

# An Empirical Formula to Compute Snow Cover Fraction in GCMs

WU Tongwen\*<sup>1,2</sup> (吴统文) and WU Guoxiong<sup>1</sup> (吴国雄)

<sup>1</sup> State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics,  
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

<sup>2</sup> Laboratory for Climate Study, National Climate Center, Beijing 100081

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## ABSTRACT

There exists great uncertainty in parameterizing snow cover fraction in most general circulation models (GCMs) using various empirical formulae, which has great influence on the performance of GCMs. This work reviews the commonly used relationships between region-averaged snow depth (or snow water equivalent) and snow cover extent (or fraction) and suggests a new empirical formula to compute snow cover fraction, which only depends on the domain-averaged snow depth, for GCMs with different horizontal resolution. The new empirical formula is deduced based on the 10-yr (1978–1987)  $0.5^\circ \times 0.5^\circ$  weekly snow depth data of the scanning multichannel microwave radiometer (SMMR) driven from the Nimbus-7 Satellite. Its validation to estimate snow cover for various GCM resolutions was tested using the climatology of NOAA satellite-observed snow cover.

**Key words:** snow cover fraction parameterization, satellite derived snow depth, GCM

## 1. Introduction

In comparison with the bare soil, snow cover has high albedo. Of all the varying surface conditions, snow cover experiences the largest spatial as well as temporal fluctuations. Global snow cover has distinct seasonal and inter-annual variations. Most observational studies (e.g., Barnett et al., 1988) and numerous simulations (e.g., Barnett et al., 1989) have demonstrated that snow cover plays important roles in modifying regional and possibly remote climate through changing surface energy balance, hydrological cycle via snow melting, and atmospheric circulation.

The snow cover fraction ( $f_{\text{SNO}}$ ) is an important factor in calculating ground albedo over the snow-covered surface. When snow pack is patchy on the ground, the domain-averaged ground albedo ( $\alpha_g$ ) is usually taken as a weighted combination of the albedos over “soil” ( $\alpha_{\text{SOI}}$ ) and snow ( $\alpha_{\text{SNO}}$ ), respectively, i.e.,

$$\alpha_g = \alpha_{\text{SOI}}(1 - f_{\text{SNO}}) + \alpha_{\text{SNO}}f_{\text{SNO}}. \quad (1)$$

Since  $\alpha_{\text{SNO}}$  is much larger than  $\alpha_{\text{SOI}}$ , overestimation (underestimation) of snow cover fraction will result in larger (smaller) surface albedo  $\alpha_g$ . Therefore, correct estimation of snow cover fraction in a grid square of a general circulation model (GCM) becomes essential

for the calculation of the surface energy balance and even in the model performance (Foster et al., 1996).

There have been a large number of advanced GCMs and land surface models (LSMs) (e.g., the Biosphere-Atmosphere Transfer Scheme (BATS), Dickinson et al., 1986, 1993; the Simple Biosphere (SiB) model, Sellers et al., 1986; NCAR LSM version 1, Bonan, 1996). However, there is not a uniform formula suitable for GCMs to compute snow cover fraction. Table 1 lists seven empirical formulae used in GCMs and LSMs. There exists a great discrepancy among them. It shows the existence of the large uncertainty in parameterizing snow cover fraction in GCMs. The purpose of this work is to explore the relationship between snow cover fraction and snow depth for use in GCMs by utilizing the snow depth data driven from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR).

## 2. Data and methodology

November 1978–August 1987 weekly passive microwave snow depth data (Chang et al., 1987) over the Northern Hemisphere, which are derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), were used in this study. The SMMR

\*E-mail: twwu@cma.gov.cn

**Table 1.** The empirical formulae to parameterize the snow cover fraction.

Formulae	Applied in Models and References
$f_{\text{sno}} = \min\left(\frac{d_s}{d_{\text{sc}}}, 1\right)$	Simple Biosphere (SiB) model (Sellers et al., 1986); Simplification of Simple Biosphere (SSiB) model (Xue et al., 1991); NCAR land surface model (LSM) version 1.0 (Bonan, 1996); Goddard Space Flight Center GLA model (Foster et al., 1996).
$f_{\text{sno}} = d_s/(d_s + 10z_0)$	Goddard Institute for Space Studies (GISS) model (Hansen et al., 1983) Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1986) Snow-atmosphere-soil transfer model (Sun et al., 1999)
$f_{\text{sno}} = f_{\text{s0}}/(1 + f_{\text{s0}}); f_{\text{s0}} = \frac{0.1W}{0.2z_0}$	Suggested by Marshall et al. (1994).
$f_{\text{sno}} = \frac{d_s}{d_s + 10z_0} \sqrt{\frac{d_s}{d_s + \max(1, 0.15 \times \sigma_z)}}$	Meteo-France climate model (Douville et al., 1995).
$f_{\text{sno}} = \tanh \frac{d_s}{2.5z_0}$	Suggested by Yang et al. (1997)
$f_{\text{sno}} = W/(W + W_c)$	Goddard Space Flight Center ARIES model (Koster and Suarez, 1992)
$f_{\text{sno}} = \sqrt{W/W_c}$	Canadian Climate Centre (CCC) GCM (Verseghy, 1991) Japanese CCSR-NIES AGCM (Watanabe and Nitta, 1998)

Note:  $f_{\text{sno}}$  snow cover fraction,  $f_{\text{s0}}$  unweighted snow cover fraction;  $d_s$  averaged snow depth (m);  $d_{\text{sc}}$  snow-masking depth of vegetation or soil (0.05 m);  $z_0$  vegetation roughness length (m);  $W$  domain-averaged depth of water equivalent snow ( $\text{kg m}^{-2}$ );  $W_c$  critical snow amount, a constant independent on  $z_0$  (e.g.,  $200 \text{ kg m}^{-2}$  in CCSR-NIES AGCM and  $100 \text{ kg m}^{-2}$  in CCC GCM);  $\sigma_z$  standard deviation (m) of the subgrid orography.

snow depth data were generated by using the algorithm developed by Chang et al. (1987) that prescribes a snow density of  $0.30 \text{ g cm}^{-3}$  and a snow grain size of 0.3 mm for the entire snowpack. The Nimbus-7 observed brightness temperature difference between the SMMR 37 GHz and 18 GHz channels is used to derive a snow depth for a uniform snow field.

SMMR snow depth data have a resolution of  $0.5^\circ \times 0.5^\circ$ . If we hypothesize that once there is SMMR snow in some grid the whole  $0.5^\circ \times 0.5^\circ$  box is covered by snow, then the region-averaged snow cover fraction in any given larger GCM box area can be obtained. For example, a  $2.5^\circ \times 2.5^\circ$  GCM box is composed of 25 boxes of  $0.5^\circ$  latitude by  $0.5^\circ$  longitude. If in a given  $2.5^\circ \times 2.5^\circ$  GCM box there is only one grid where the SMMR snow depth is larger than 0, the snow cover fraction in the GCM box is taken as  $1/25$ . Following the method above, datasets of area-averaged snow depths and snow cover fractions at  $1.5^\circ \times 1.5^\circ$ ,  $2.5^\circ \times 2.5^\circ$ ,  $3.5^\circ \times 3.5^\circ$ ,  $4.5^\circ \times 4.5^\circ$ , and coarser resolutions for the time period of November 1978 to August 1987 can be estimated.

In this work, we derive an empirical relation be-

tween our reanalyzed region-averaged SMMR snow depth and snow cover fraction using the method of regression analysis. In order to test its validation, the National Oceanic and Atmospheric Administration (NOAA) satellite-derived weekly snow cover (SC, the percent area of land covered by snow) dataset is used in this work. It spans the period from November 1966–December 1991 and has  $89 \times 89$  grid points over the Northern Hemisphere based on a polar stereographic projection. Each grid cell is assigned the value 0 for the absence of snow and 1 for the presence of snow. In order to analyze the fine substructure, the data were interpolated onto  $2^\circ \times 2^\circ$  latitude/longitude grid points using a routine supplied by the U.S. National Snow and Ice Data Center (NSIDC). Since the snow cover prior to 1972 is underestimated, it was excluded in this study. So, the 19-year (1973–1991) averaged climatology of annual mean snow cover over the Northern Hemisphere was analyzed in this work.

### 3. Results

For the purpose of universal use in GCMS, the em-

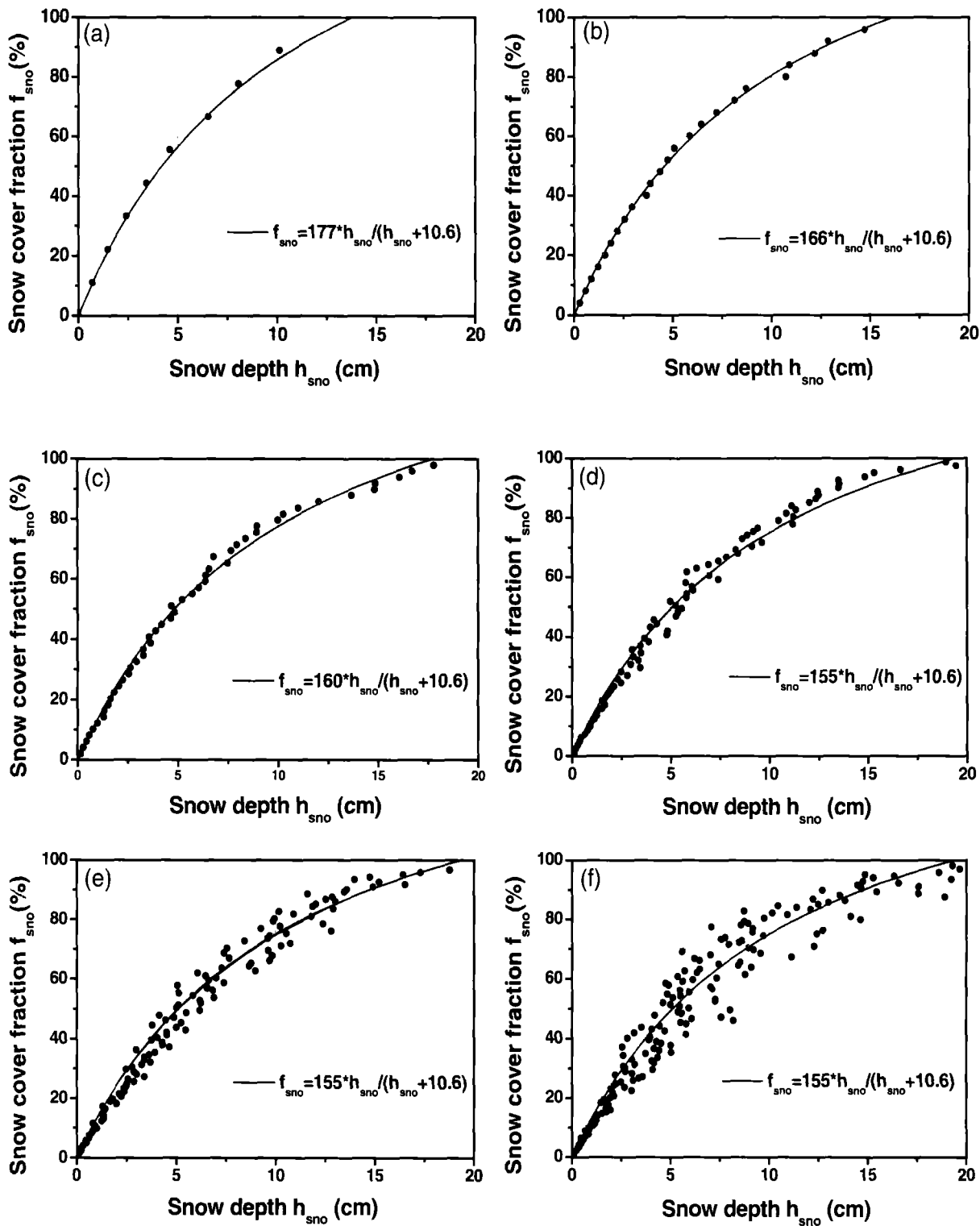
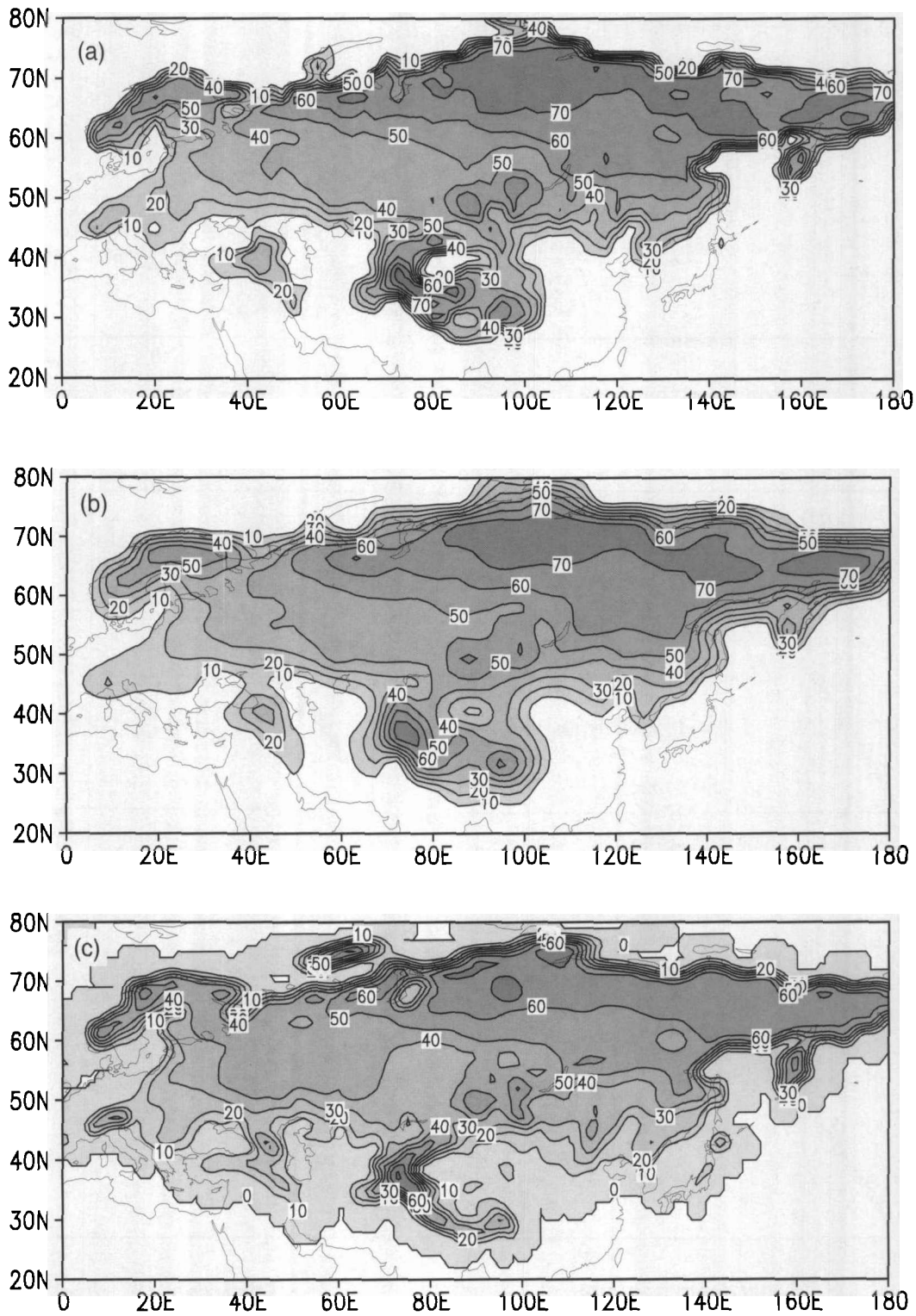
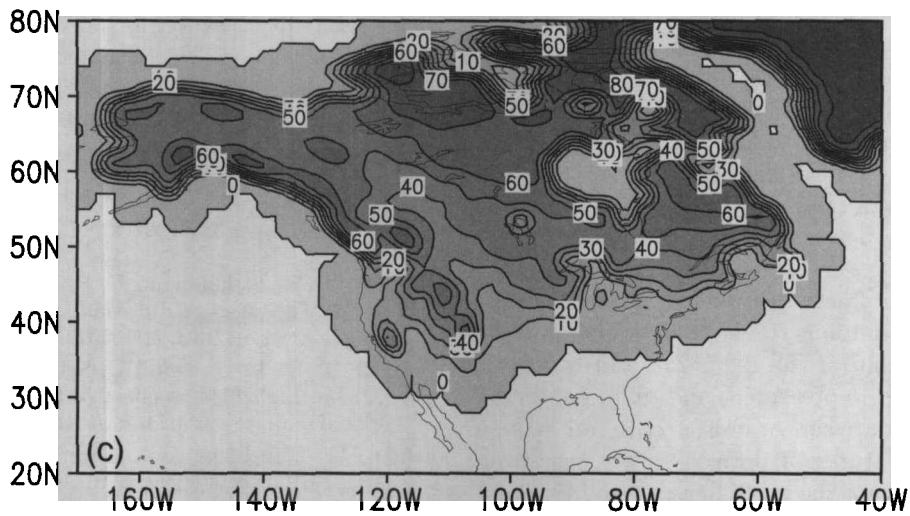
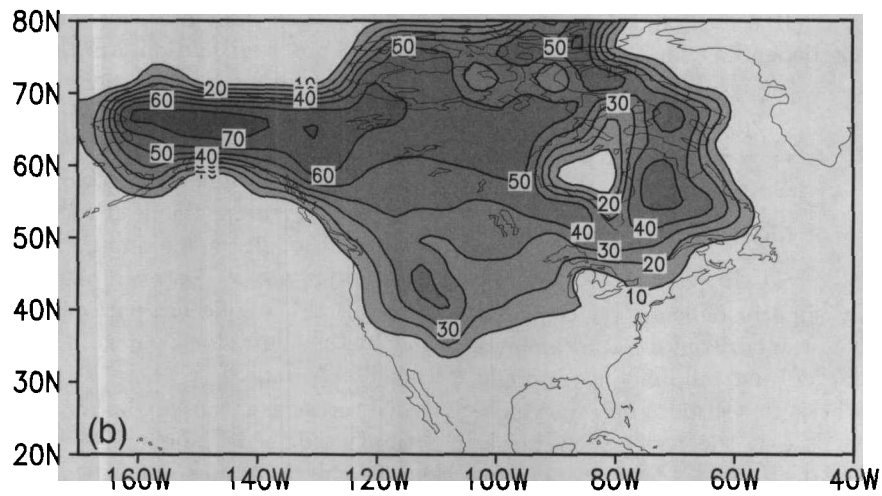
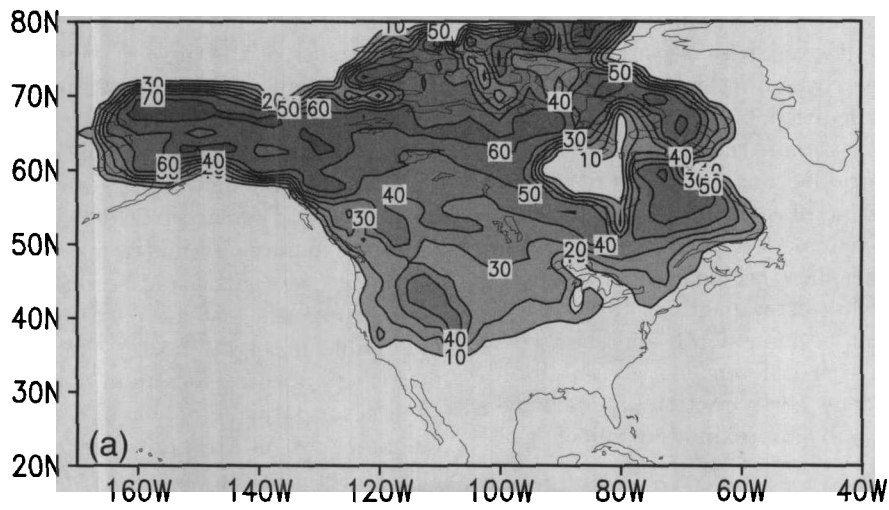


Fig. 1. Scatter diagrams of snow-cover fraction (%) and snow depth (cm) for all the Northern Hemisphere grid boxes with resolutions of (a)  $1.5^\circ \times 1.5^\circ$ , (b)  $2.5^\circ \times 2.5^\circ$ , (c)  $3.5^\circ \times 3.5^\circ$ , (d)  $4.5^\circ \times 4.5^\circ$ , (e)  $5.5^\circ \times 1.5^\circ$ , and (f)  $6.5^\circ \times 6.5^\circ$ . All results are calculated from  $0.5^\circ \times 0.5^\circ$  lat/lon SMMR weekly snow depth during the period of November 1978-December 1987. The solid lines are the empirical fitting (2).



**Fig. 2.** Climatology of annual mean snow cover (SC) fraction (%) over the Eurasian continent derived from SMMR snow depth at the resolutions of (a)  $2.5^\circ \times 2.5^\circ$  and (b)  $4.5^\circ \times 4.5^\circ$  using the empirical formula (2), and (c) those from NOAA snow cover observation.



**Fig. 3.** Same as in Fig. 2, but for climatology of annual mean snow cover fraction (%) over the North American continent. In (a) and (b), there are no observational SMMR data over Greenland.

empirical relation between the Northern Hemisphere and annual mean of our derived region-averaged SMMR snow depth and snow cover fraction for several GCM resolutions can be deduced. For any given snow cover fraction, we can estimate the correspondent snow depth at any GCM gridded box in various resolutions so that the annual mean of correspondent snow depth averaged for the 10-year period of 1978–1987 and for all the Northern Hemisphere gridded boxes can be calculated. Figure 1 is the scatter diagrams of the 10-year and hemispheric mean of snow depth and snow cover fraction for GCMs with different horizontal resolutions. It shows that snow cover fraction ( $f_{\text{snow}}$ ) changes with snow depth ( $d_{\text{snow}}$ ) by approximately following the empirical relation:

$$f_{\text{snow}} = \min\left(\frac{b \cdot d_{\text{snow}}}{d_{\text{snow}} + a}, 1\right), \quad (2)$$

where  $a$  is a constant (10.6 cm) and  $b$  is a non-dimensional coefficient depending on the GCM grid horizontal resolution, i.e.,

$$b = \begin{cases} 1.77 & \text{for } 1.5^\circ \times 1.5^\circ, \\ 1.66 & \text{for } 2.5^\circ \times 2.5^\circ, \\ 1.60 & \text{for } 3.5^\circ \times 3.5^\circ, \\ 1.55 & \text{for } 4.5^\circ \times 4.5^\circ \text{ or coarser resolution.} \end{cases} \quad (3)$$

The coefficient  $b$  only slightly depends on the horizontal resolution. When the horizontal resolution gets finer,  $b$  gets slightly larger, and the influence brought forth under the hypothesis in section 2 becomes more and more evident. In Fig. 1, the mean snow masking depth on the ground is about 14 to 18.5 cm for different resolutions.

Due to the limitation of the short time period of the SMMR snow data, the influence of vegetation roughness is not included in Expression (2).

In order to explore practicality of the new empirical relation between snow depth and snow cover fraction, a comparison between estimated snow cover fraction using the empirical formula (2) for various resolutions from SMMR snow depth data and that from NOAA observation is made. The climatology of annual mean derived snow cover fractions over the Eurasian continent at various resolutions (for simplification, only the geographical distributions for  $2.5^\circ \times 2.5^\circ$  and  $4.5^\circ \times 4.5^\circ$  lat/lon resolutions are presented) and that of observed NOAA snow cover are shown in Fig. 2. It can be seen that large-scale features of derived snow cover from SMMR snow depth for the two different resolutions are very similar to those of the NOAA snow covers. Especially for the derived snow cover in the  $2.5^\circ \times 2.5^\circ$  resolution (Fig. 2a), the regional features are much closer to those of the NOAA snow cover (Fig. 2c). A large

amount of snow cover is mainly located to the north of  $50^\circ\text{N}$ , such as the three maximums in Siberia, Kamchatskiy peninsula, and West Europe, respectively. In Figs. 2a and 2c, it seems that the derived snow cover in most parts of the Eurasian continent is slightly more than the NOAA snow cover, especially north of  $60^\circ\text{N}$  where there exists about a 10% bias. The largest difference is mainly distributed over the Tibetan Plateau, especially the central and eastern parts east of  $80^\circ\text{E}$ . This divergence may be partly due to possible error of satellite observation over the Tibetan Plateau. In fact, there are large errors in cloudy areas for NOAA snow cover data and in heavily forested and mountainous areas for SMMR snow depth data (Chang et al., 1987) where the microwave snow signatures tend to be masked.

Nearly consistent distributions in Figs. 2a, 2b, and 2c imply that the empirical relation (2) is usable for the snow cover estimation over the Eurasian continent. It is also valid for North American snow cover estimation. As shown in Fig. 3, not only for the  $2.5^\circ \times 2.5^\circ$  resolution but also for the  $4.5^\circ \times 4.5^\circ$  coarse resolution, centers of large snow cover derived from SMMR snow depth correspond well to those of NOAA snow covers, although the maximums in snowy regions have some differences. For example, derived snow covers (Fig. 3b) in the southern part of the Rocky Mountains and in the Labrador Peninsula are slightly less than the NOAA data (Fig. 3c).

Nevertheless, the validation of the new empirical formula still needs to be further verified in GCMs. The details will be discussed in future work.

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