Snow Process Modeling in the North American Land Data Assimilation System (NLDAS). Part II: Evaluation of Model Simulated Snow Water Equivalent

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Abstract

This is the second part of a study on the cold season process modeling in the North American Land Data Assimilation System (NLDAS). The first part concentrates on the assessment of model simulated snow cover extent. In this second part, the focus is on the evaluation of simulated snow water equivalent (SWE) from the four land surface models (Noah, MOSIAC, SAC and VIC) in the NLDAS. Comparisons are made with observational data from the Natural Resources Conservation Service's SNOTEL network for a 3-year retrospective period at selected sites in the mountainous regions of the western United States. All models show systematic low bias in the maximum annual simulated SWE that is most notable in the Cascade and Sierra Nevada regions where differences can approach 1000mm. Comparison of NLDAS precipitation forcing with SNOTEL measurements revealed a large bias in the NLDAS annual precipitation which may be lower than the SNOTEL record by up to 2000mm at certain stations. Experiments with the VIC model indicated that most of the bias in SWE is removed by scaling the precipitation by a regional factor based on the regression of the NLDAS and SNOTEL precipitation. Individual station errors may be reduced further still using precipitation scaled to the local station SNOTEL record. Furthermore, the NLDAS air temperature is shown to be generally colder in winter months and biased warmer in spring and summer when compared to the SNOTEL record, although the level of bias is regionally dependent. Detailed analysis at a selected station indicate that errors in the air temperature forcing may cause the partitioning of precipitation into snowfall and rainfall by the models to be incorrect and thus may explain some of the remaining errors in the simulated SWE.

1. Introduction

The terrestrial hydrologic system has two types of state variables; one related to temperature (skin, ground and snow temperatures) and one related to moisture (soil or snow water). The ability of land surface models to accurately determine these state variables is critical for their ability to provide information to atmospheric weather prediction models [*Groisman et al.*, 1994a; *Entekhabi et al.*, 1996]. For coupled models, these state variables are prognostic but within a land data assimilation system they would be variables assimilated by a numerical weather prediction system. Within the North American Land Data Assimilation System (NLDAS) [*Mitchell et al.*, 1999, 2000, this issue], predictions of land surface moisture and temperature states could be used to improve forecasts from weather prediction models [*Mitchell et al.*, this issue]. Cold season processes play a major role in defining these land surface states, being the dominant regime over much of North America during the winter and spring periods [*Groisman et al.*, 1994b, *Brown*, 2000]. Through the storage of moisture and influence on incoming energy fluxes, snow and ice are not only important in determining current hydrological conditions but also in shaping future states via snow accumulation and spring melt [*Yeh et al.*, 1983; *Namias*, 1985]. The subsequent effects on flooding and water resources are of considerable interest to the social and agricultural communities.

This paper is the second part of two-part study on the modeling of cold season processes within the NLDAS project. The first part focuses on the evaluation of model simulated snow cover extent [*Sheffield et al.*, this issue]. This second part concentrates on the validation of model-derived snow water equivalent (SWE). Snow water equivalent is defined as the depth of water that would be obtained if a column of snow were completely melted. It quantifies the amount of frozen moisture storage and determines the amount of spring melt and subsequent flooding. The NLDAS project has completed a 3-year, retrospective simulation over the conterminous United States using the four participating LSMs - MOSAIC [*Koster, et al.*, 1996], Noah [*Betts et al.*, 1997; *Chen et al.*, 1996, 1997; *Koren et al.*, 1999], SAC [*Burnash et al.*, 1973; *Burnash* 1995], and VIC [*Liang et al.*, 1994, 1996, 1999; *Cherkauer and Lettenmiaer*, 1999]. Modeled snow water equivalent from these simulations is compared with measurements from the SNOTEL station based observing system [*Crook*, 1977; *Serreze et al.*, 1999] and the reasons for the differences are discussed.

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 effects 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. In the case of rainfall falling on snow, the snowmelt rate in SAC is controlled by heat exchange between the liquid water and the snow pack. The Noah, SAC and VIC models all include liquid water content in the snow pack but the MOSAIC model routes rainfall falling onto a snow pack directly to the soil surface for subsequent infiltration or runoff [*Koster et al.*, 1996]. Details of the model parameterizations of snow cover extent are given in part one of this study [*Sheffield et al.*, this issue].

2. Data

2.1. SWE Measurements

Available validation data for snow water equivalent is limited in terms of the length of record and area of coverage. In comparison to snow cover extent (SCE), which is generally measured at large scales via satellite remote sensing techniques, for example the IMS [*Ramsay*, 1998] and MODIS [*Hall et al.*, 2002] products, SWE is relatively difficult to retrieve, especially from satellite imagery. The NWS National Operational Hydrologic Remote Sensing Center (NOHRSC) provide daily maps of snow cover, derived from the NOAA GOES and AVHRR satellites, for the conterminous United States and Alaska [*Hartman et al.*, 1995]. As part of their remote sensing analysis, the NOHRSC product also includes rough estimates of snow water equivalent based on ground and airborne observations combined with snow cover information from the satellite maps [*Carroll et al.*, 1999]. In addition, estimates of SWE based solely on airborne gamma survey have been available for since 1980 [*Carroll and Carroll*, 1989], but the spatial coverage of airborne flight lines are limited and change from time to time.

The lack of reliable, large-scale measurements of SWE, especially in mountainous regions that are most important for flood and water supply information, hampers an evaluation of modeled estimates. As a result, this paper uses point observations based on the Natural Resources Conservation Service's (NRCS) SNOTEL network (see http://www.wcc.nrcs.usda.gov/snotel/SNOTEL_Info/snotel_info.html). Data from ground-based point observations are a good choice for model validation if the number of observing points is large and if the stations are well spread geographically. SNOTEL has been successfully used for large scale analysis of snow pack estimation and water supplies [*Crook*, 1977; *Serreze et al.*, 1999]. The SNOTEL network, which has been in operation since 1980 and is operated by NRCS's Western Regional Climate Center (WRCC), provides measurements of SWE and basic meteorology using a pressure sensing snow pillow, a storage precipitation gage and air temperature sensor. Data are recorded every 15 minutes and reported daily. Currently there are approximately 600 stations across the western U.S. and Alaska. In this study we use the SNOTEL daily observations for SWE, air temperature and precipitation.

The geographic region for the comparison between the SNOTEL station observations and the NLDAS model predictions is west of -104^{o} longitude, which includes the Rockies, Cascades, and the Sierra Nevada mountains. In this region there area a total of 560 SNOTEL stations with good quality records which are well distributed throughout this area. The majority of the stations are at elevations above 1000m, with the mean elevation around 2500m and a mean annual temperature of about 4˚C. The high elevation locations of the SNOTEL stations provide a good opportunity to evaluate the cold season parameterizations of the NLDAS LSMs.

The NLDAS models use a 1/8 degree (approximately 12km) computational grid and so how representative the SNOTEL site is of the grid average is somewhat questionable, especially in relation to elevation and temperature effects. Comparison of the elevation of SNOTEL stations with that at the equivalent grid box (not shown) indicate no systematic bias but significant differences at a number of individual locations. Therefore it was decided to screen from the comparisons all SNOTEL stations where the absolute difference in elevation was greater than 50m. This resulted in 110 SNOTEL stations remaining.

2.2. 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 water equivalent 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. Analysis

3.1. Comparison of Model Simulated and SNOTEL Measured SWE

Figure 1 shows the mean annual maximum SWE for the model simulations and the SNOTEL measurements for the 110 stations remaining after elevation screening. It can be seen that all models underestimate maximum SWE over all regions. The bias is most prominent over the Sierra Nevada and the Cascade Mountains where differences between model simulations and observed data approach 1000mm. The differences generally reduce as we move eastwards into the Rocky Mountains where a few stations on the eastern edge are within 100mm of the observations. Figure 2 depicts the same information as a scatter plot for the four models, which highlights the consistent low bias in all the models. It should also be noted that the largest discrepancies are in the Cascades (diamond symbols) and in the Sierra Nevada mountains (square symbols), although the bias in this latter region is less obvious because of the smaller amounts of accumulated snow.

3.2. Comparison of NLDAS and SNOTEL Precipitation

The low bias in the predicted mean annual maximum SWE is most likely explained by either deficiencies in the model physics or errors in the input meteorological forcings, although there may be other contributing factors. Figures 3 and 4 compare the mean annual precipitation from the NLDAS with the measurements at the 110 SNOTEL stations. It can be seen that the

NLDAS precipitation data are consistently low for all stations. One should also note that the stations with the highest precipitation and the largest bias are those in the Cascade Mountains and those with the lowest bias are located on the eastern edge of the Northern Rockies.

The differences in precipitation are consistent with the differences seen in the model simulated SWE (Figures 1 and 2) in which all models under predict the annual maximum SWE. Errors in the precipitation may therefore explain some of the errors in the model simulation. To test this, the VIC model was run for the 110 stations using precipitation forcing scaled by a regional factor based on the regression fit of the NLDAS and SNOTEL mean annual precipitation (Figure 4). The regression between the local SNOTEL precipitation and the NLDAS precipitation yields the following relationship:

$$P_{SNOTEL} = 2.1693\ P_{NLDAS} \qquad (1)$$

with an R^2 value of 0.64. This relationship provides an indication of the average under-estimation of mountainous precipitation by the NLDAS. As explained in *Mitchell et al.* [this issue], NLDAS precipitation amounts are based on NWS precipitation gauges, and it is well known that gauges located in valleys underestimate higher elevation precipitation [*Schultz et al.*, 2002].

The VIC model simulated annual maximum SWE using the adjusted precipitation is shown in figure 5. The low bias has been removed with the values now clustered around the 1:1 regression line, although the level of scatter in the values remains. This is to be expected as the precipitation scaling is carried out on a regional basis and so individual stations may still be biased. To address this, a second experiment was carried out in which the VIC model was forced with locally adjusted precipitation such that the NLDAS precipitation at each station was scaled so that the annual total matched that of the SNOTEL measured record. The resulting simulated SWE is shown as a scatter plot in Figure 6 (the label for "Lone Pine" is referred to in section 3.4). Note that the bias is still low but the scatter has been reduced significantly as shown by the improved R^2 of 0.82. The few stations that still show significant errors are all from the Cascades region.

3.3. Comparison of NLDAS and SNOTEL Air Temperature

Despite the improved model predictions using the corrected precipitation, differences still remain between the model predicted and measured SWE data. In addition to precipitation, air temperature also has a large influence on the dynamics of the snow pack and thus errors in the given NLDAS air temperature may explain some of the remaining errors in the simulated SWE. An analysis of the difference in mean annual air temperature between the NLDAS and the SNOTEL is shown in Figures 7 and 8. These indicate biases of less than $1^{o}C$ in the mean annual temperature, with the NLDAS temperature being too cold in the Rockies and being warmer but essentially unbiased in the Cascades and Sierra Nevada regions.

The differences in mean temperature as shown in Figure 8 indicate that the bias is constant with elevation. This suggests that the elevation lapse rate of the NLDAS system, as the analysis fields are downscaled to 1/8 degree computational grid are, on average, correct [*Cosgrove et al.*, this issue]. Average monthly temperatures for all stations and variability amongst stations are show in Figure 9. It is quite apparent that, in general, the NLDAS temperature is biased colder in winter months and biased warmer in spring and summer. The level of average bias and variability amongst individual stations is regionally dependent however. In the Cascades the variability is quite large but is negligible in the Sierra Nevada, although this is based on a small number of stations. In the Rockies, the variability appears to be relatively less than that found in the Cascades although the maximum bias can reach as much as 6°C colder during the winter.

The biases seen in the temperature comparisons, which although in general are relatively small compared with those seen in the precipitation analysis, are still of the order of 2°C colder during the winter and 1°C warmer in the spring in the Rockies, for example, and may have a significant impact on the temporal evolution of the snow pack. This may be especially true at specific sites where average winter and spring temperatures may be biased from 3 to 6°C. The effect that these biases have on the snow pack and the SWE depends on the timing of the switch between cold and warm bias and the number of days on which the NLDAS temperatures and the SNOTEL measurements are of opposite sign, in the sense that one is below freezing while the other is above freezing. This would have implications on the partitioning of precipitation into snowfall and rainfall by the models and subsequent effects on the accumulation and melt of the snow pack.

Figure 10 shows a scatter plot of the first day of snow and last day of snow plotted as the difference between the model simulation and the SNOTEL measurements. The first day of snow was chosen to be the day at which the SWE first exceeds 10mm to avoid days with missing data in the SNOTEL record in the early part of the cold season and those days when model simulated SWE periodically melts and reappears due to fluctuations around freezing temperatures. It can be seen that all models simulate the onset of snow accumulation later than the measured data. The consistency between models is to be expected as they are all forced by the same precipitation and air temperature and employ the same temperature criteria for partitioning the precipitation into snowfall and rainfall. Small differences between the models are due to how the models handle the accumulation/melt process and the effect of temperature lapsing over sub-grid elevation banding in the VIC model. In terms of the last day of snow, the Noah and SAC models tend to under-estimate the last day of snow and are thus melting the snow pack too early. The same is true of the MOSAIC model but to a lesser extent. Noah tends to have shorter snow period (later start and earlier end), and this is consistent with the lower maximum SWE for the Noah model that was indicated previously. Some of the errors may be due, in part, to the location of SNOTEL stations which are generally found in clearings in which the ground snow pack is much easier to initiate at small snow events than under heavy vegetation covers.

3.4. Detailed Comparison at a Selected Site

The previous analysis indicated large biases in the model simulated annual maximum SWE and showed that these biases can be explained largely by errors in the NLDAS precipitation forcing. Furthermore, seasonal biases in air temperature exist and may in turn account for some of the remaining errors. To understand the seasonal dynamics of the snow pack and how temperature biases may affect its evolution, a single site was selected for detailed analysis. The Lone Pine site (station ID = LPSW1, latitude = 46.267N, longitude = 121.967W, elevation = 1158.24m) was chosen as it had one of the largest errors in maximum SWE of all the stations. It is located in the Cascade Mountains and receives over 5000mm of precipitation of annually during the simulation period. The relatively complex topography and the spatially variable meteorology associated with this terrain ensure that modeling cold season processes in such a region is challenging.

After removing the bias in the precipitation by scaling the model precipitation forcing to match the annual precipitation total at the SNOTEL site, the simulated SWE still showed large errors when compared with the SNOTEL measurements (see Figure 6, Lone Pine lies to the lower right of the cloud of points). Figure 11 shows the 3-year accumulation time series of the several water balance components for the SNOTEL measurements and the VIC model simulation using the locally adjusted precipitation forcing. The underestimation of SWE in the VIC model simulation can be clearly seen. The total precipitation is the sum of the snowfall and rainfall, i.e. the solid and liquid precipitation, and the time series of snowfall and rainfall shown in Figure 11 indicate that the total amount of precipitation is sufficient to produce the measured SWE. This is to be expected as the model precipitation forcing was adjusted to match the measured annual total. As accumulation of SWE is governed by snowfall inputs, it appears that the snowfall component is underestimated, especially in the second and third years. Therefore the underestimation of SWE may be attributed, in part, to the partitioning of precipitation into snowfall and rainfall. All models within the NLDAS use a threshold air temperature of 0°C to partition the precipitation inputs, such that if the air temperature is above this value then the precipitation is considered to be rainfall and conversely, it is considered to be snowfall if the air temperature is below this value. Figure 12 shows the average monthly air temperature bias of the NLDAS compared to the SNOTEL measurements and indicates a consistent positive bias in the NLDAS data that is most prominent in the summer. Figure 13 shows the monthly number of freezing days (below 0°C) and non-freezing days (above 0°C) for the NLDAS air temperature and the SNOTEL measurements. Over the 3-year period the NLDAS data had 241 freezing days compared to the 324 freezing days in the SNOTEL measurement record (43 days on which the SNOTEL record was missing were excluded). By using the model precipitation partitioning scheme, this bias would lead to a general underestimation of snowfall. Furthermore, warm rain falling onto an existing snow pack causes an increase in the rate of snowmelt as more heat energy is available for transfer to the underlying snow pack [*Harr*, 1981; *Kattelmann*, 1987; *Berg et al.*, 1991]. These factors and the direct effect of warm-biased air temperatures, combine to produce an underestimation of SWE.

4. Conclusions

Simulated snow water equivalent from the four models within the NLDAS was compared with measured data from 110 SNOTEL sites situated in the western United States for a 3-year retrospective period. All models showed consistent underestimation of maximum annual SWE that can be explained to a large extent by biases in the prescribed NLDAS precipitation model forcing. Additionally, relatively smaller biases (but potentially significant in terms of cold season processes) were also identified in the air temperature forcing. The smaller number of freezing days in the NLDAS temperature series suggest that the partitioning by the models of precipitation into snowfall and rainfall may result in too much rain falling onto the existing snow pack and causing an overestimation of snow pack melt and thus an underestimation of SWE. These results highlight the problems in determining meteorological variables over mountainous and complex terrain, where small numbers of measurement stations generally located at lower elevations, do not capture the full variability of the meteorology. Further work is required to remove the temperature biases from the model forcings so that model inter-comparisons may reveal more useful information about their ability to represent cold season processes and provide accurate simulations of snow states within data assimilation systems.

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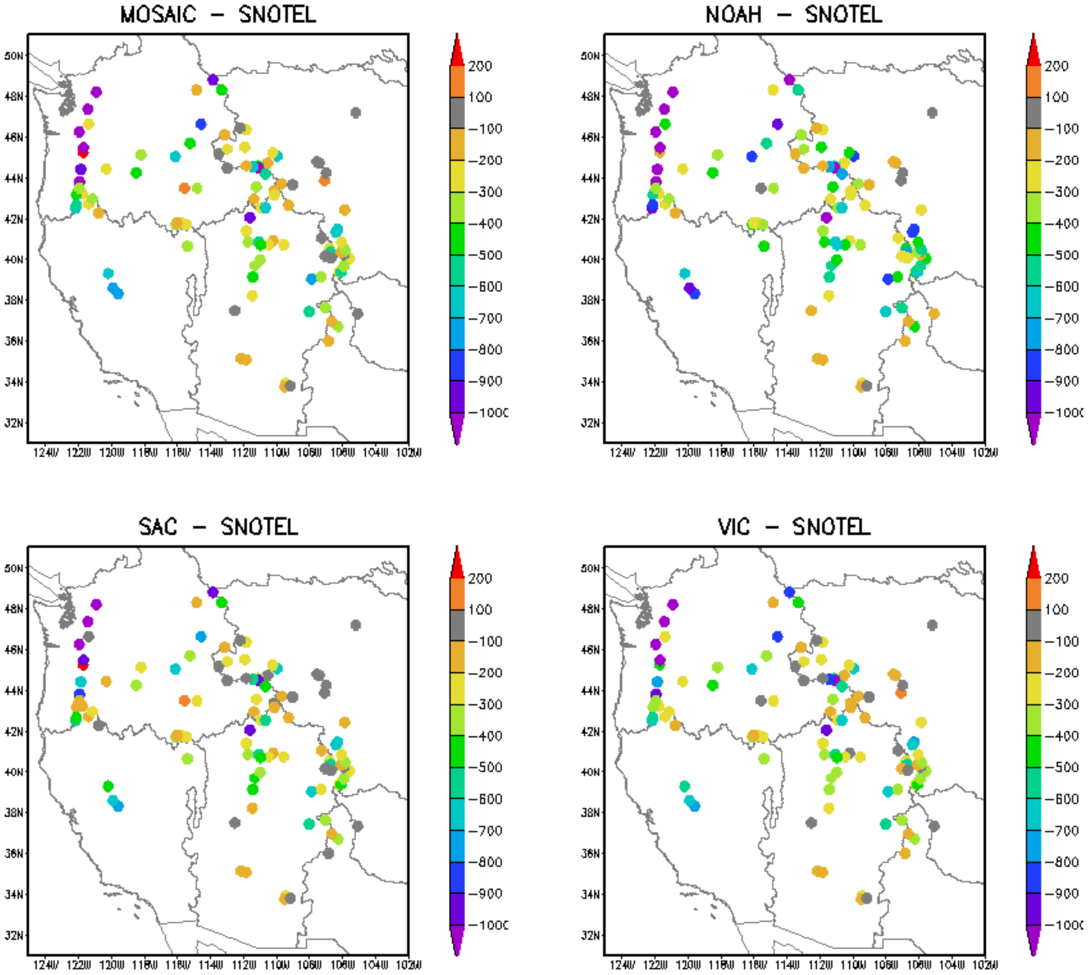

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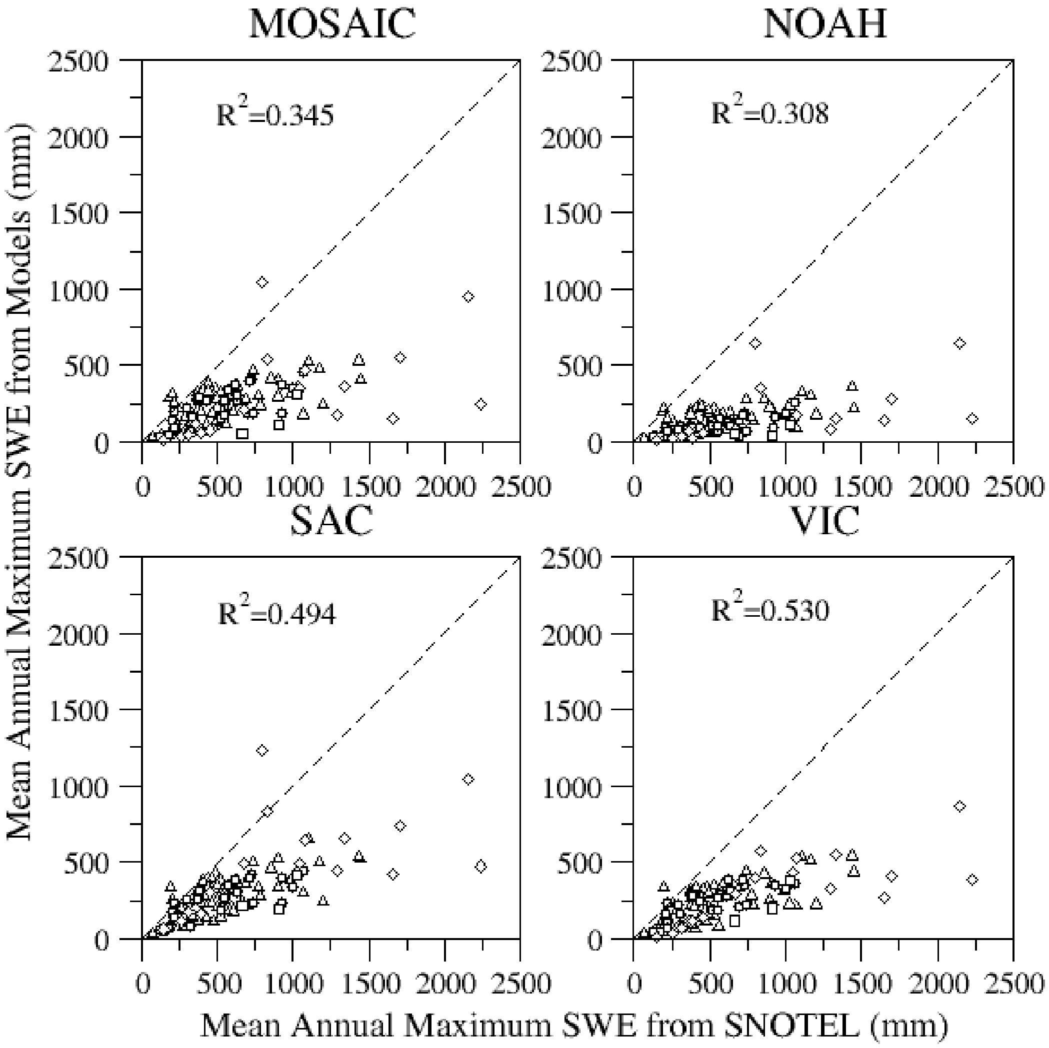

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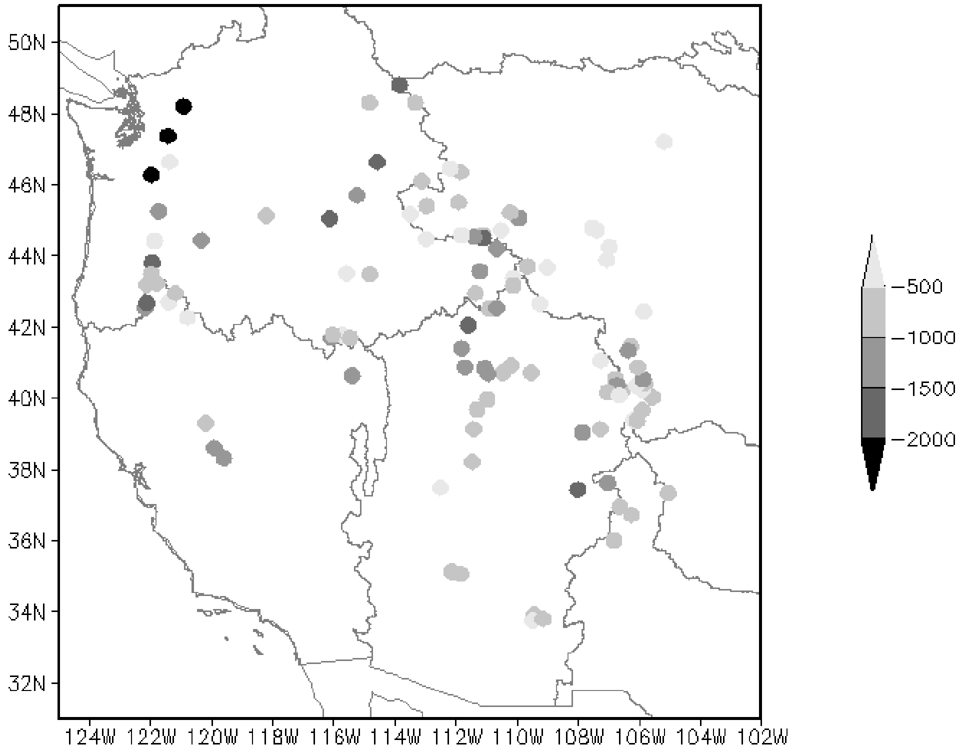

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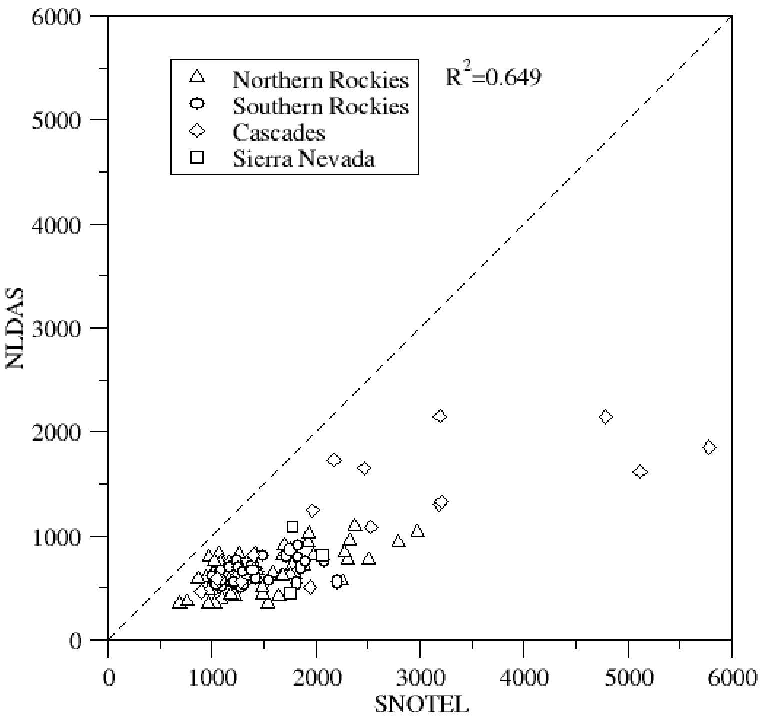

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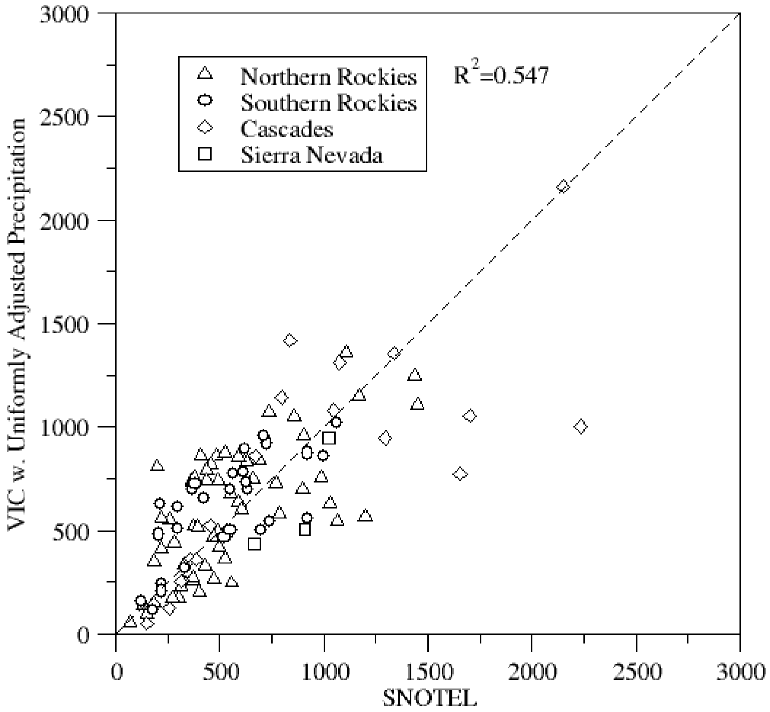

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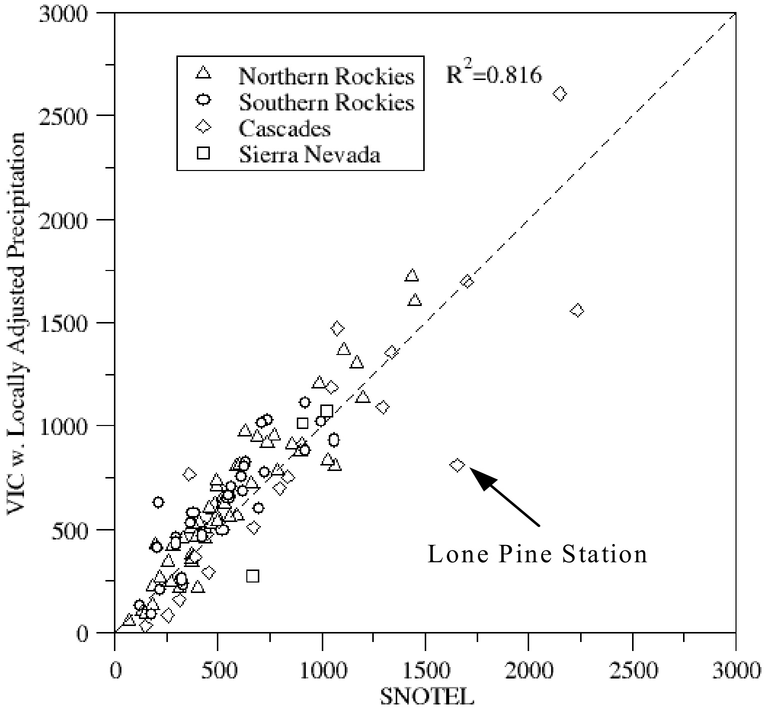

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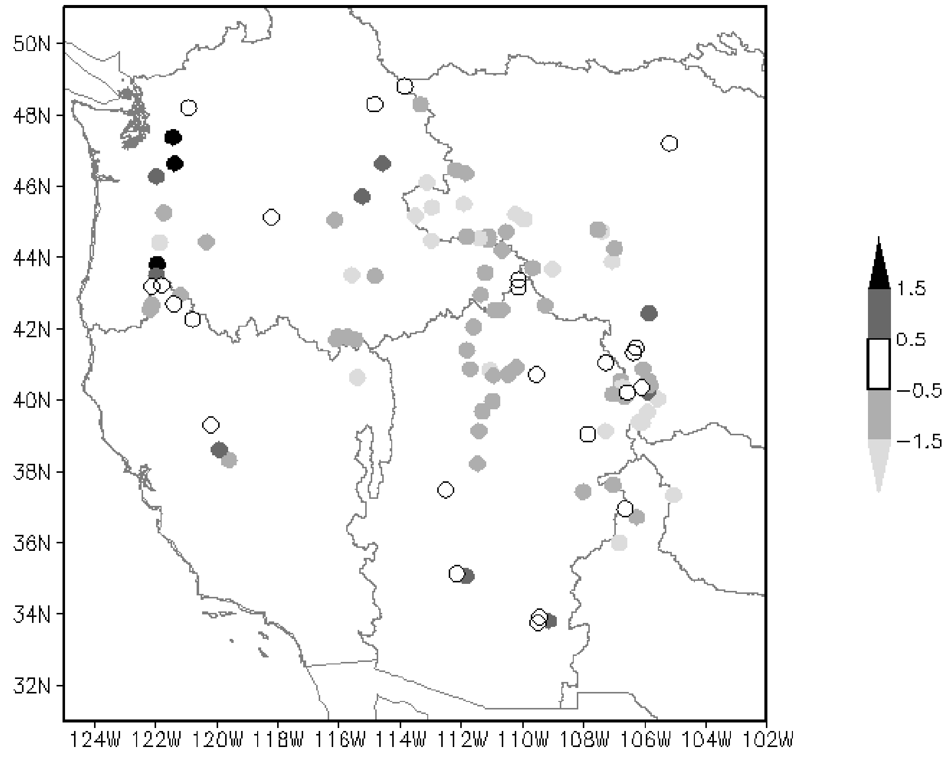

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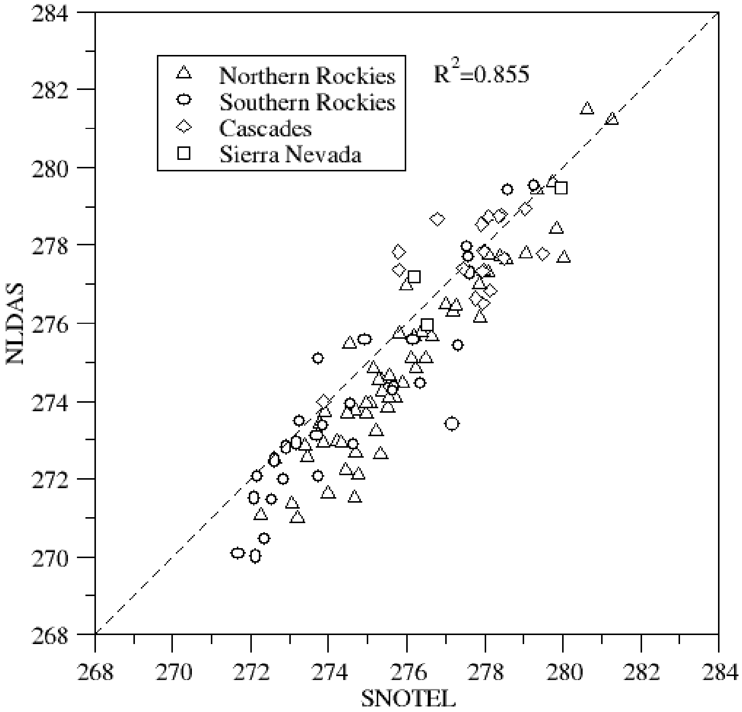

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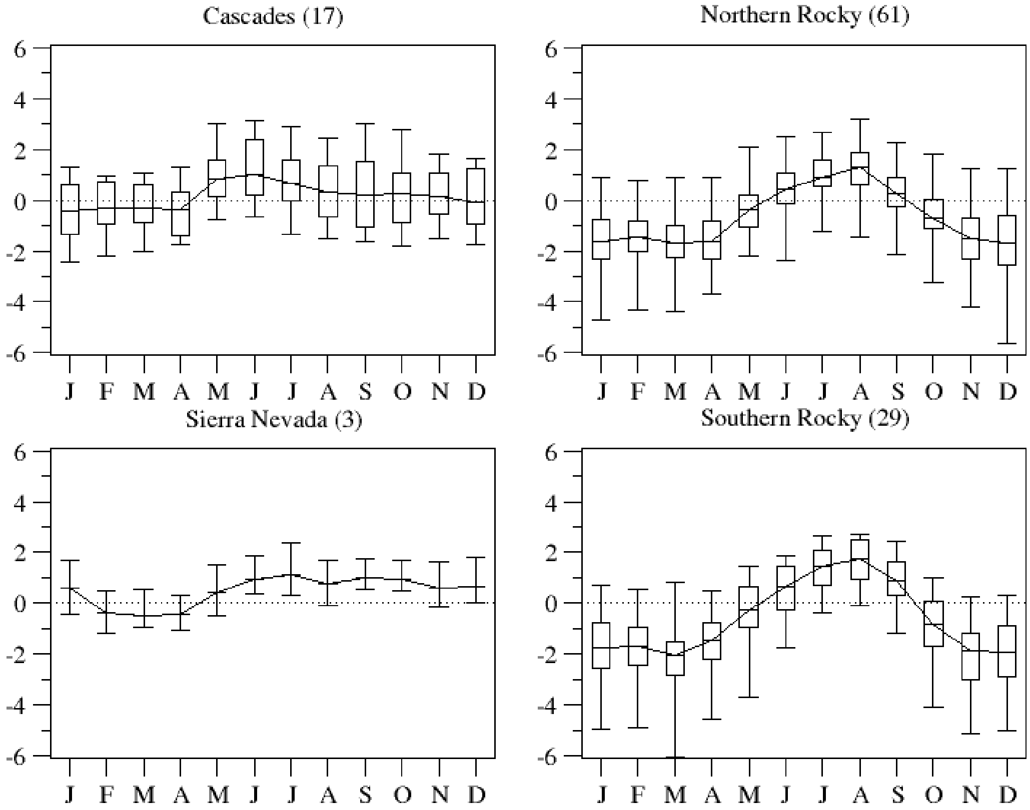

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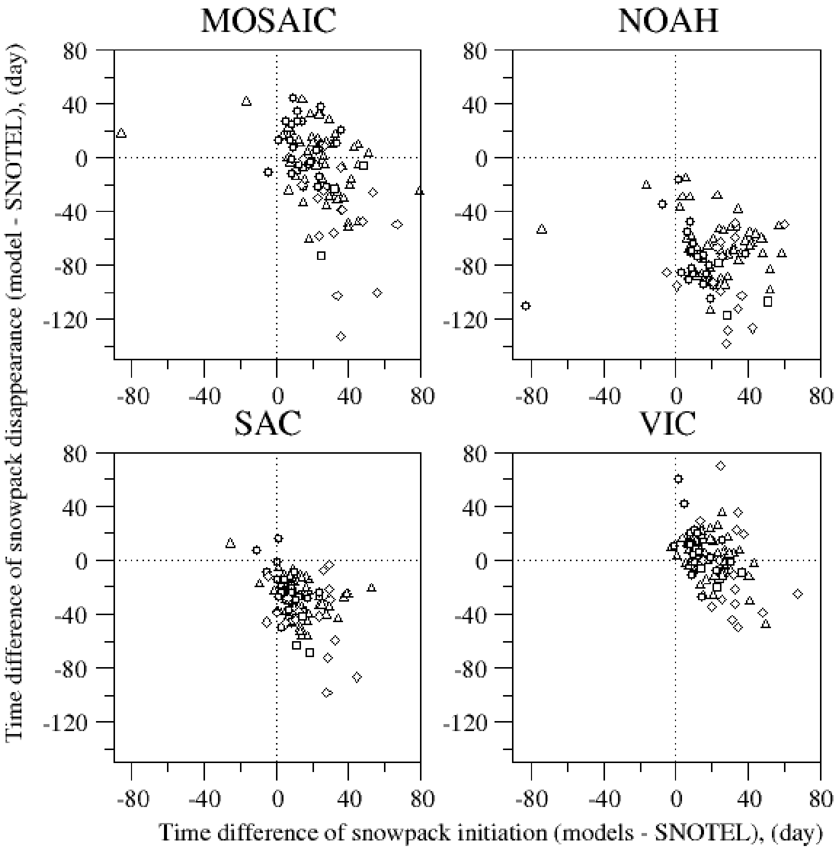

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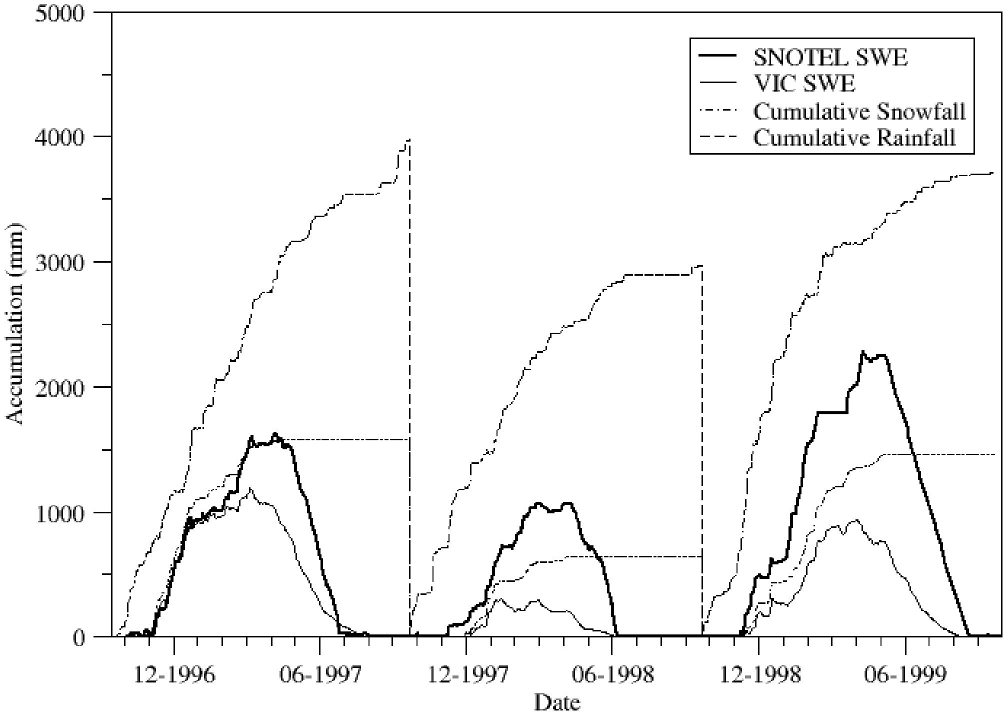

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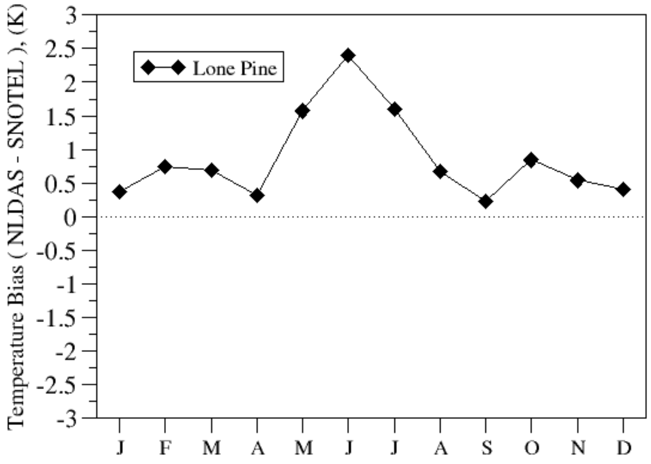

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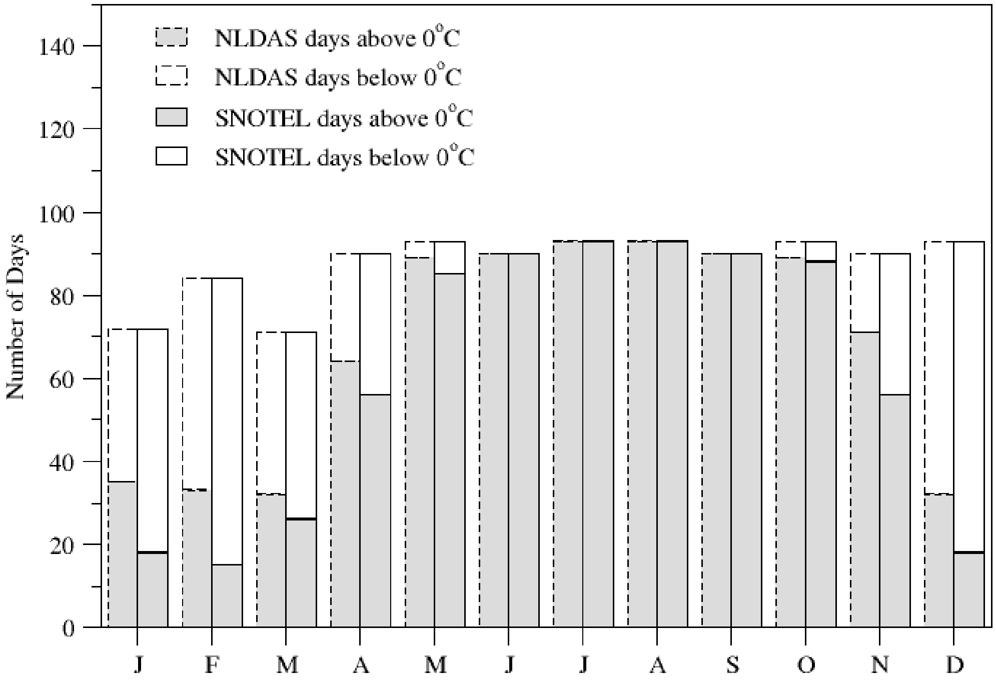

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