HYDROLOGICAL PROCESSES
*Hydrol. Process.* **22**, 347–355 (2008)
Published online 25 September 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6616

# Evaluation of snow models in terrestrial biosphere models using ground observation and satellite data: impact on terrestrial ecosystem processes

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## Abstract:

Snow is important for water management, and an important component of the terrestrial biosphere and climate system. In this study, the snow models included in the Biome-BGC and Terrestrial Observation and Prediction System (TOPS) terrestrial biosphere models are compared against ground and satellite observations over the Columbia River Basin in the US and Canada and the impacts of differences in snow models on simulated terrestrial ecosystem processes are analysed. First, a point-based comparison of ground observations against model and satellite estimates of snow dynamics are conducted. Next, model and satellite snow estimates for the entire Columbia River Basin are compared. Then, using two different TOPS simulations, the default TOPS model (TOPS with TOPS snow model) and the TOPS model with the Biome-BGC snow model, the impacts of snow model selection on runoff and gross primary production (GPP) are investigated. TOPS snow model predictions were consistent with ground and satellite estimates of seasonal and interannual variations in snow cover, snow water equivalent, and snow season length; however, in the Biome-BGC snow model, the snow pack melted too early, leading to extensive underpredictions of snow season length and snow covered area. These biases led to earlier simulated peak runoff and reductions in summer GPP, underscoring the need for accurate snow models within terrestrial ecosystem models. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS snow water equivalent; snow distribution; remote sensing; water cycle; carbon cycle; terrestrial ecosystem model

*Received 23 May 2006; Accepted 30 October 2006*

## INTRODUCTION

Snow plays important roles in hydrology, climate, and the terrestrial biosphere. Water accumulated as the winter snowpack is released during the spring snowmelt season and is a critical component of the annual water budget. In terms of the surface radiation budget, snow surfaces have a much higher albedo than surrounding snow-free land surfaces and consequently absorb less incoming solar radiation. Therefore, changes in the snowmelt season affect land surface temperature and may be linked to distinct spring warming trends in northern high latitudes regions (e.g. Groisman *et al*., 1994; Dye and Tucker, 2003). The changes in spring temperature and timing of spring snowmelt may also affect land surface phenology and the seasonality of the terrestrial carbon budget (e.g. Keeling *et al*., 1996; Myneni *et al*., 1997).

Although snow modelling is important for the simulation of terrestrial water and carbon cycles, snow model predictions have large uncertainties. For example, the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase 2(e) compared snow simulations from 21 models against satellite snow cover maps over a Scandinavian basin; there were large differences between modelled and observed snow water equivalents (Nijssen *et al*., 2003). The Atmospheric Model Intercomparison Project (AMIP-2) also showed large uncertainties in northern hemisphere snow covered area simulated by Atmospheric General Circulation Models (Frei *et al*., 2003; Frei *et al*., 2005).

Due to the importance of snow in terrestrial ecosystem models, these types of uncertainties will affect carbon and water cycle simulations. The conceptual foundation for this premise is simple: snowpack stores water in winter and early spring and releases it during the snowmelt season; changes in snowpack or in the timing and duration of the snowmelt season will affect seasonal patterns of runoff, water supply, soil water content, and consequently carbon processes. For example, future changes in the snowmelt season caused by warming may advance the timing of peak stream-flow, increasing the chance of late-summer water shortage (Hamlet and Lettenmaier, 1999).

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In the late twentieth and early twenty-first centuries, the advent of satellite remote sensing and extensive ground observations provided an unprecedented opportunity to assess and improve snow models. In particular, snow cover products (Hall *et al*., 2002; Riggs *et al*., 2003) from the Moderate Resolution Imaging Spectroradiometer (MODIS) have capitalized on improved spectral, spatial, and temporal resolutions for monitoring snow cover. In comparisons against ground observations, several authors have already found promising results for the MODIS snow products (e.g. Klein and Barnett, 2003; Maurer *et al*., 2003; Brubaker *et al*., 2005; Tekeli *et al*., 2005; Zhou *et al*., 2005).

The goals in this study were to assess current snow models included in terrestrial ecosystem models and to test the sensitivity of terrestrial ecosystem processes to the choice of snow model. To do so, the snow models included in two terrestrial biosphere models were first evaluated, the Terrestrial Observation and Prediction System (TOPS) (Nemani *et al*., 2003; White and Nemani, 2004) and Biome-BGC (Thornton, 1998; Thornton *et al*., 2002), against ground and satellite observations. Next, using two different TOPS models, the default TOPS model (i.e. TOPS with TOPS snow model) and the TOPS with the Biome-BGC snow model, the impacts of choice of snow model on simulated runoff and gross primary production (GPP) were analysed.

## METHOD

### *Study area*

An assessment in the Columbia River Basin was conducted, an area spanning 690, 000 km$^2$ over regions of Washington, Oregon, Idaho, Montana, Nevada and Utah in the US, and British Columbia in Canada (Figure 1). Dominant land cover classes include evergreen needleleaf forest in the north, west, and east, grassland and cropland in the centre and south, and shrubland in the south. Topography is complex, ranging from 0 m to over 3000 m.

### *Models*

For the snow sub-model evaluations, two different snow models included in the terrestrial ecosystem models (Biome-BGC and TOPS snow model) were used. For the terrestrial ecosystem process evaluations (runoff and GPP), a terrestrial carbon and water cycle model (TOPS)

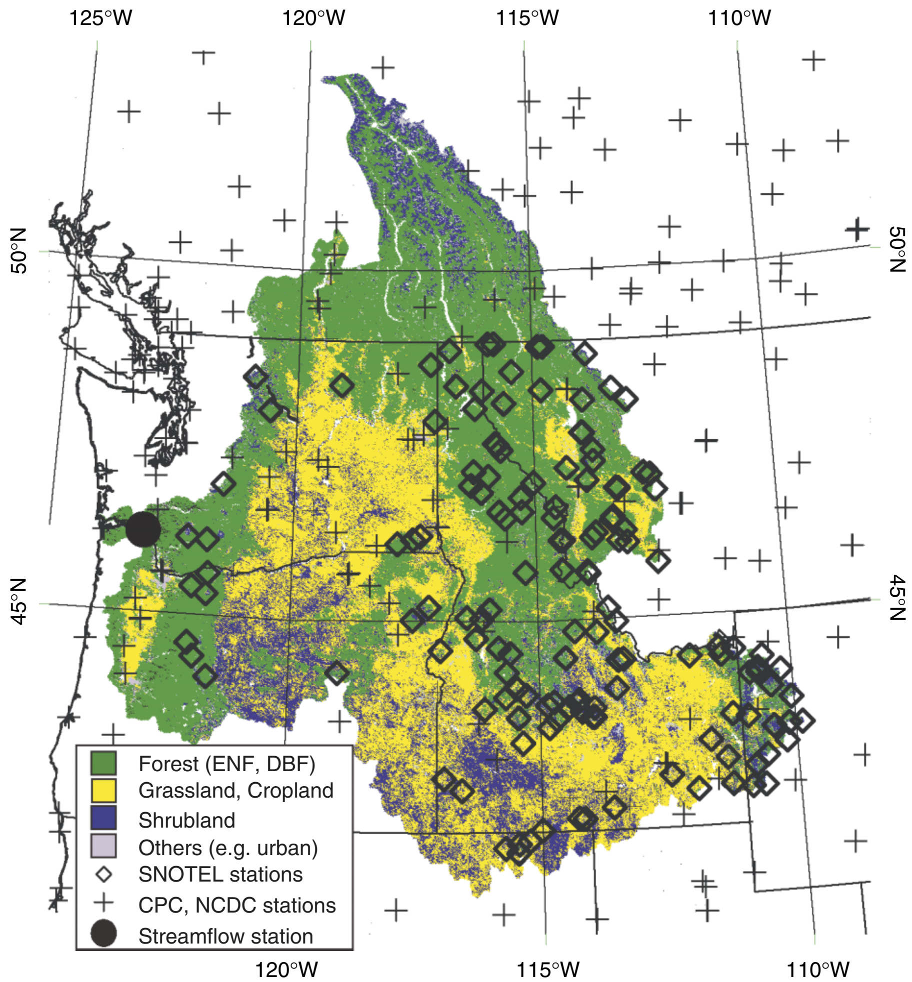


Figure 1. Land cover of the study area derived from MODIS land cover products (MOD12Q1). The 143 SNOTEL stations with no missing data for three snow years from October 2000 to September 2003 are marked as diamond (◊). The CPC and NCDC climate observations used in this study are marked as pluses (+)



DOI: 10.1002/hyp

forced by two snow models (TOPS model with TOPS and Biome-BGC snow sub-models) for terrestrial carbon and water cycle simulations was used.

*Snow models. (1) Biome-BGC snow model:* The Biome-BGC snow model is based on empirical temperature-index model with radiation-driven melting (e.g. Rango and Martinec, 1995). The model uses daily air temperature, precipitation, and solar radiation to simulate daily snow accumulation and melting processes (Thornton, 1998; Thornton *et al*., 2002). The model consists of one snow pool with fluxes of snowfall, snow melting, and snow sublimation. At temperatures below 0 °C, precipitation is predicted to occur as snowfalls. Snow melt and sublimation ($S_{ms}$, in kg m$^{-2}$ day$^{-1}$) is predicted by:

$$S_{ms} = k_{index} \cdot T_{ave} \ (\text{if } T_{ave} > 0\,^{\circ}\text{C}) + \Delta R / [\lambda_s \ (\text{if } T_{ave} < 0\,^{\circ}\text{C}) \text{ or } \lambda_f \ (\text{if } T_{ave} \geq 0\,^{\circ}\text{C})] \quad (1)$$

where $k_{index}$ is a temperature driven snowmelt coefficient (in kg m$^{-2}$ °C$^{-1}$), $T_{ave}$ is daily average air temperature, $\Delta R$ is net shortwave radiation on snow surface, $\lambda_f$ is the latent heat of fusion (335 kJ kg$^{-1}$), and $\lambda_s$ is the latent heat of sublimation (2835 kJ kg$^{-1}$). The first term is an empirical temperature index approach; the second term is a physical radiation-driven process. All parameters were set to their Biome-BGC default values.

*(2) TOPS snow model:* A TOPS process-based snow melting and accumulation model based on Walter *et al.* (2005) was developed, which is conceptually similar to other process-based snow models (e.g. US Army Corps of Engineers, 1960; Anderson, 1968). The model runs at a daily time step using maximum, minimum, and average temperature, precipitation, vapour pressure, and solar radiation. In contrast to the Biome-BGC snow model, the TOPS snow model consists of two separate pools: snow and snow surface liquid water. At temperatures below 2 °C, precipitation is predicted to occur as snow. Snow melting and sublimation are modelled based on the water and energy budget of snow and atmosphere. The energy and water budget equation is as follows:

$$\lambda_f \cdot \Delta\text{SWE} \ (\text{if } T_{ave} \geq 0) + \lambda_s \cdot \Delta\text{SWE} \ (\text{if } T_{ave} < 0) = Q_{net} - \text{SWE} \cdot (C \cdot \Delta T_s) \quad (2)$$

where $\Delta$SWE (in kg m$^{-2}$ day$^{-1}$) is change in snow water equivalence (SWE), $Q_{net}$ (in J m$^{-2}$) is net radiation energy including shortwave and longwave, $C$ is the specific heat of ice (2·1 kJ kg$^{-1}$ °C$^{-1}$), and $\Delta T_s$ is the change in snow temperature (in °C). In addition to the formulation of the Walter *et al.* (2005) model, snow sublimation is calculated if excess energy to melt or vaporize snow is present and temperature is below zero (second term in Equation (2)). The value of $Q_{net}$ is expressed by the term of net shortwave and longwave radiation, sensible heat, latent heat, ground heat conduction, and heat added by precipitation (Walter *et al*., 2005). The modifications to Walter's model are (1) the addition of a sublimation routine as explained earlier, (2) assignment of the snow versus rain transition at 2 °C [based on observations of changes in SNOpack TELemetry (SNOTEL, US Natural Resources Conservation Services) SWE], and (3) use of the DAYMET algorithm (Thornton *et al*., 1997) for solar radiation calculations.

*Terrestrial carbon and water cycle model.* TOPS (Nemani *et al*., 2003; White and Nemani, 2004) was used to simulate daily carbon and water processes. TOPS integrates satellite data, ecosystem modelling, and static land cover and soil information to simulate ecosystem status. Simulations of hydrologic states and fluxes are based largely on the Biome-BGC model (Thornton, 1998; Thornton *et al*., 2002) with the use of remotely sensed leaf area index (LAI). The summary of the water cycle and GPP model in TOPS will be shown, and details are described in White and Nemani (2004).

Daily water budgets are calculated as the net flux of rainfall, snowfall, evapotranspiration (ET, sum of transpiration, soil evaporation, canopy water evaporation, and snow sublimation), snowmelt, and runoff. ET is calculated based on a Penman–Monteith approach using LAI and meteorology. Soil water content, which affects stomatal conductance through leaf water potential, is the balance between inputs (snowmelt and precipitation) and outputs (ET and runoff). Soil water in excess of soil water holding capacity is routed to runoff.

Daily GPP is calculated based on a Production Efficiency Model (PEM):

$$\text{GPP} = \varepsilon_{max} \cdot \text{APAR} \cdot f(\text{environment}) \quad (3)$$

where $\varepsilon_{max}$ is the maximum dry matter conversion efficiency, APAR is absorbed photosynthetically active radiation calculated as the product of photosynthetically active radiation (PAR) and FPAR (the fraction of PAR absorbed by plant canopies), and $f$(environment) is an environmental stress scalar set as the minimum of limitations among minimum temperature, vapour pressure deficit, and leaf water potential. Leaf water potential is assumed to be equivalent to soil water potential in the model, which is calculated by soil volumetric water content and soil texture information. The environmental stress scalar in each limitation factor ranges linearly 0 (total inhibition of photosynthesis) to 1 (no inhibition). Ecophysiological parameters for each plant functional type are derived from Biome-BGC values (White *et al*., 2000).

In this study, two different TOPS simulations are used to analyse the impacts of different snow models on simulated ecosystem processes: (1) the default TOPS model (i.e. TOPS with TOPS snow model); and (2) the TOPS model with the Biome-BGC snow model, in which case the TOPS snow model is replaced with the Biome-BGC snow model without other modifications.

### *Data*

Data was required for (1) point-based snow model simulations, (2) spatial snow model simulations, and

(3) terrestrial carbon and water cycle simulations. For time-variant datasets, all data for the three snow years from October 2000 to September 2003 were collected. A summary of the data sets and their purposes in this study is presented in Table I.

*Point-based snow model simulations.* Measurements of SWE, precipitation, and maximum, minimum, and average temperature from the SNOTEL dataset were used. For each SNOTEL station, vapour pressure based on the assignment of daily minimum temperature as dew point temperature (Campbell and Norman, 1998) and surface solar radiation using DAYMET algorithms (Thornton *et al*., 1997) with topography data (elevation, slope, and aspect) from HYDRO1K (http://edcdaac.usgs.gov/gtopo30/hydro/, accessed 5 July 2005) were calculated. Selected were 143 stations with no missing data within the basin (Figure 1).

For model evaluation purposes, the MODIS snow cover products (Hall *et al*., 2002; Riggs *et al*., 2003) at each observation site in addition to SWE from SNOTEL data were used. To minimize the cloud contamination, the 8-day composited product (MOD10A2 collection 4·0) was used. The composited product is derived from the daily MOD10A1 product (500 m spatial resolution), in which a cloud mask algorithm (Riggs *et al*., 2003) is processed with the Normalized Difference Snow Index (NDSI) and a combination of NDSI and the Normalized Difference Vegetation Index (NDVI) to produce a daily snow cover map. In MOD10A2, the pixel is identified as snow if snow cover was present on any of the 8 days. The closest four pixels at each observation site were used to identify snow, cloud, snow-free land and others by taking the most frequent category among them with priority to snow, cloud, snow-free in order.

*Spatial snow model simulations.* As model inputs, daily meteorological data from three independent sources (National Climatic Data Center, NCDC, http://www.ncdc.noaa.gov/oa/climate/climatedata.html#DAILY, accessed 5 July 2005; Climate Prediction Center, CPC, http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/prcp_temp_tables/, accessed 5 July 2005; and SNOTEL) were obtained and ordinary kriging (Jolly *et al*., 2005) to create 1 km surfaces of daily maximum and minimum temperature (average temperature calculated) was used. Using the same data, inverse distance weighting (Jolly *et al*., 2005) was used to generate precipitation maps. Vapour pressure and solar radiation as described earlier were calculated. For model evaluation purposes, MODIS snow cover products were used after converting original 500 m data into 1 km using four pixels in each grid to identify snow, cloud, snow-free land and others in the same way as described in the previous section.

*Terrestrial carbon and water cycle model simulations.* TOPS requires meteorological data (temperature, precipitation, vapor pressure deficit, and radiation), satellite based data (LAI, FPAR), and ancillary data (land cover, elevation, and soil texture). The gridded meteorological data described in the previous section and the 8-day composited MODIS FPAR and LAI products (MOD15A2 collection 4; Myneni *et al*., 2002) as time-variant forcings for the TOPS model were used. Missing or cloud contaminated FPAR and LAI data were replaced with the average of other years. In addition, the MODIS land cover product (MOD12Q1; Friedl *et al*., 2002), elevation from HYDRO1K, and soil texture from the Global Soil Data Products (IGBP-DIS, Global Soil Data Task, 2000) were used. The rooting depth was set to 1 m for the study area.

For the model evaluation purpose, monthly mean stream-flow data at Beaver Army Terminal NR Quincy (46°10′53″N, 123°10′56″W; Figure 1) available from US Geological Survey National Water Information System (NWISWeb; http://waterdata.usgs.gov/nwis/, accessed 5 July 2005) were used. The station is located near the mouth of the Columbia River (Figure 1) with a drainage area of 658, 000 km$^2$ (95% of study area). The monthly

Table I. Data set used in the study

| Analysis | Parameter[a] | Data source or method | Purpose |
|---|---|---|---|
| Point snow model | Temp, Prec | SNOTEL | Model simulation |
| | VPD | Campbell and Norman (1998) | Model simulation |
| | Rad | Thornton *et al.* (1997) | Model simulation |
| | SWE | SNOTEL | Model evaluation |
| | Snow cover | MODIS (MOD10A2) | Model evaluation |
| Spatial snow model | Temp, Prec | NCDC, CPC, SNOTEL with spatial interpolation | Model simulation |
| | VPD | Campbell and Norman (1998) | Model simulation |
| | Rad | Thornton *et al.* (1997) | Model simulation |
| | Snow cover | MODIS (MOD10A2) | Model evaluation |
| Terrestrial carbon and water cycle | Temp, Prec, VPD, Rad | Same as spatial snow model anaylsis | Model simulation |
| | LAI, FPAR | MODIS (MOD15A2) | Model simulation |
| | Land cover | MODIS (MOD12A1) | Model simulation |
| | Stream-flow | USGS NWIS web | Model evaluation |

[a] Temp, Prec, VPD, Rad, and SWE refer to temperature, precipitation, vapor pressure deficit, surface solar radiation, and snow water equivalence, respectively.

mean stream-flow was calculated using the data from October 2001 to September 2003.

## EXPERIMENTS

Using the SNOTEL data, Biome-BGC and TOPS snow models, MODIS snow cover products, and TOPS carbon and water simulations with different snow models, three analyses were conducted over the three snow years from 1 October 2000 to 30 September 2003. First, a point-based evaluation was conducted of snow dynamics among SNOTEL observation, the two snow models, and MODIS snow cover extracted for the point locations. Using the SNOTEL site meteorology (see earlier), the snow models at all SNOTEL stations were run. The models were evaluated with observed SWE and snow season length (number of days covered by snow in a year) and evaluated satellite data with observed snow season length. Second, using the gridded meteorology, the snow models were applied over the entire Columbia River Basin and they were compared to snow season length and total snow-covered area from the MODIS snow cover products. Lastly, we ran TOPS with the Biome-BGC and TOPS snow models were run and the impact of different snow models on terrestrial ecosystem processes in terms of runoff and GPP was analysed.

## RESULTS AND DISCUSSION

### *Point evaluation with SNOTEL observation*

*Snow models.* Predictions of snow season length from both snow models were linearly related to SNOTEL observations, but the TOPS snow model simulated variations in observed snow season length better than the Biome-BGC model (Figure 2). In particular, the Biome-BGC snow model underestimated snow season length. Biome-BGC snow model predictions of snow season length had a mean absolute error of 56·3 days versus only 15·0 days for the TOPS snow model (Figure 2), supporting the finding of superior predictions from the TOPS snow model.

The TOPS snow model successfully simulated seasonal and interannual variations in SWE for the three snow years while the Biome-BGC model did not, especially in mid and late winter (Figure 3). Specifically, the TOPS snow model accurately predicted the observed start of snow accumulation, end of the snow melting, and

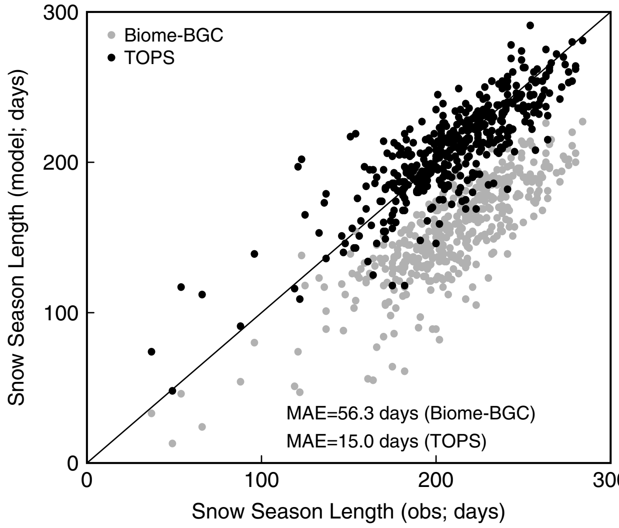


Figure 2. Observed (SNOTEL) and modelled snow season length (days). Three snow years from October 2000 to September 2003 are used. The Biome-BGC model was assessed with a 2 °C snow/rain transition threshold: differences of simulated snow season length were extremely minor, indicating that differences in model performance were not due to the melt transition

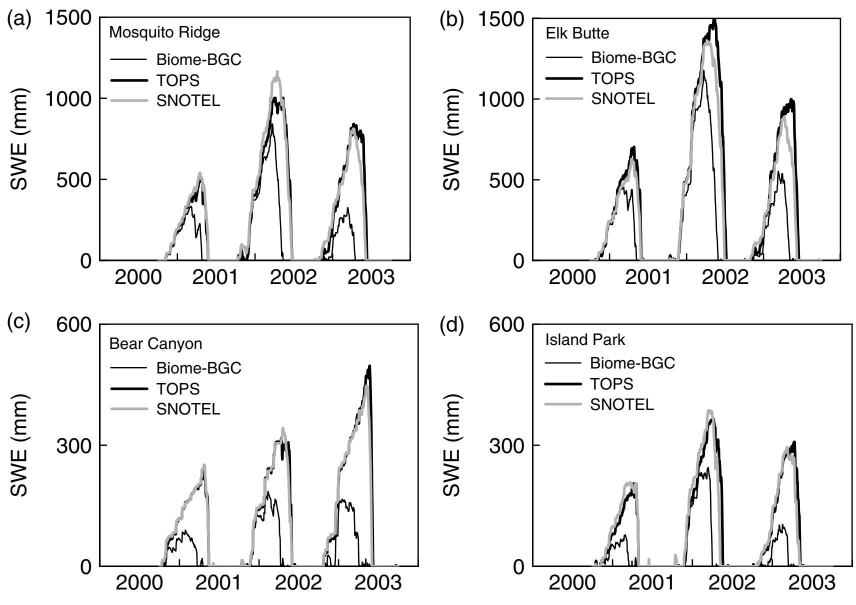


Figure 3. Time variations in observed and modelled (TOPS snow model and Biome-BGC snow model) snow water equivalent (in mm) from October 2000 to September 2003. Four sites are selected: (a) Mosquito Ridge (116·23 °W, 48·05 °N), (b) Elk Butte (46·85 °N, 116·12 °W), (c) Bear Canyon (43·75 °N, 113·93 °W), (d) Island Part (44·42 °N, 111·38 °W)



DOI: 10.1002/hyp

maximum SWE. However, the Biome-BGC snow model underestimated snow season length (earlier melting season) and SWE. Results for other SNOTEL stations were similar and are not presented here.

*MODIS snow cover product.* The original MOD10A2 snow products underestimated snow season length (Figure 4) because of problems in cloud screening. In essence, if users of MOD10A2 assume cloud-flagged pixels to be non-snow, snow season length will be underestimated. To illustrate this concept, snow season length was calculated and all cloud pixels for the whole year were assigned as snow. Improvements were dramatic: $R^2$ increased from 0·43 to 0·62 and mean absolute error decreased from 39·2 to 19·1 days (Figure 4). In addition, cloud pixels in the MODIS snow cover product existed almost exclusively in the snow season (Figure 5), suggesting that MOD10A2 tends incorrectly to identify snow as cloud. Therefore, in the following analysis, all cloud pixels in

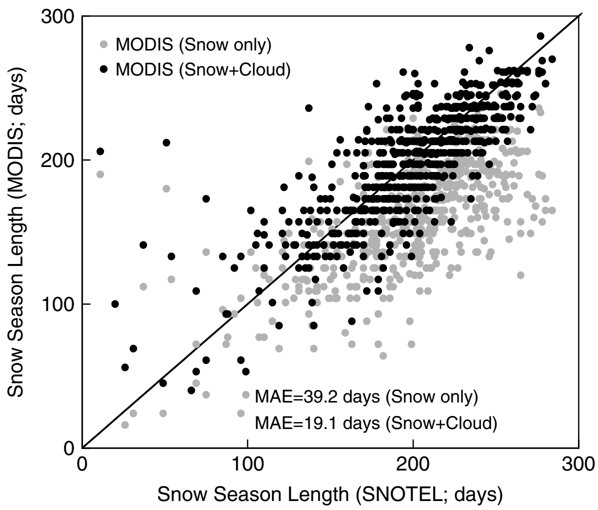


Figure 4. Observed (SNOTEL) and satellite-based (MODIS) snow season length (in days). Two methods for snow season length estimation were used: both snow and cloud pixels are counted as snow or only snow pixels are counted as snow. Linear regression results are $y = 0{\cdot}763x + 46{\cdot}3$, $R^2 = 0{\cdot}62$ (when snow and cloud pixels are both counted as snow) and $y = 0{\cdot}613x + 43{\cdot}5$, $R^2 = 0{\cdot}43$ (when only snow pixels are counted as snow)

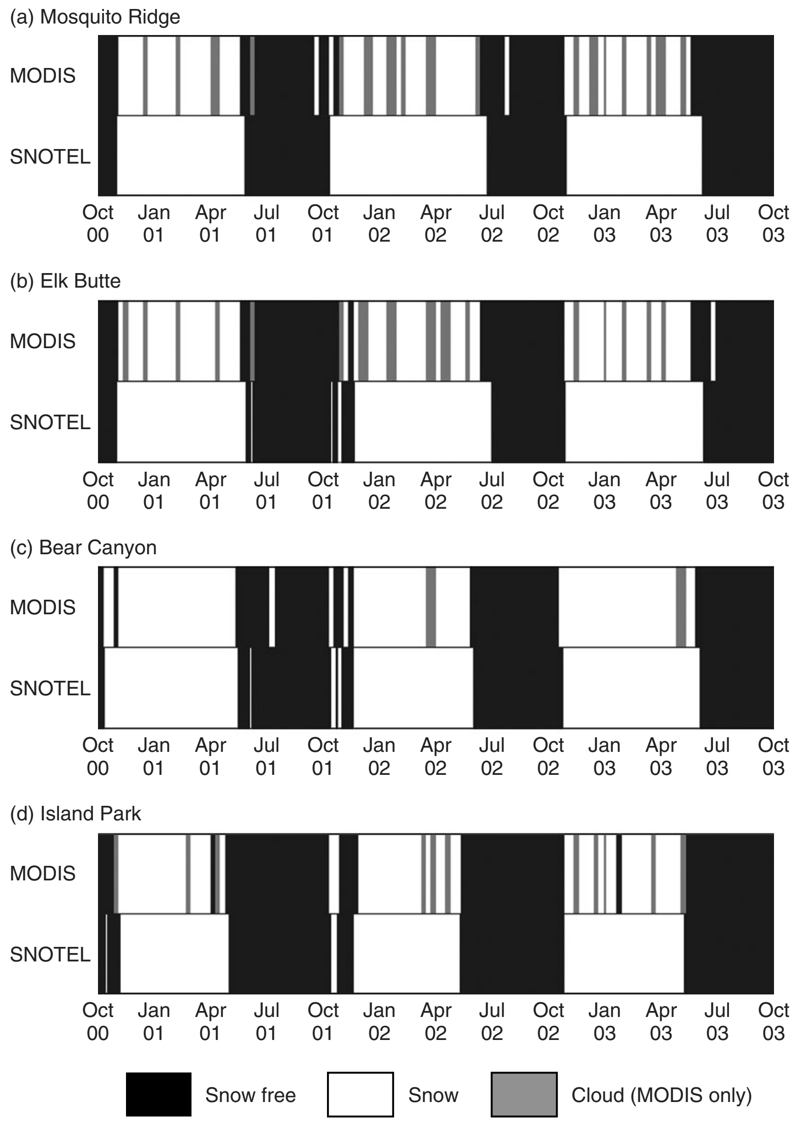


Figure 5. Time variations in satellite-based (top) and observed (bottom) presence of snow, snow free, and cloud (satellite-based only) at four SNOTEL observation sites (same as those in Figure 3)



DOI: 10.1002/hyp

the MODIS snow cover products were categorized as snow.

*Spatial evaluation of snow models*

Spatial patterns in the snow season length from the TOPS snow model and MOD10A2 were generally consistent (Figure 6a and 6c). As expected, snow season length was long (>250 days) in high elevation areas and short (<100 days) in low elevation shrub and cropland areas. Scattered regions of over and underprediction occurred (Figure 6d), mostly in areas with low station density (Figure 1). As the distributed snow models used interpolated meteorology derived from station data, sparse station distribution was likely a factor in model bias (Figure 1). For example, strong TOPS snow model overestimates of snow season length in central Oregon (Figure 6d) were associated with fewer climate stations (Figure 1). Similar conditions existed at the northern tip of the Columbia River Basin, an area of snow season length underprediction. Thus, it appears that even in a heavily instrumented region of industrialized North America, station density may be insufficient to prevent interpolation-generated biases in simulated snow pack dynamics. Other regions with large differences between TOPS snow model and MOD10A2 can be characterized by the complex topography, where interpolation of climate data is difficult even if climate station density is high.

In contrast to the TOPS snow model and consistent with results from the point evaluation, the Biome-BGC snow model (Figure 6b) pervasively underestimated MOD10A2 snow season length (Figure 6e), often by 30 to 100 days. Differences were especially large in all but the southern regions of the Columbia River Basin.

In a basin-wide comparison of seasonal and interannual variations in total snow covered area, both the TOPS and Biome-BGC snow models were consistent with MOD10A2 (Figure 7a). In all approaches, snow covered area was larger in the first two snow years than in the last. However, while differences between the TOPS snow model and MOD10A2 were minor (Figure 7b), the Biome-BGC snow model systematically underestimated the area and length of snow seasons in late winter to spring (Figure 7b). In summary, the results strongly suggest that the TOPS snow model can reproduce seasonal and interannual variations in snow cover significantly better than the Biome-BGC snow model.

Better snow simulation of TOPS snow model at point and spatial scale evaluation suggests (1) robustness of process-based snow model to different regions than empirical temperature index model (e.g. Walter *et al*., 2005) and (2) requirement of model calibration in Biome-BGC snow model in this basin. Since observed temperature-index snowmelt factors vary largely in area (van der Leeden *et al*., 1990) and season (Rango and

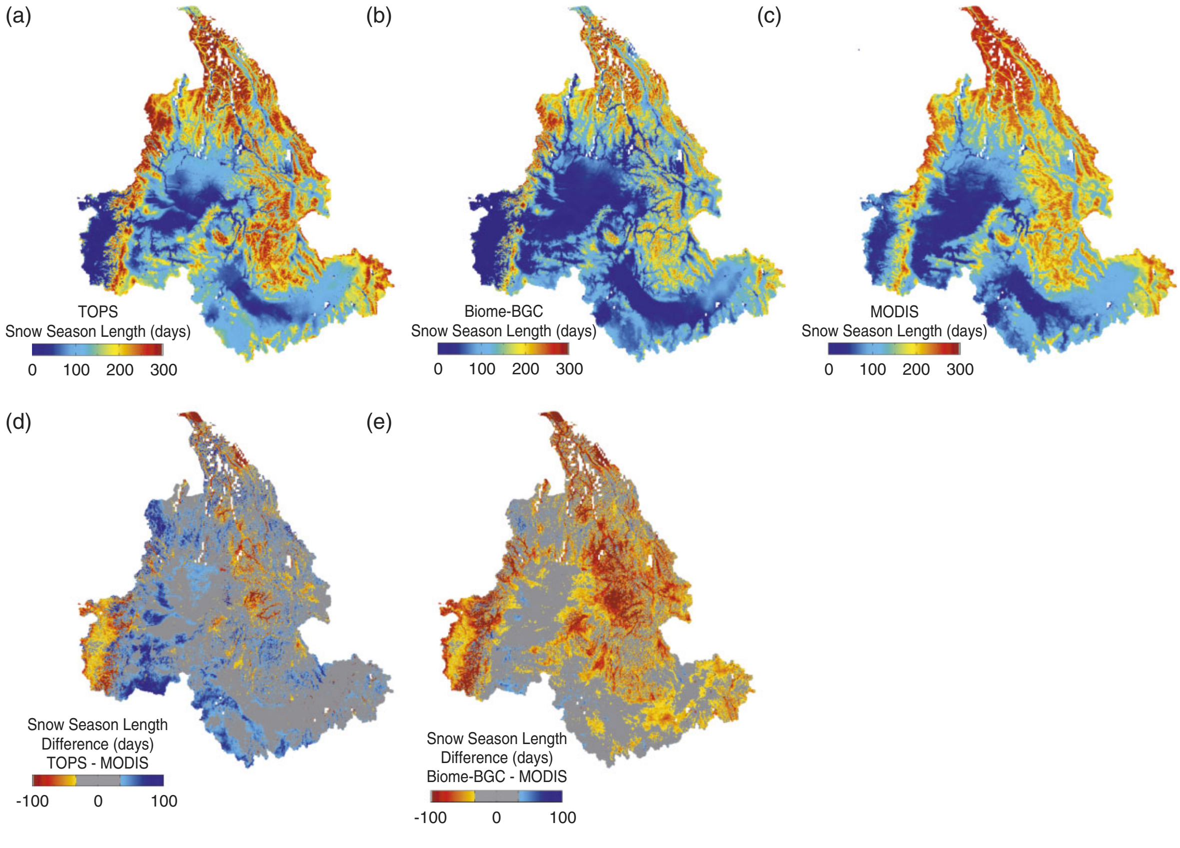


Figure 6. Spatial patterns in (a) TOPS snow model based, (b) Biome-BGC snow model based, (c) MODIS based snow season length averaged over snow year 2001 to 2003 and differences in snow season length between (d) TOPS snow model and MODIS observation and (e) Biome-BGC snow model and MODIS observations. In MODIS-based estimation, both snow and cloud pixels are counted as snow. In (d) and (e), the pixels with less than 30 days differences are coloured mid-grey

 

Martinec, 1995), calibration of empirical temperature index applicable to wide regions are difficult.

*Impact of differences in snow models on terrestrial ecosystem simulation*

Differences in the simulated snow pack dynamics, especially in the snow-melting season, affected seasonal patterns in runoff (Figure 8a). In TOPS simulations, runoff peaked in April when forced by the Biome-BGC snow model and in June when forced by the TOPS snow model. Based on these simulations and results presented earlier, it is likely that runoff simulations using the Biome-BGC snow model will tend to overpredict in late winter and early spring and to underpredict thereafter. In this application, although observed stream-flow and simulated runoff are not directly comparable (simulations do not include the effects of water storage, lateral water flow, and human consumption), the TOPS snow model based runoff was more consistent with observations than the Biome-BGC snow model based runoff especially in the snow melting season.

Differences in seasonal snowmelt patterns also affected seasonal GPP patterns (Figure 8b). GPP forced by both snow models increased from March to June, peaked in June, and decreased in summer and fall, reflecting seasonal patterns in meteorological parameters. However, in summer, GPP forced by the Biome-BGC snow model was about 30–40% (28, 39 and 37% for July, August and September, respectively) lower than GPP forced by the TOPS snow model. When the Biome-BGC snow model was used, two processes led to reductions in summer GPP: (1) earlier snowmelt promoted increased soil evaporation, a process otherwise limited by snow cover, leading to reduced soil moisture; and (2) earlier loss of snowpack as runoff reduced subsequent summer soil moisture. These comparisons show that differences in the snow models affected terrestrial carbon cycle processes through snowmelt and soil water budgets, and accurate snow models are needed to simulate terrestrial ecosystem processes properly.

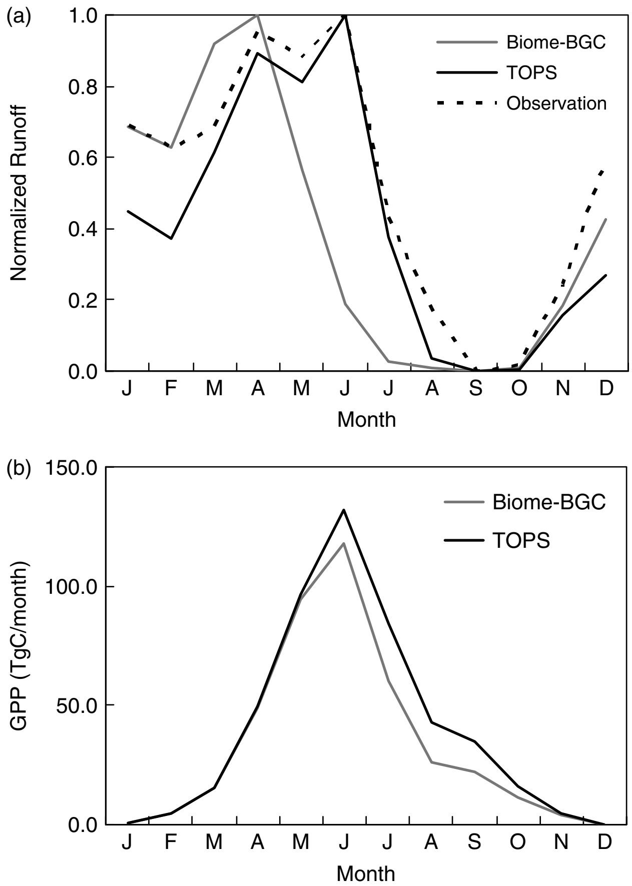


Figure 8. Monthly variations in (a) simulated (TOPS with TOPS snow model; TOPS with Biome-BGC snow model) runoff and observed stream-flow, and (b) GPP based on TOPS with TOPS snow model and with Biome-BGC snow model over the study area. Average results from October 2001 to September 2003 are shown. Normalized stream-flow and runoff are calculated by $(F - \mathrm{Min})/(\mathrm{Max} - \mathrm{Min})$, where $F$ is monthly stream-flow and runoff, and Min and Max are annual minimum and maximum stream-flow or runoff

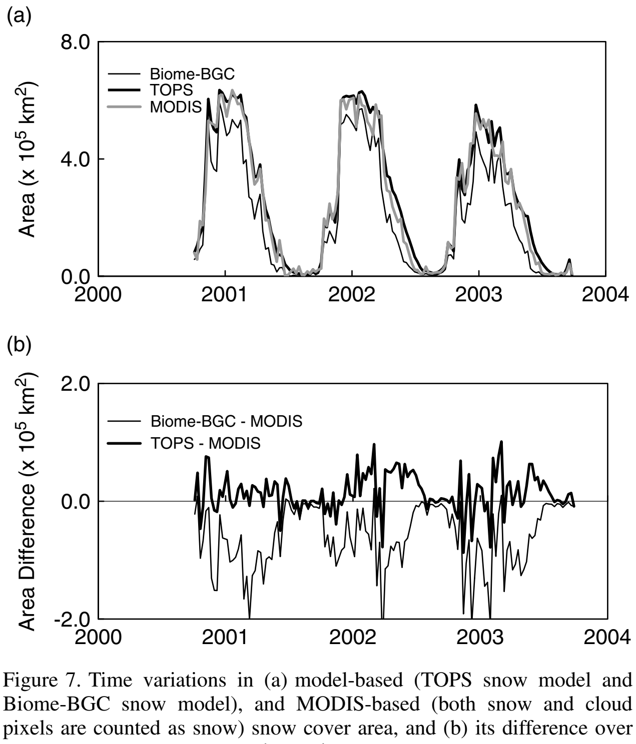


Figure 7. Time variations in (a) model-based (TOPS snow model and Biome-BGC snow model), and MODIS-based (both snow and cloud pixels are counted as snow) snow cover area, and (b) its difference over the study area

## CONCLUSION

This study demonstrates that current snow models included in terrestrial biosphere models have large uncertainties in simulating snow cover variations and that these uncertainties have impacts on terrestrial water and carbon cycle simulations. Snow models included in the Biome-BGC and TOPS terrestrial biosphere models were evaluated with ground and satellite observations over the Columbia River Basin. The Biome-BGC snow model, which is based on an empirical temperature-index snowmelt model, underestimated snow season length and SWE substantially, in turn affecting runoff, soil water content, and GPP. The TOPS snow model, which is based on a process-based snowmelt model, predicted



DOI: 10.1002/hyp

snow cover dynamics that were consistent with point and satellite observations; however, even for the TOPS snow model, predictions were dependent on adequate gridded meteorological data and complexity of topography. The comparison of these two simple models illustrated that choice of snow model may introduce extensive biases in simulated states and fluxes of simulated carbon and water cycles. Further efforts to calibrate the snow model portion of terrestrial biosphere models using recently available satellite and ground observations should be pursued.

## ACKNOWLEDGEMENTS

Funding from NASA's Science Mission Directorate through EOS (K. Ichii and R. R. Nemani) and NIP (M. A. White) programmes facilitated this research.

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DOI: 10.1002/hyp