Snow Process Modeling in the North American Land Data Assimilation System (NLDAS).

Part I: Evaluation of Model Simulated Snow Cover Extent

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Abstract

This study evaluates the cold season process modeling in the North American Land Data Assimilation System (NLDAS) and consists of two parts: 1) assessment of land surface model simulations of snow cover extent and 2) evaluation of snow water equivalent. In this first part, predictions of snow cover extent from the four land surface models (Noah, MOSAIC, SAC and VIC) in the NLDAS were compared with observational data from the IMS (Interactive Multisensor Snow and Ice Mapping System) for a 3 year retrospective period over the conterminous United States. In general, all models simulate reasonably well the regional scale spatial and seasonal dynamics of snow cover. Systematic biases are seen in the model predictions with certain models consistently under- or over-estimating snow cover extent, although the level of bias is dependent on geographic location and elevation variability. Larger discrepancies are seen over higher elevation regions of the northwest of the United States that may be due, in part, to errors in the meteorological forcings and also at the snow line boundary where most temporal and spatial variability in snow cover extent is likely to occur. The spread between model simulations is fairly low and generally envelopes the observed data at the mean regional scale indicating that the models are quite capable of simulating the general behavior of snow processes at these scales. Inter-model differences can be explained to some extent by differences in the model representations of sub-grid variability and parameterizations of snow cover extent.

1. Introduction

Cold season processes play an important role within the hydrological cycle through their influence on the dynamics of moisture storage and the partitioning of incident radiation [*Groisman et al.*, 1994]. The strength of this influence is due in part to the large spatial scales involved and quantity of equivalent water held in frozen storage. Snow cover extent accounts for vast regions of the northern hemisphere during the winter and permanent snow cover exists over much of northern Eurasia, North America and areas of high elevation [*Groisman et al.*, 1994; *Brown*, 2000]. Frozen moisture in the soil and overlying snow pack form large reservoirs that may store water for many months before being released during the spring melt. This has great implications for the environment and water resources which rely on the regularity of the melting process and subsequent flooding. In turn, the high albedo of the snow pack reflects a large proportion of incoming radiation, altering the radiation balance with the atmosphere and instigating changes to circulation patterns that may be felt thousands of kilometers away [*Cohen and Entekhabi*, 2001; *Yang et al.*, 2001].

Accurate prediction of snow cover processes is therefore vital in determining the budgets of water and energy and the feedbacks to the atmosphere. Within the North American Land Data Assimilation System (NLDAS) [*Mitchell et al.*, 1999, 2000, this issue] predictions of snow cover, along with soil moisture, have a central role in improving forecasts from Numerical Weather Prediction models, which benefit from enhanced predictions of the water and energy fluxes and states at the lower boundary of the earth's surface [*Mitchell et al.*, this issue]. To this end, the NLDAS will assimilate predictions from land surface models (LSM) of snow process variables to improve the accuracy of weather forecasts. This paper assesses the snow process simulations from the four land surface models (LSM) participating within the NLDAS.

Assessment of the accuracy of model simulations and identification of the differences between models will enhance the understanding of cold season processes and help identify the applicability and limitations of LSM models in this area. Previous cold season modeling studies have looked at model inter-comparisons and validation against observations but these have been limited in spatial scale, e.g. the PILPS Phase 2(d) catchment scale experiment in Russia [*Slater et al.*, 2001] and the PILPS Phase 2(e) experiment in northern Scandinavia (Nijssen et al., Simulation of high latitude hydrological processes in the Torne-Kalix basin: PILPS Phase 2(e). 2: Comparison of model results with observations, submitted to Global and Planetary Change, 2002), or have used coupled models that suffer from errors in the atmospheric forcings, e.g. *Freil and Robinson* [1998].

Two of the most important snow process variables are snow cover extent and snow water equivalent (also referred as SCE and SWE). Snow cover extent is a measure of the spatial extent of snow and determines the spatial influence of snow on the atmosphere through the partitioning of incident radiation. Snow water equivalent quantifies the amount of frozen moisture storage and will in turn determine the amount and timing of runoff during subsequent spring melt. This study is split into two parts in which these two quantities are treated separately. The first part of the paper concentrates on the assessment of model predictions of snow cover extent through inter-model and observational data comparisons. The second part of this study [*Pan et al.*, this issue] evaluates the predictions of snow water equivalent.

2. Cold Season Process Modeling

The four land surface models that contribute to the NLDAS modeling effort (MOSAIC, Noah, SAC and VIC) simulate cold season processes with varying degrees of complexity. In general, all models simulate the physical processes of changes of moisture states and the related partitioning of energy fluxes (except the SAC model which does not simulate the land surface energy balance) but the parameterizations used may differ between models. In addition, each model handles sub-grid variability of vegetation and elevation at different levels of complexity, which affects snow cover predictions through sub-grid variations in precipitation, temperature and radiation budgets.

All of the snow modules used in the different models are based on balances of mass and energy in the snow pack. The change in snow pack SWE is balanced by the input snowfall and output snowmelt and snow sublimation. The heat flux through the snow pack (sum of net radiation, sensible/latent heat, ground heat fluxes) is used to change the temperature, phase composition, and amount of snow pack. MOSAIC, Noah, and VIC run at full energy mode, which means that the snow energy process is coupled into the energy transfer processes of the entire LSM. Thus in one time step, temperatures of soil layers, soil surface, and snow pack layers (if any) will be solved from heat transfer/balance equations for the entire system (soil, snow pack, vegetation, and air) together with the corresponding water balance equations. Each individual model may have different simplifying assumptions, e.g., linearization of the heat transfer equation (MOSAIC) or constant temperature boundary conditions in the deep layer (VIC). Noah, uniquely, addresses the change of snow density due to compaction in time, and assumes the maximum liquid water storage capacity in the snow pack to be 13%, above which it is removed from the snow pack [*Koren et al.*, 1999]. Noah also accounts for effects from frozen soil, e.g., reduction of soil infiltration capacity. VIC accounts for snow aging by decreasing its albedo with time, and assumes the maximum liquid water storage capacity to be 6% [*Wigmosta et al.*, 1994]. SAC is different from the other three in that it only calculates the water balance, and the snow calculation is done separately by an independent snow model developed by the Hydrologic Research Laboratory of the Office of Hydrology [*Anderson*, 1973] which calculates snowmelt as a function of air temperature. Different models also apply slightly different approaches to convert SWE to snow cover extent as described below.

Figure 1 illustrates how each model represents sub-grid processes and the parameterizations used for deriving snow cover extent. All models parameterize SCE as a function of SWE. The MOSAIC model [*Koster et al.*, 1996] uses the following formulation:

$$SCE = \frac{SWE}{SWE + SWE_{mid}} \tag{1}$$

where SWE_{mid} is a vegetation dependent parameter. Each computational grid is divided into vegetation tiles and SCE is calculated independently over each vegetation type within a grid. The Noah model [*Betts et al.*, 1997; *Chen et al.*, 1996, 1997; *Koren et al.*, 1999] has no sub-grid vegetation tiling but uses the following vegetation-dependent formulas to calculate fractional snow covered area:

$$\begin{aligned} &If\ \ SWE < SWE_{\max},\ \ then\ \ SCE = 1 - [\exp(-\alpha_s \frac{SWE}{SWE_{\max}}) + \frac{SWE}{W_{\max}} \exp(-\alpha_s)] \\ &If\ \ SWE \geq SWE_{\max},\ \ then\ \ SCE = 1 \end{aligned} \tag{2}$$

SWE_{max} is the value of SWE at which the snow cover reaches full coverage and $\alpha_s = 2.6$ is a curve shape parameter. This formula is equivalent to an empirical areal snow depletion curve [*Anderson*, 1973; *Koren et al.*, 1999]. The SAC model [*Burnash et al.*, 1973, 1995] has no sub-grid variability, but also uses the empirical areal snow depletion curve [*Anderson,* 1973] with the maximum SWE determined as:

$$SWE_{\max} = \min(SI,\ SWE_{\max,s}) \tag{3}$$

where $SWE_{max,s}$ is the maximum SWE for the grid over the simulation period and *SI* is the lower limit of SWE at which there is full snow coverage (set to 90mm here). The VIC model [*Liang et al.*, 1994, 1996, 1999; *Cherkauer and Lettenmaier*, 1999] uses both sub-grid vegetation tiling and elevation banding and simply that any snow fully covers the tile:

$$\begin{aligned} &If\ \ SWE = 0,\ then\ \ SCE = 0 \\ &If\ \ SWE > 0,\ then\ \ SCE = 1 \end{aligned} \tag{4}$$

Note that VIC handles the water/energy budgets and tracks all the states separately for each tile depicting a specific vegetation cover and for each elevation band. Precipitation input is uniformly distributed (weighted only by area) to each tile, and temperature forcing was adjusted according to elevation with a lapse rate 6.5 ˚C.

3. Data

3.1. Land Surface Model Simulations

The land surface models participating in the NLDAS operate within a framework that consists of a common 1/8 degree geographic grid over the conterminous United States, using common soil and vegetation parameters and distributions, and common meteorological forcings. Simulations were run retrospectively for the period October 1996 to September 1999. Model outputs include predictions of grid average snow cover extent as well as standard water and energy states and fluxes. Details of the NLDAS modeling framework and the retrospective simulations are given in the NLDAS overview paper of *Mitchell et al.* (this issue).

3.2. Observed Snow Cover Extent

In this study the snow cover product from the Multi-Sensor Snow and Ice Mapping System (IMS) [*Ramsay*, 1998] is used to compare with model simulated snow cover extent. The IMS product was designed to replace and improve upon the older NESDIS Northern Hemisphere snow analysis and is currently operated by the Satellite Analysis Branch (SAB) of the national Oceanic and Atmospheric Administration/Satellite Services Branch (NOAA/SSB). The IMS product is a spatially complete dataset of snow cover extent from 1997 to the present and is derived from a number of data sources. Snow and ice maps are produced each day by human snow analysts using the IMS to incorporate a series of snow observations, including geostationary satellites (GOES E/W, Meteosat 5/7, GMS) polar orbiting satellites (AVHRR (POES), AMSU, DMSP SSM/I), station data and some other ancillary data sources for cloud obscured areas. IMS products cover the northern hemisphere and are projected to a polar stereographic grid with spatial resolution of about 25 km, and classify each land grid to have presence or absence of snow. Figure 2 shows an example of an IMS image. For comparison with the higher spatial resolution NLDAS model data, the IMS product was resampled to the NLDAS grid (~12km) using the nearest neighbor algorithm. This may introduce errors at the snowline boundary but as the occurrence of snow is primarily controlled by meteorological processes that behave at a much larger scale these errors should be relatively small. Validation of IMS was carried out under a joint effort by NESDIS, the National Weather Service (NWS) and Rutgers University [*Ramsay*, 1998].

4. Analysis

To compare with the observed IMS data, the model predicted data were converted to presence/absence values using a threshold of 0.1 fractional cover, i.e. if a pixel has at least 0.1 fractional coverage, then it is considered as snow covered and snow free if the fractional cover is less than 0.1. The threshold value and its effect on the comparisons are discussed in section 5.

4.1. Snow Cover Extent at Regional Scales

Comparison of the observed and modeled snow cover extent was carried out over eight River Forecast Center (RFC) regions chosen to encompass higher elevations and the winter time snow cover extent of the United States (see Figure 3). The mean SCE value for the observed IMS product and the model predictions was calculated over each RFC region for each day and the time series is shown in Figure 4.

In general, the results indicate a good agreement between the modeled and observed mean regional SCE although there are systematic biases for all models and regionally dependent differences in how well the models perform. For all regions, the VIC model predicts the highest agreement and Noah the lowest, while the MOSAIC and SAC models fall somewhere in between. The more mountainous regions (Colorado, California/Nevada and Northwest) appear to show the largest differences. This is especially the case in the Northwest region during the spring melt period where the VIC model overestimates the snow cover extent more significantly in the third year and the Noah and MOSAIC models tend to make underestimates.

Although comparison of the regional mean SCE provides valuable information about the general performance of the models in terms of the predicted total cover of snow in a region, it does not necessarily indicate whether the models are predicting snow to be in the correct place. To address this, a pixel-by-pixel comparison of snow cover was undertaken to determine how well the models simulate the spatial pattern of snow through the year. Again, comparisons were carried out for the eight RFC regions and the time series of the percentage of matching pixels are shown in Figure 5.

Overall, all models match at least 50% of the observed data throughout most of the comparison period and on average predict about 75% of the pixels correctly during the winter months. The exceptions to this are in the flatter regions such as the North Central and Northeast where the models periodically predict less than 50% of the pixels correctly. During the summer when there is usually no snow over each region, the match between modeled and observed data is 100%, which is to be expected. In general, the SAC model appears to perform well over mountainous regions and less well over flatter areas such as the Middle Atlantic region. The VIC model tends to do better in the mid-winter months (except in the Colorado basin) and the MOSAIC and Noah models predict snow cover more accurately during the late winter and spring melt periods.

4.2. Temporal Analysis of Snow Cover Extent

To assess model performance at the pixel level rather than just at the regional mean level, maps of annual cumulative snow covered days were plotted for water years 1997 and 1998, for the observed data and model predictions (see Figure 6). In this way, it can be seen whether the models over-estimate or underestimate the snow cover for any one pixel over the year. The cumulative snow day maps indicate that the models predict the general spatial pattern of snow over the USA well, although each model may differ somewhat at smaller scales in individual regions. Overall, the following general relationship holds: $SCE_{VIC} > SCE_{SAC} > SCE_{MOSAIC} > SCE_{Noah}$ while the observed data lie somewhere in between. This is consistent with the mean SCE time series shown in Figure 4.

Figure 7 shows maps of the percentage of days that were incorrectly simulated by the models. An incorrect day is defined as one on which the measured record indicated the presence of snow but the model simulation indicated otherwise or vice versa. This shows how well the models perform in predicting the timing of the occurrence of snow. There is reasonable agreement between the observations and the models with the percentage of incorrect days being generally less than 20% for the majority of the domain. The exception is in the regions of higher elevation and most notably over the Cascades and the Sierra Nevada mountains for all models. In general, the Noah model tends to have the most incorrect days and the SAC model the least.

4.3. Distribution of Snow Cover Extent with Elevation

Elevation is one of the key factors in governing cold season processes in mid-latitude regions due to its relationship with temperature. This controls the partitioning of precipitation into snowfall and rainfall and is a limiting factor in the melting of the snow pack in the spring. Figure 8 shows the histograms of elevation distribution for each RFC region using 200m elevation intervals. The four western RFC regions (Northwest, Missouri, California/Nevada and Colorado) have a wide elevation range, indicating that topography may play an important role in cold season processes.

Figure 9 shows i) the mean and ii) the standard deviation of snow cover extent as a fraction of the total area over each elevation interval for the RFC regions during the winter/spring period (Dec-May). All model predictions show reasonable agreement with the mean observed data in terms of the shape of the histograms. Again it can be seen that the VIC model tends to over-estimate snow cover, especially in mountainous regions. The Noah model tends to under-estimate snow cover extent at all elevations except in the eastern regions (Northeast, Mid Atlantic and Ohio) where it does reasonably well. The opposite is true for the MOSAIC model which tends to match the observed data less well in eastern regions and better in the western regions, although here it tends to underestimate the lower elevation snow cover extent and over-estimate at higher elevations. Most noticeable is the good agreement with observations for the SAC model with the sole exception of the California/Nevada region where there is a somewhat spurious drop in the observed snow cover percentage at very high elevations. This may be due to the lower spatial resolution of the IMS observations which may limit the accuracy to which it can represent the small number of high elevation pixels that exist in this region (see elevation distribution, Figure 8)

The plots of standard deviation indicate the variability of snow cover at different elevations. For flatter regions observed variability increases with elevation and all models reproduce this well, although the MOSAIC model tends to under-estimate the variability in the Middle Atlantic and Ohio regions. All models do less well in representing the variability in the mountainous regions of the western USA, especially at higher elevations.

5. Discussion

5.1 General

All models do reasonably well in simulating the seasonal cycle of mean snow cover extent over the 8 RFC regions. The spread between model simulations is fairly low and generally encompasses the observed data. The differences between model simulations may be attributed, to some extent, to model specific parameterizations of snow cover extent. The VIC model tends to over-predict snow cover extent and this may be due to its parameterization of snow cover as only fully covered or snow free within a sub-grid tile. Although the sub-grid tiling in the VIC model translates into a fractional coverage at the grid scale, the coverage within each tile is biased towards full coverage. This will in turn bias the full pixel scale value towards presence of snow. In addition, the VIC model uses sub-grid elevation banding, which through temperature lapsing and lower temperatures at the higher elevation bands, increases the probability of the existence of snow cover within the grid as a whole. Despite the relative simplicity of the representation of snow processes in the SAC model, its predictions appear to perform just as well, if not better, than the other models when compared at these large regional scales. By forcing a simple snow model with only the primary controlling factors on snow pack development (e.g. air temperature), the SAC model may actually be able to capture the major dynamics of the snow pack whilst avoiding the propagation of errors that may occur in a fully coupled energy and water balance scheme.

It appears that all models do less well over the mountainous regions to the northwest of the United States. This is to be expected due to the inherent difficulties in modeling snow processes over variable topography where meteorological variables such as precipitation, air temperature and downward solar radiation are more variable and any errors in these input forcings may be higher due to the sparsity of observational data over these regions. A comparison of NLDAS forcing data with station measurements in high elevation western regions of the United States is presented in the second part of this paper [*Pan et al.*, this issue]. The results of this show a reasonable agreement for air temperature but large differences in precipitation. Such biases in the precipitation forcing data may account for some of the differences seen between the observed data and the model predictions.

The pixel-by-pixel comparison of model predicted snow cover extent and observation data indicate reasonable skill by the models to reproduce the spatial pattern of snow over large regions. Although there are periods when the number of matching pixels drops below 50% for any model, the average wintertime value is in the region of 75%. The cumulative snow maps are consistent with the mean regional time series and pixel-by-pixel comparisons, reflecting the general underestimation of the Noah model and the overestimation of the VIC model, with the other two models falling somewhere in between.

5.2. Spatial and Temporal Scales of Comparison

For meaningful conclusions to be drawn about the validity of the model simulations, the reliability of the observational data with which it is compared must be sufficient in terms of the length of record, the spatial and temporal resolution and the level of error in the data. The IMS dataset provides daily observations of snow cover extent which have sufficiently high temporal resolution to evaluate model predictions given the relatively low variability of snow cover over daily scales.

The IMS dataset is essentially binary data, i.e. snow is either present or absent at the pixel scale. Satellite sensors can only report the pixel-averaged surface radiative emissions, which means that the value for snow cover (fully covered or snow free) obtained from the retrieval algorithms will be a compromise. For example, a pixel may in reality have only 20% snow cover but may be classified as fully snow covered in the final product. This may be inconsistent with the model predictions, which through parameterizations of snow cover extent and sub-grid variability in vegetation cover and elevation may have quite variable total fractional snow cover at the full pixel scale. Thus the threshold value of model predicted fractional snow cover used in classifying pixels as snow covered or not snow covered has an important effect on the comparisons. Setting the threshold value too high may lead to the number of model predicted snow covered pixels being set too low and conversely, biased too high when a low threshold is used. In addition, given the differences in parameterizations of snow cover extent between models, a specific threshold value may give better results for some models and not for others and this may vary according to the region of comparison. The threshold value chosen in this study (0.1) was set low so as to encompass the majority of pixels that were predicted to have snow coverage. In this way a model is not penalized for modeling the sub-grid variability of snow processes that may result in small concentrated areas of snow cover within the whole grid. In addition to a number of satellite and ancillary data sources, the IMS also includes the use of human operators, which may result in a certain level of subjectiveness in the classification process. Therefore, it is difficult to ascertain what the standard threshold level should be in relation to the observational data.

The spatial resolution of the IMS dataset (~25km) is lower than the model data (~12km) but the low spatial variability of snow cover means that the effect of disaggregating the observed data to the modeled resolution will be small over large regions of continuous snow cover. Any detrimental effects are likely to be seen at the snow line and in regions of high topographic variability where the snow line may be more dynamic and spatially variable.

5.3. Effect of Elevation

The analysis of snow cover extent with respect to elevation indicates a generally good agreement between the model predictions and the observed data, although there appears to be systematic biases in some of the models. Differences are also seen in how well the models perform between the western and eastern regions. This may be due in part to regional differences in which cold season processes are dominant and the varying ability of models to simulate these processes. For example, in mountainous regions where the cold season weather may be dominated by low temperatures and heavy snowfalls and thus large snow packs, certain models may fair better than others at simulating the long-term development and decay of deep snow packs. Conversely, the parameterizations used in other models may be more suitable over the flatter areas of the Midwest and east, where pack depths may be lower and the freeze/melt process is more dynamic. Further analysis is required to determine the exact nature of the differences exhibited by the models and whether these differences depend on the type of cold season process that is dominant in a certain region.

All models generally perform worse at higher elevations and this is likely due in part to the difficulties in specifying the meteorological forcings correctly at high elevations and over complex terrain. The large differences in precipitation between the NLDAS forcing and station measurements as described in the second part of this paper [*Pan et al.*, this issue] may account for some of the differences seen at these higher elevations but the number of pixels at these elevations is relatively small and so the effect on the regional mean is not significant.

5.4. Inter-Model Differences in Simulated Snow Cover Extent

The differences between model predictions are clearly apparent and are consistent in all the analysis presented so far. Although these differences may be due to model specific parameterizations of SCE and representations of sub-grid variability of vegetation and elevation, more detailed analysis of the modeled cold season processes are required to gain insight into the reasons for these differences. To this end, Figure 10 shows mean monthly time series of snowmelt, snow sublimation, surface albedo and surface temperature averaged over the Northwest RFC for the four models (SAC does not calculate sublimation or surface temperature and does not use albedo in its snow model). This region showed some of the largest differences between model predictions. The recent PILPS Phase 2 high latitude modeling experiments [*Slater et al.*, 2001; Nijssen et al., Simulation of high latitude hydrological processes in the Torne-Kalix basin: PILPS Phase 2(e). 2: Comparison of model results with observations, submitted to Global and Planetary Change, 2002) found large differences in snow ablation and snowmelt among 21 LSMs and concluded that the differences in model parameterizations of albedo and snow cover had a large effect on available energy to the snow pack.

Figure 10 clearly illustrates that the Noah model simulates significantly higher wintertime snowmelt and sublimation than the other models. During the late spring, the snowmelt and sublimation reduce to almost zero as much of the snow pack has already melted. This reflects the behavior seen in the regionally averaged time series in Figure 4 where the Noah predicted snow cover extent tends to disappear early. SAC and MOSAIC tend to have higher melt in the spring than the winter months whilst VIC melts at a more constant rate throughout the winter and spring and has virtually zero sublimation in the second year.

The Noah model simulated albedo values shown in Figure 10 are consistently lower than the other two models. Lower albedo values will lead to greater absorption of downward solar radiation by the snow pack and thus more available energy for snowmelt. Conversely, the VIC model tends to have relatively higher albedo values and this is reflected in the overestimates of snow cover extent seen previously. The effect of lower albedo on the energy balance of the snow pack may be reinforced as reduced snow cover within a grid may lead to further reductions in the albedo value and thus further melting. In addition, the calculated albedo for the Noah model represents a grid mean value and not just a value for the snow covered fraction. Therefore, when the snow covered fraction within a grid is less than 100%, the albedo used may be unrepresentative of the snow pack, as it also represents vegetation and bare soil which generally have lower albedo values.

6. Conclusions

Simulations of snow cover extent from the four land surface models within the NLDAS were compared with observational data from the IMS over a 3 year retrospective period over the continental United States. In general, all models do reasonably well in simulating the regional scale spatial and seasonal dynamics of snow cover. Systematic biases are seen in the model predictions with certain models consistently under- or over-estimating snow cover extent, although the level of bias is dependent on geographic location and elevation variability. Larger discrepancies are seen over higher elevation regions that may be due in part to errors in the meteorological forcings and also at the snow line boundary where most temporal and spatial variability in snow cover extent is likely to occur. However, the spread amongst model simulations is fairly low and generally envelopes the observed data at the mean regional scale, indicating that the models are quite capable of simulating the general behavior of snow processes at these scales. Although inter-model differences can be explained to some extent by differences in the model representations of sub-grid variability and parameterizations of snow cover extent, further analysis is required to understand where and why the differences between models are occurring and why certain models perform better than others under different conditions. In addition, errors in meteorological forcings may have a significant effect on the performance of the models and further validation of these data is needed.

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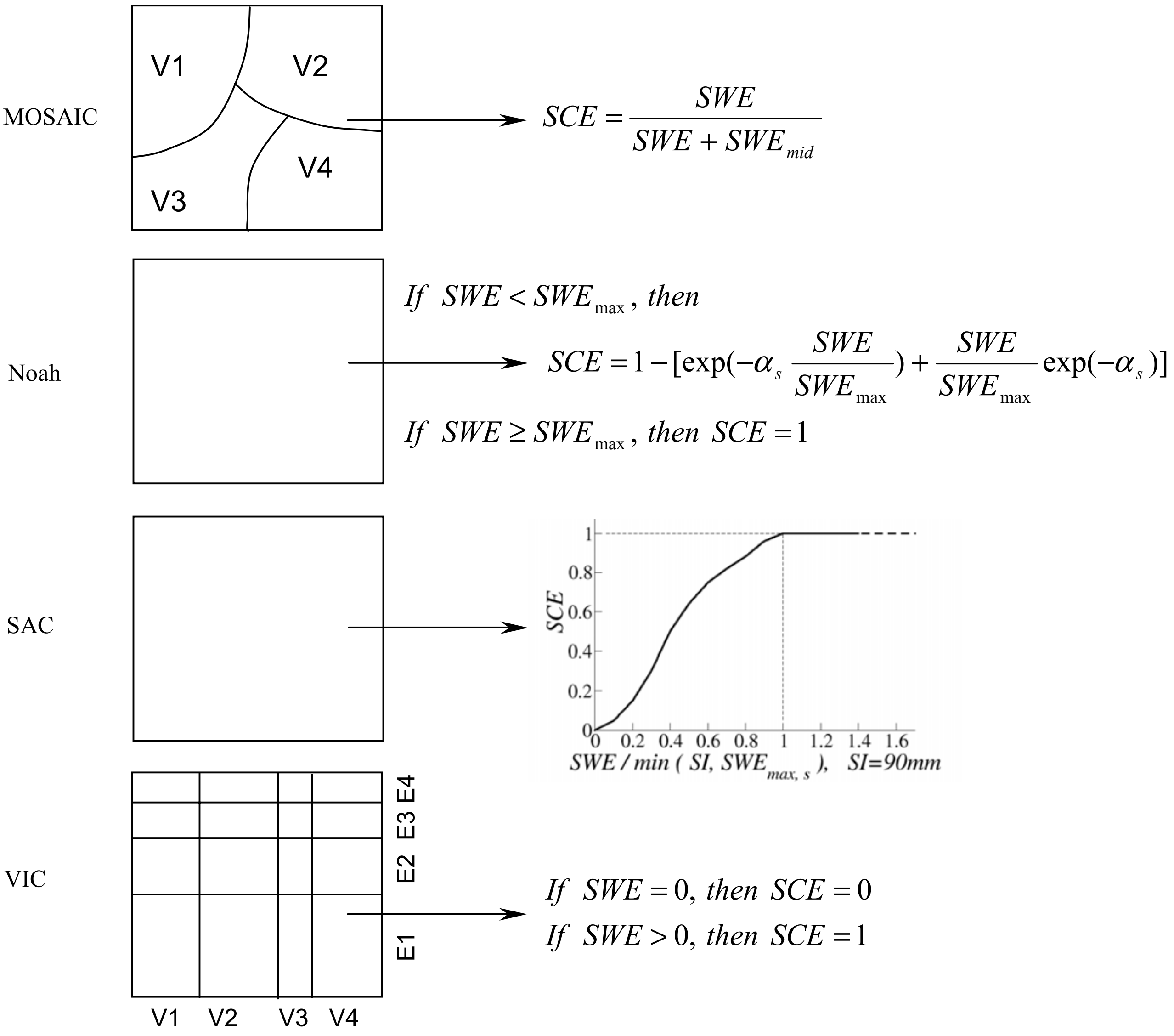

$$SCE = \frac{SWE}{SWE + SWE_{mid}}$$

$$If \;\; SWE < SWE_{\max}, \; then$$

$$SCE = 1 - [\exp(-\alpha_s \frac{SWE}{SWE_{\max}}) + \frac{SWE}{SWE_{\max}} \exp(-\alpha_s)]$$

$$If \;\; SWE \geq SWE_{\max}, \; then \;\; SCE = 1$$

$$If \;\; SWE = 0, \; then \;\; SCE = 0$$

$$If \;\; SWE > 0, \; then \;\; SCE = 1$$

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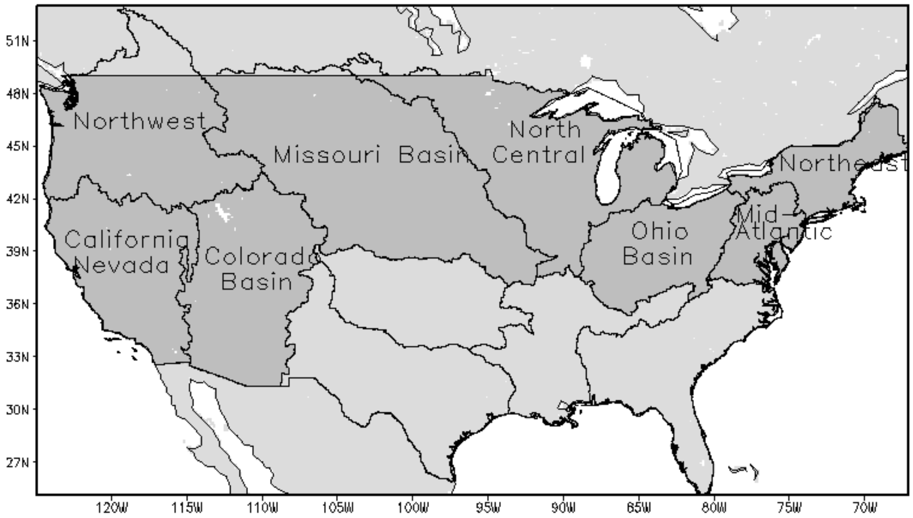

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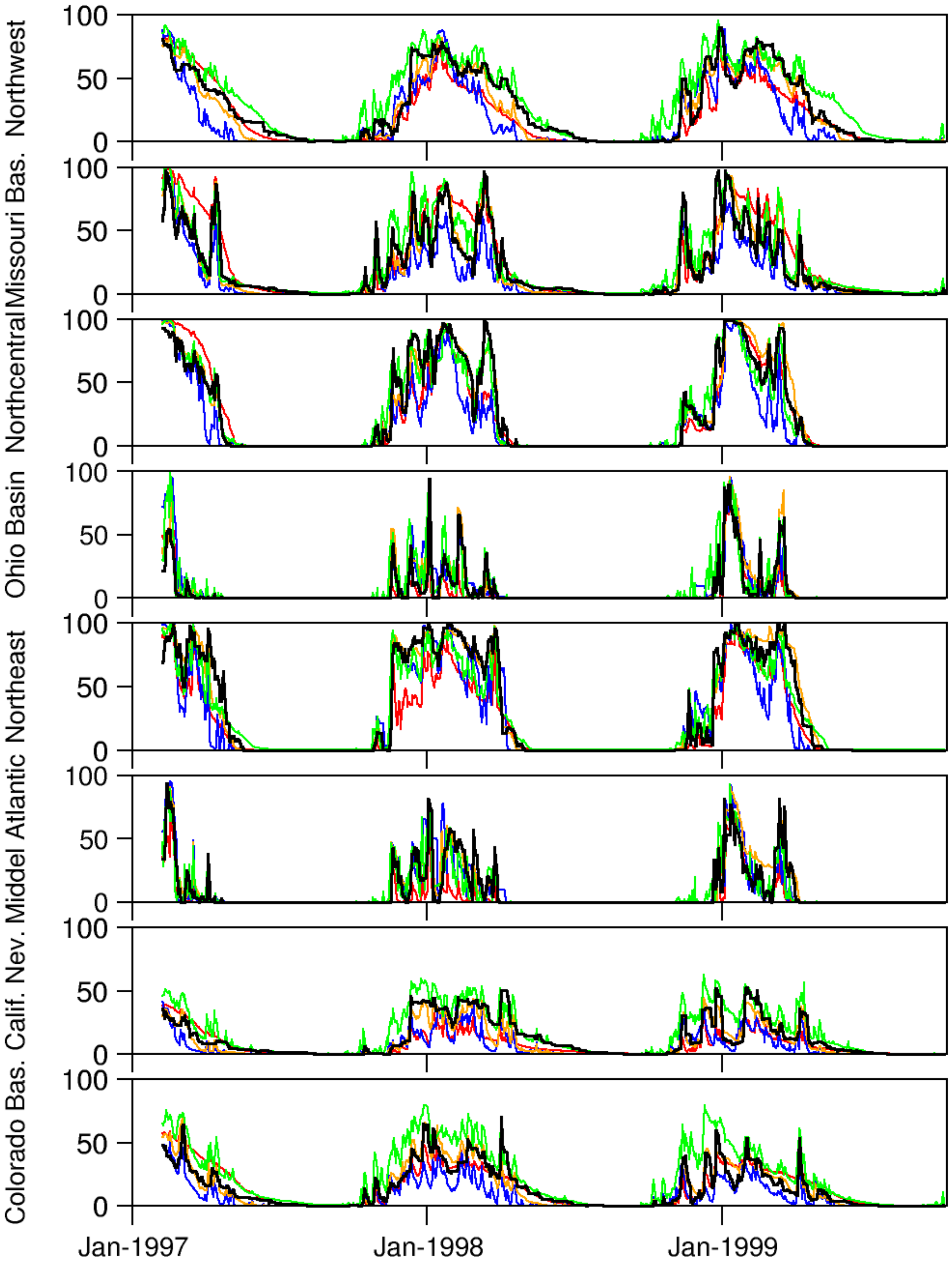

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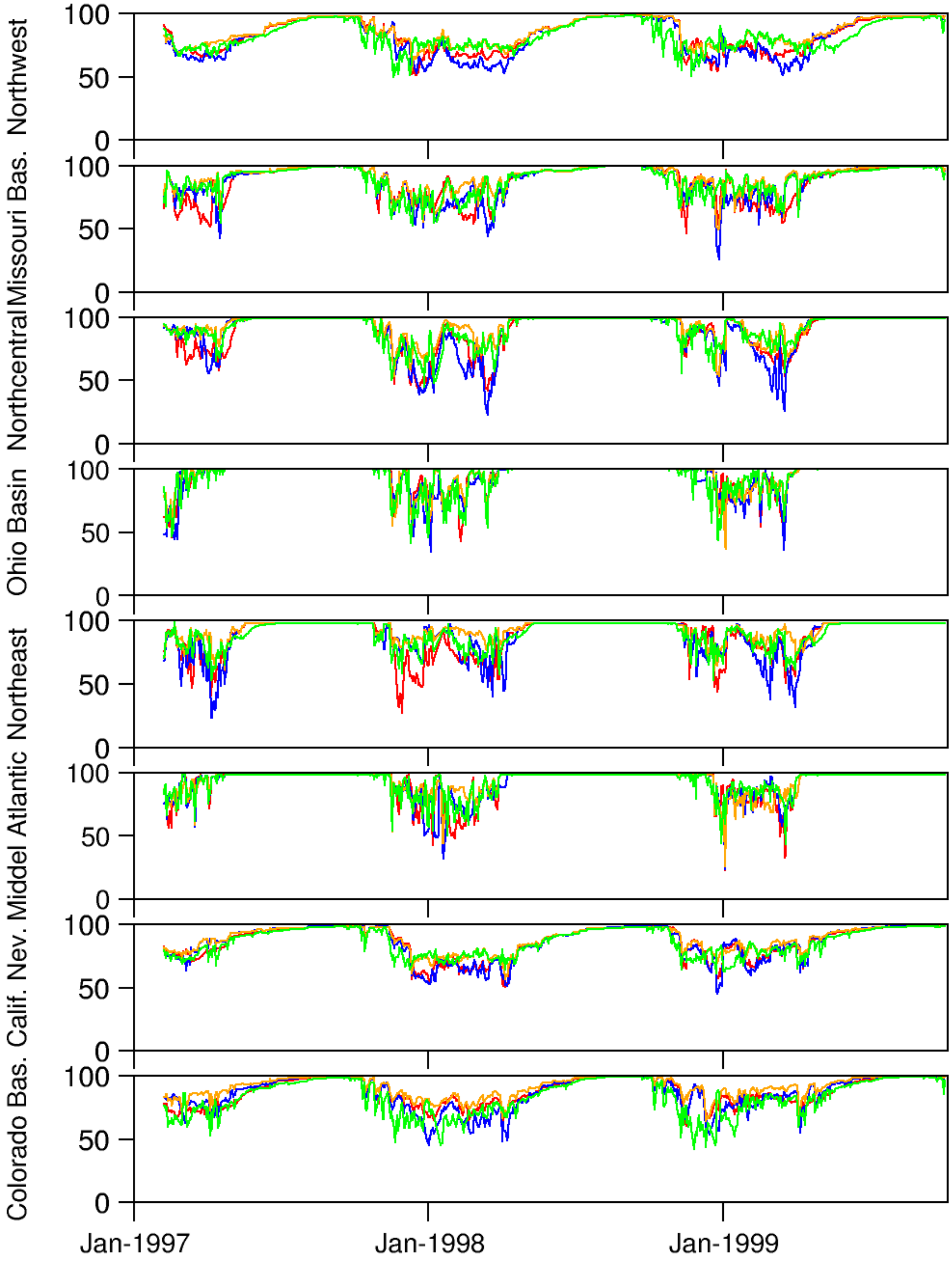

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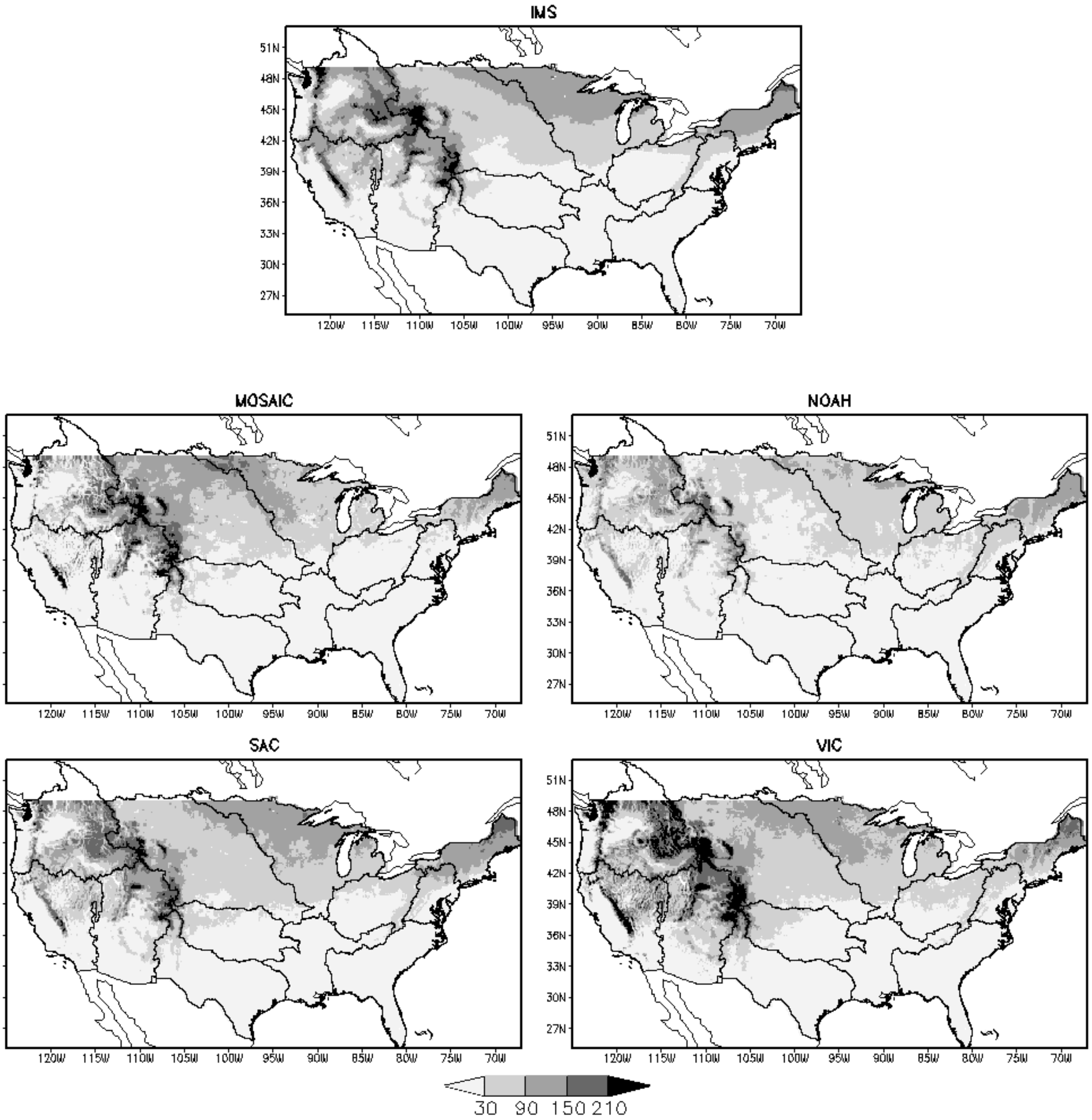

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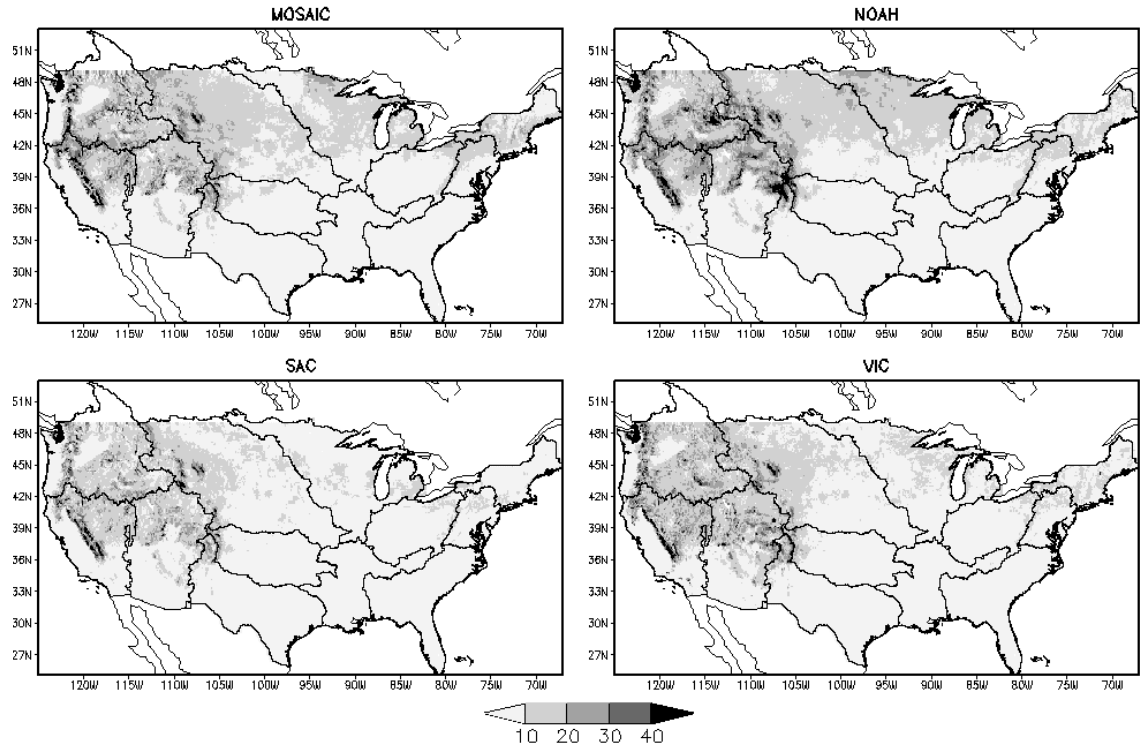

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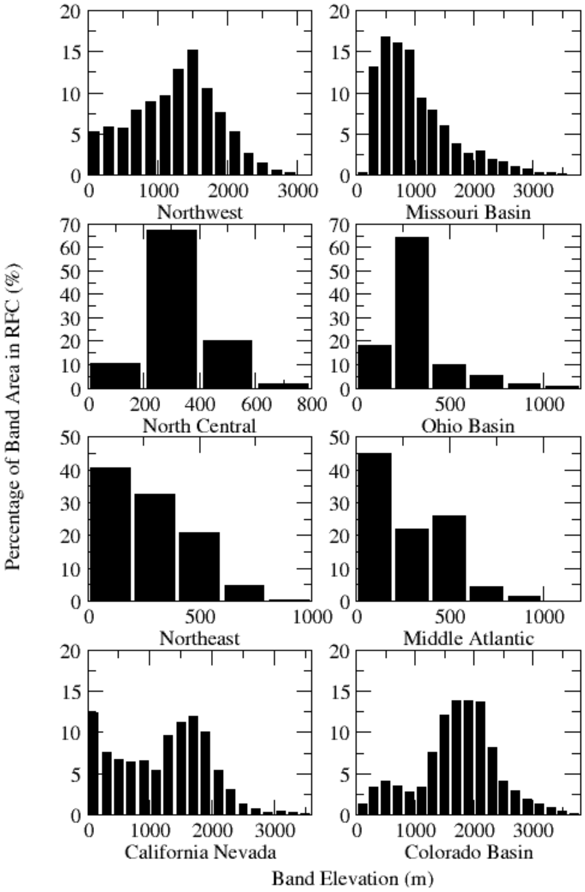

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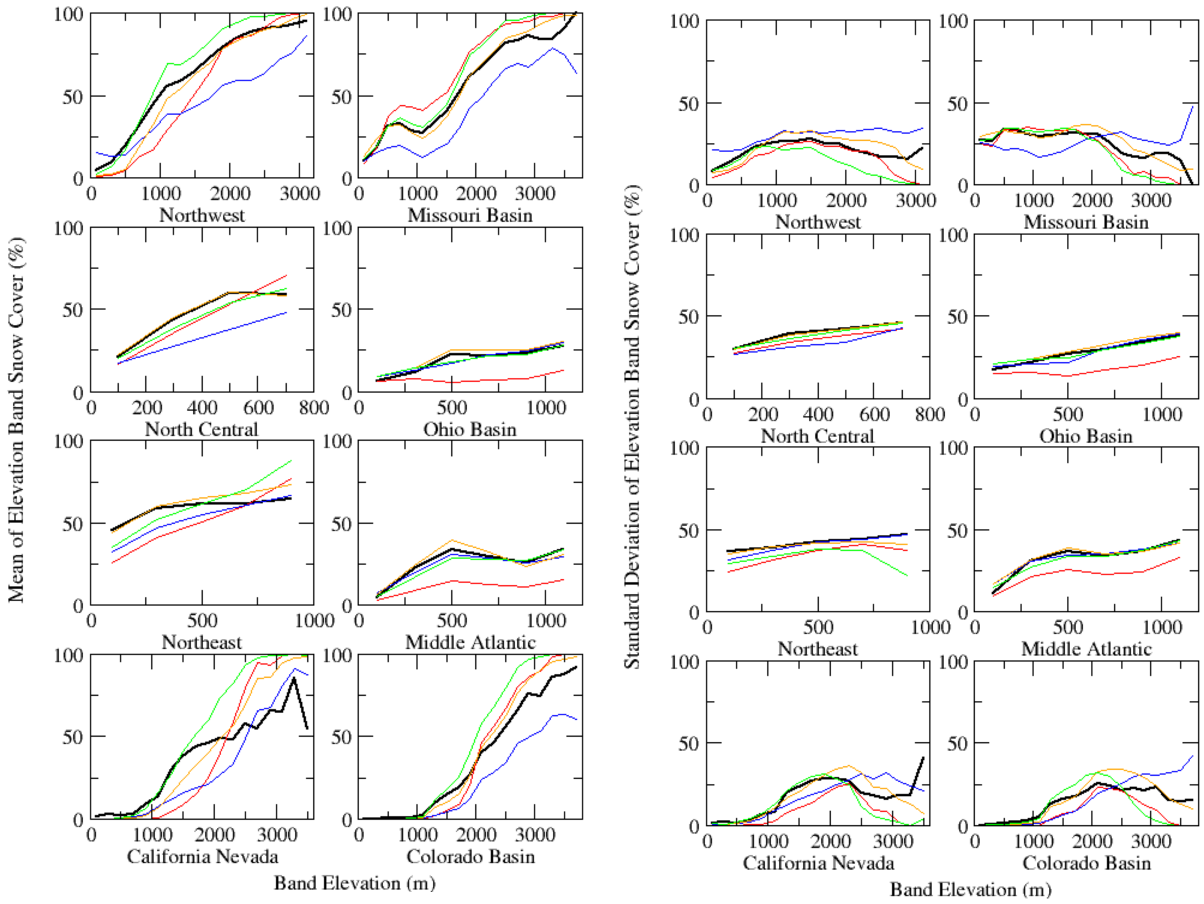

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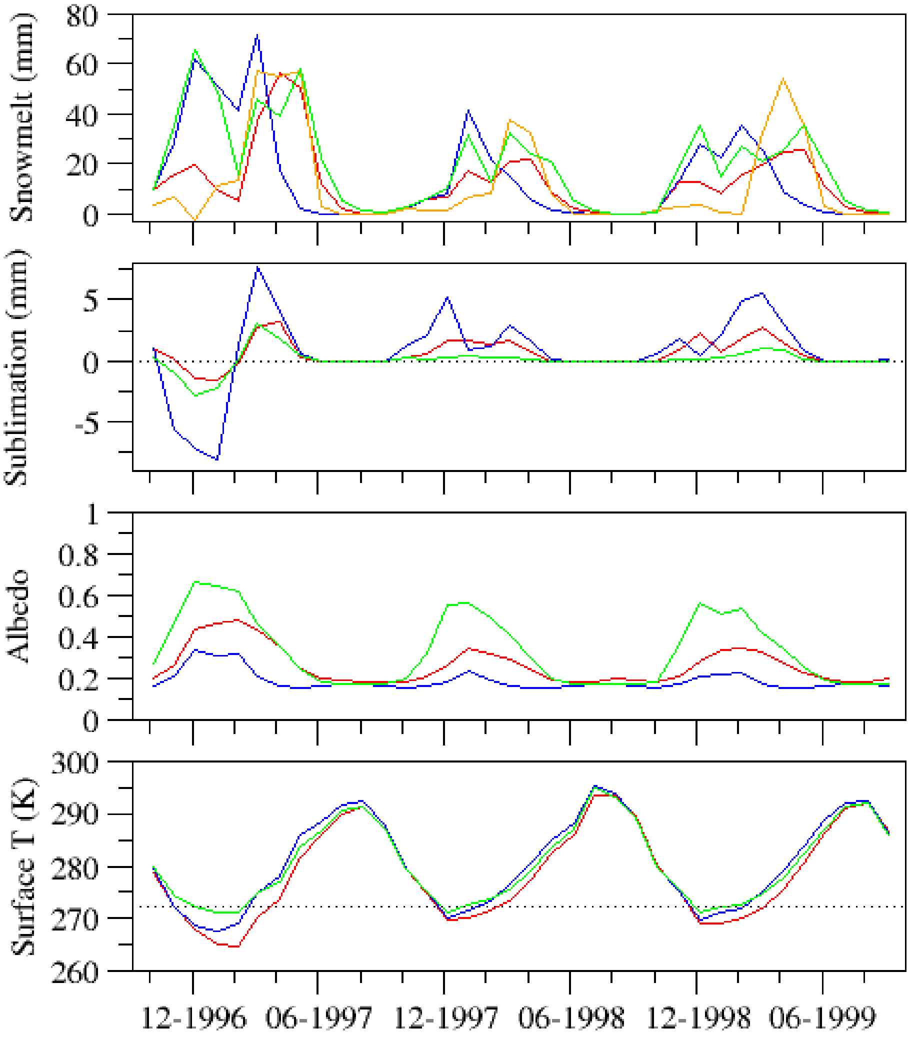

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