrast with the ∼2.5–5 K surface warming over North America that is predicted for the end of this century (Christensen *et al.*, 2007). The N1 and N2 case studies, therefore, suggest that potential increases in forest albedo values caused by, for example, nitrogen fertilization from human activities or a general warming of the climate, would likely have a cooling effect on near-surface temperatures that could partially offset the expected atmospheric warming caused by greenhouse gas emissions. This cooling effect should be considered in the development of future climate scenarios.

Further modeling research is needed to determine how changes in albedo affect the entire climate system, including feedback processes between climatic variables. Future research is also needed to assess the significance of the correlation between albedo changes and surface temperature changes and to determine the relative impacts of albedo changes associated with PFTs in other parts of the world on surface temperature patterns over North America.

Acknowledgement

This work was funded by the US Department of Agriculture Forest Service under Agreement 07-JV-11242300-138.

References

Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A. 2007. Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 6550–6555.

Betts RA. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* **408**: 187–190.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon WT, Laprise R, Magaña Rueda V, Mearns L, Menèndez CG, Räisänen J, Rinke A, Sarr A, Whetton P. 2007. Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Quin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, New York.

Collins WD, Bitz CM, Blackmon ML, Bonan GB, Bretherton CS, Carton JA, Chang P, Doney SC, Hack JJ, Henderson TB, Kiehl JT, Large WG, McKenna DS, Santer BD, Smith RD. 2006. The Community Climate System Model Version 3 (CCSM3). *Journal of Climate* **19**: 2122–2143.

Dorman JL, Sellers PJ. 1989. A global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere model (SiB). *Journal of Applied Meteorology* **28**: 833–855.

Gibbard S, Caldeira K, Bala G, Phillips TJ, Wickett M. 2005. Climate effects of global land cover change. *Geophysical Research Letters* **32**: L23705. DOI: 10.1029.2005GL024550.

Gruber N, Galloway JN. 2008. An earth-system perspective of the global nitrogen cycle. *Nature* **451**: 293–296.

Hollinger DY, Ollinger SV, Richardson AD. 2010. Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration. *Global Change Biology* **16**: 696–710.

Hope AS, Fleming JB, Stow DA, Aguado E. 1991. Tussock tundra albedos on the North Slope of Alaska: effects of illumination, vegetation composition, and dust deposition. *Journal of Applied Meteorology* **30**: 1200–1206.

Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo JJ, Fiorino M, Potter GL. 2002. NCEP-DOE AMIP-II reanalysis (R-2). *Bulletin of the American Meteorological Society* **83**: 1631–1643.

North American Forest Commission. 2008. Report of the twenty-fourth session of the North American Forest Commission, 9–13 June 2008, San Juan, Puerto Rico. Food and Agricultural Organization of the United Nations: Rome; 27.

Oleson KW, Dai Y, Bonan G, Bosilovich M, Dickinson R, Dirmeyer P, Hoffman F, Houser P, Levis S, Niu GY, Thornton P, Vertenstein M, Yang ZL, Zeng X. 2004. *Technical description of the Community Land Model (CLM)*, NCAR Technical Note, NCAR/TN-461+STR, May; 186.

Ollinger SV, Richardson AD, Martin ME, Hollinger DY, Frolking SE, Reich PB, Plourde LC, Katul GG, Munger JW, Oren R, Smith ML, Paw UKT, Bolstad PV, Cook BD, Day MC, Martin TA, Monson K, Schmid HP. 2008. Canopy nitrogen, carbon assimilation and albedo in temperate and boreal forests: functional relations and potential climate feedbacks. *Proceedings of the National Academy of Sciences of the United States of America* **105**: 19336–19341.

Ridgwell A, Singarayer JS, Hetherington AM, Valdes PJ. 2009. Tackling regional climate change by leaf albedo bio-geoengineering. *Current Biology* **19**: 146–150.

Sellers P. 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing* **6**: 1335–1372.

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG. 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications* **7**: 737–750.