# Simulations of seasonal snowpack duration and water storage across New Zealand

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## Abstract

Seasonal snow dramatically alters surface-atmosphere exchanges of heat and moisture, particularly in the South Island of New Zealand. Despite this, detailed simulations of seasonal snow and comparisons to remotely sensed snow observations are lacking in New Zealand, partly due to uncertainties in near-surface meteorology in mountainous areas with sparse in-situ observations. Here we simulate seasonal snow cover and water storage across New Zealand on a 250 m x 250 m grid over a 3-year period (April 2017 to March 2020) with a simple snow model and near-surface meteorology extracted from the New Zealand Convective Scale Model (NZCSM). Simulations are validated against snow cover derived from MODerate Resolution Imaging Spectroradiometer (MODIS) satellite remote sensing observations. While NZCSM near-surface meteorology is generally colder and wetter than observations, we find that the spatial patterns and elevation distribution of simulated snow cover duration (SCD) agrees well with MODIS observations. Biases in SCD are found in areas, particularly the ranges east of the main divide, where simulated snow cover persists longer than observed. In contrast, alternate simulations using daily gridded observations of near-surface meteorology show a poor fit to MODIS SCD, with large areas having little or no simulated snow cover. The simulated seasonal cycle of New Zealand-wide total snow water storage shows a peak around 1 September equating to around half the long-term average monthly total rainfall for the South Island. The correspondence between simulated and MODIS snow covered area is found to be sensitive to the threshold used to define simulated snow cover, particular in early winter when widespread thin snow cover is common. To improve estimates of snow cover and water storage, future work should exploit new remote sensing products for validation and assimilation as well as disentangle uncertainties in snow model parameters and meteorological input using detailed meteorological and snow observations.

## 1. Introduction

The growth and recession of the seasonal snowpack dramatically changes surface-atmosphere exchanges of heat and moisture, as well as altering the seasonal distribution of streamflow. Satellite observations show that, on average, 20% of New Zealand is covered in snow throughout winter[1]. Despite this, analysis of published simulations of the distribution and seasonality of New Zealand's seasonal snowpack and comparison to remotely sensed snow cover are lacking. Fitzharris and Garr (1995) simulated the snowpack of the main hydroelectric catchments within the South Island, showing large interannual variability in total water storage. Clark et al.

[1]Average snow covered area between 1 June and 31 August https://www.otago.ac.nz/surveying/potree/pub/mrc/projects/snotago/modis-snow-cover

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(2009) presented simulations for the South Island of New Zealand, with a focus on model parameter sensitivity and validation against catchment water balance and point snow measurements. Hendrix et al. (2012) made simulations for all New Zealand with a focus on patterns of peak snow water equivalent (SWE). Kerr (2013) simulated the contribution of snowmelt to river flows across the South Island by calculating the fraction of precipitation falling as snowfall in each catchment. The Statistics NZ water accounts (Henderson et al., 2011) provide national- and regional-level estimates of total snow storage changes between 1st July each year, with the most recent accounts also including regional storage changes in quarterly periods, but no maximum storage values are given (Griffiths et al., 2021).

The paucity of simulations is partly due to the lack of near-surface meteorological observations in mountainous regions of New Zealand, despite recent efforts to install automatic weather stations at high elevations (Hendrix and Harper, 2013). The lack of observations hampers efforts to produce interpolated surface meteorology products and produces large uncertainties in the precipitation and temperature inputs that are critical to snow simulations (Tait et al., 2012; Tait and Macara, 2014). Lundquist et al. (2019) posit that meso-scale meteorological models are becoming more skilful in estimating mountain precipitation compared to traditional observational networks. In mountainous areas, meso-scale models greatly improve the representation of near-surface meteorology compared to reanalysis products (e.g. Alonso-González, E. et al. 2021). The New Zealand Convective Scale Model (NZCSM) is a meso-scale numerical weather prediction model with 1.5 km horizontal grid spacing that covers all of New Zealand and has produced weather forecasts since its operationalisation in 2014. The archive of NZCSM forecasts provides hourly near-surface meteorology fields that can be used as input to simulations of seasonal snowpack across New Zealand. At the same time, the availability of remotely sensed snow cover products has increased, and these products can be used to assess the reliability of simulations in areas without *in-situ* snowpack observations (e.g. Quéno et al., 2016).

Despite recent advances in observing snow cover, snow models provides a means to bridge the gap between routinely collected remotely sensed snow cover information (e.g. Redpath et al., 2019), which has good spatial and temporal coverage, but no snow depth or SWE information, and the site-specific snow depth and SWE data available at a limited number of sites (e.g. Porhemmat et al., 2020; 2021). Gridded snow information can also inform surface boundary conditions in meteorological models, snowpack state for rain-on-snow flooding, and quantify snow storage and melt in specific catchments. Therefore, improved simulations of seasonal snow cover will improve forecasts of streamflow, snow hazard and near-surface climate.

The aims of this paper are to 1. assess if NZCSM output has value as input to snow simulations, 2. evaluate national-scale model simulations against remotely sensed snow cover on common grid, and 3. present the timing and elevational distribution of simulated snow storage. Remotely sensed snow cover derived from MODerate Resolution Imaging Spectroradiometer (MODIS) satellite observations (Hall and Riggs, 2016) will be used to evaluate the quality of the simulations. There will be a focus on the typical snow cover dynamics as well as snow storage.

## 2. Methodology

The snow simulations were performed on a 250 m x 250 m square grid using the Clark et al. (2009) snow model. This empirical model requires only temperature and precipitation as input and calculates snowpack storage (in mm water equivalent (w.e.)) as the sum of snowfall and snowmelt over an hourly timestep. Snowfall is defined as precipitation falling below an air temperature threshold (Tacc). Snow melt occurs when air temperature exceeds a melt threshold (Tmelt), with the rate of melt depending on air temperature, season, time since snowfall and occurrence of rain-on-snow. Default values were used for all parameters (Table 1.; Clark et al., 2009).

Previous studies have identified that simulated snow is particularly sensitive to the temperature threshold for snowfall (e.g. Clark et al, 2009). The default value (1 °C) used here represents the most commonly used threshold in NZ modelling studies (Anderson et al., 2021; Conway and Cullen, 2016; Clark et al., 2009) and is congruent with physically based estimates of equal rain-snow partitioning (Harder and Pomeroy, 2013) for air close to saturation (90% relative humidity).

The air temperature and precipitation input were derived from the NZCSM forecast archive in two steps. In the first, archived surface meteorology was concatenated to form a continuous hourly timeseries from 1 April 2017 to 30 March 2020. Output from forecast hours 7 to 12 was used to avoid the reduced convective precipitation that occurs in the first few hours of each forecast (Cattoën et al., 2016). Earlier forecasts (April 2014 to March 2017) were not used as to avoid the discontinuity in surface meteorology introduced by a major update to the dynamics and physics schemes within NZCSM in mid-2017.

The second step was to reproject and bilinearly interpolate the surface meteorology from the NZCSM grid (a rotated pole projection with ~1.5 km horizontal grid spacing) to the snow model grid (250 m x 250 m square grid on New Zealand Transverse Mercator (NZTM) projection. The model grid was chosen to match the grid of the MODIS snow cover observations, as catchment-based spatial units (e.g. those NZ Water Model used in Statistics NZ water accounts) make direct validation against remotely sensed snow cover challenging. Differences in grid elevation were accounted for by lapsing NZCSM temperature down to sea level, bilinearly interpolating to the snow model grid, then lapsing back up to the snow model elevation. The interpolation was performed on-the-fly within the snow model using a constant lapse rate of 0.005 K m-1 which equates to the annual mean lapse rate from Norton (1985). Hourly snowfall and rainfall totals from NZCSM were combined into total precipitation, then bilinearly interpolated without adjustment for elevation.

Simulations were made for three hydrological years (1 April – 30 March) ending in 2018, 2019 and 2020. Note the hydrological years are named by the year they end in, so most snow accumulation occurs in the calendar year before the name of the hydrological year.

Simulated snowpack was validated against daily MODIS MOD10A1 Collection 6 snow cover product (Hall and Riggs, 2016) that had been reprojected and cloud-gap filled. The reprojection from the original sinusoidal grid (SIN) to the NZTM snow model grid was performed using nearest neighbour interpolation. The 250 m x 250m grid was chosen for resampling MODIS observations as it better preserves the original data given the large distortion between SIN and NTM projection. The 250 m x 250m grid is also preferable to the NZCSM grid (~1.5 km

**Table 1:** Mean bias in near-surface air temperature from NZCSM to observed air temperature at all stations shown in Figure 1 and the 12 SIN sites. Bias shown here as (NZCSM minus observed).

| Sites | Season | Daily min. air temperature | Daily max. air temperature | Mean air temperature |
|---|---|---|---|---|
| **All stations** *(n=343)* | MAM | 0.98 | -1.55 | -0.02 |
| | JJA | 0.76 | -1.34 | -0.02 |
| | SON | 0.51 | -1.48 | -0.36 |
| | DJF | 0.62 | -1.76 | -0.45 |
| **SIN stations** *(n=12)* | MAM | -0.98 | -1.52 | -1.15 |
| | JJA | -1.25 | -1.91 | -1.21 |
| | SON | -0.87 | -1.68 | -1.09 |
| | DJF | -0.77 | -1.29 | -1.05 |

x 1.5km) for simulations as larger grid sizes will smooth terrain and change the hypsometry. The normalised difference snow index (NDSI) values from MOD10A were converted to fractional snow-covered area using Hall et al. (2007). Following Redpath et al. (2019), the cloud-gap filling implements the approach of temporal filtering proposed by Dozier et al. (2008) whereby a temporal smoothing spline is fitted through the valid data points for each grid point to produce a continuous record in time.

To compare the simulations to MODIS observations, binary snow cover maps were created for simulated and observed snow cover for each day. To derive simulated snow cover maps, a 30 mm w.e. threshold was used to define a binary snow cover from the modelled SWE at noon each day (Gascoin et al., 2015; Queno et al. 2016). Following Sirguey et al. (2009), a threshold of 50% fractional snow-covered area was used to classify MODIS observations as snow covered. The snow cover duration (SCD) in the MODIS and model products is simply the number of days classed as snow cover in each year for a given grid point. Similarly, the snow-covered area (SCA) is defined as the total area of grid points defined as having snow cover on each day. Grid points over water were excluded from the analysis by creating a mask from the MODIS data with a grid point being masked if it was flagged as ocean or inland water within the study period.

To test the sensitivity of the snow model output to a -1 °C bias in air temperature, a second 'Sensitivity' simulation was performed with Tacc = 0 °C and Tmelt = -1 °C. This is a reduction of 1 °C from those in the 'Default' simulation (Tacc = 1 °C and Tmelt = 0 °C) and simulates correcting a -1 C bias in air temperature input. The sensitivity of the model SCD to the model SWE threshold is also assessed by reanalysing the results with a 5 mm w.e. threshold, which equates to 5 cm fresh snow (at density of 100 kg m$^{-3}$) or 1 cm spring snow (at density of 100 kg m$^{-3}$). By comparison, 30 mm w.e. equates to 30 cm fresh snow or 6 cm spring snow.

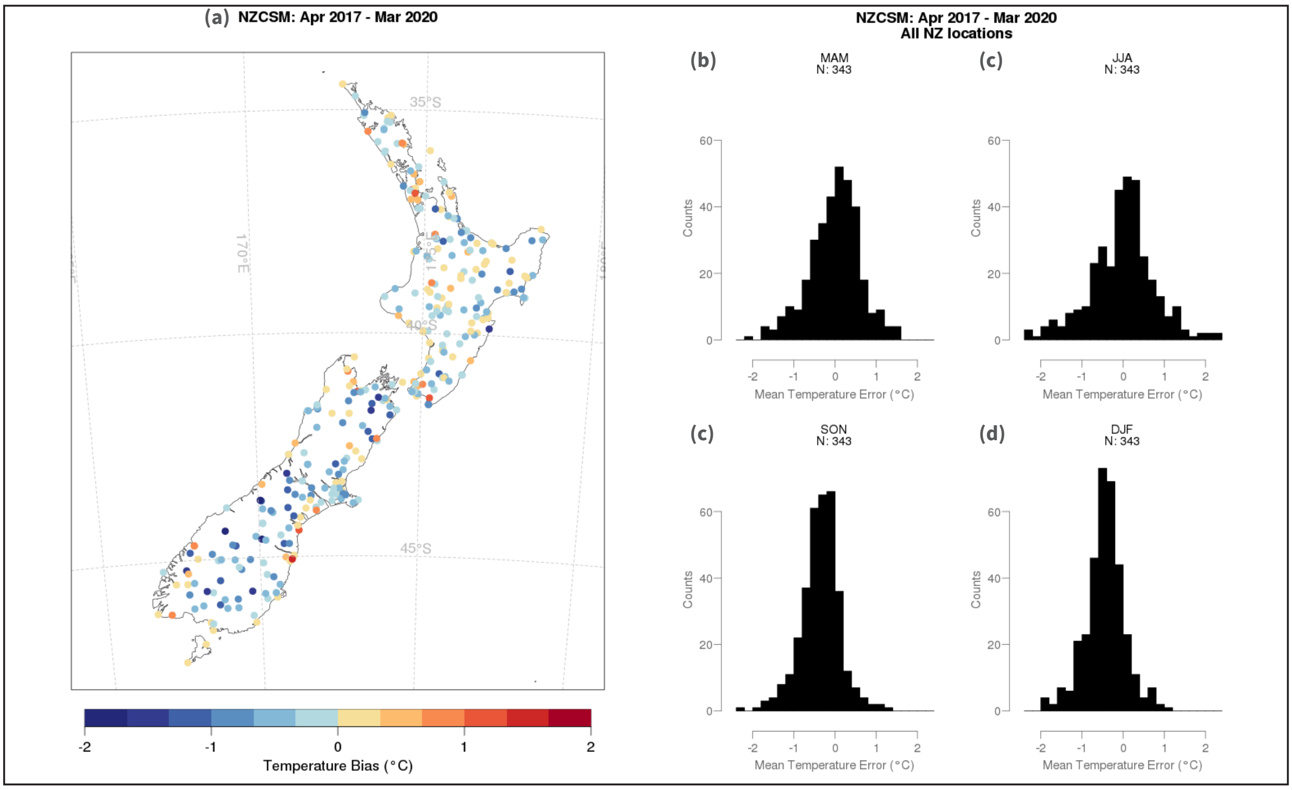


**Figure 1:** Comparison of near-surface air temperature from NZCSM to observations at selected sites (n=343): (a) mean bias April 2017 - March 2020, (b-e) histograms of biases at all stations by season.

## 3. Results

### *3.1 Comparison of NZCSM near-surface meteorology to observed climate*

Comparison of NZCSM near-surface air temperature to a climate station records (Table 1, Figure 1b) shows biases are centred around zero for autumn and winter but show negative biases (model less than observations) in spring and summer. High-elevation SIN sites have more negative bias around -1 °C in all seasons (Table 1) and some sites have annual air temperature biases up to -2 °C in the central Southern Alps. We note these biases are similar to meso-scale model output used in similar snow model efforts internationally (e.g. Alonso-González et al. 2021). The larger negative bias at the SIN sites compared with all stations appears to be due to differences in the negative daily minimum temperature bias. The minimum temperature bias at SIN sites is quite different from the overall minimum temperature bias which is positive when averaged over all stations. The cause of this difference isn't clear but may be due to poor representation of surface-atmosphere exchange processes at high elevations, particularly during the night.

Precipitation totals from NZCSM are generally higher than observations, with biases of a few 10s of percent across much of the inland areas of the South Island (Figure 2a). A distinct west-east gradient is also apparent, with precipitation totals at sites on the West Coast, upwind of prevailing westerly airflow, being lower than observations and sites to the east above normal. A cluster of sites in Central Otago have the largest percentage differences from observations, where low precipitation totals make

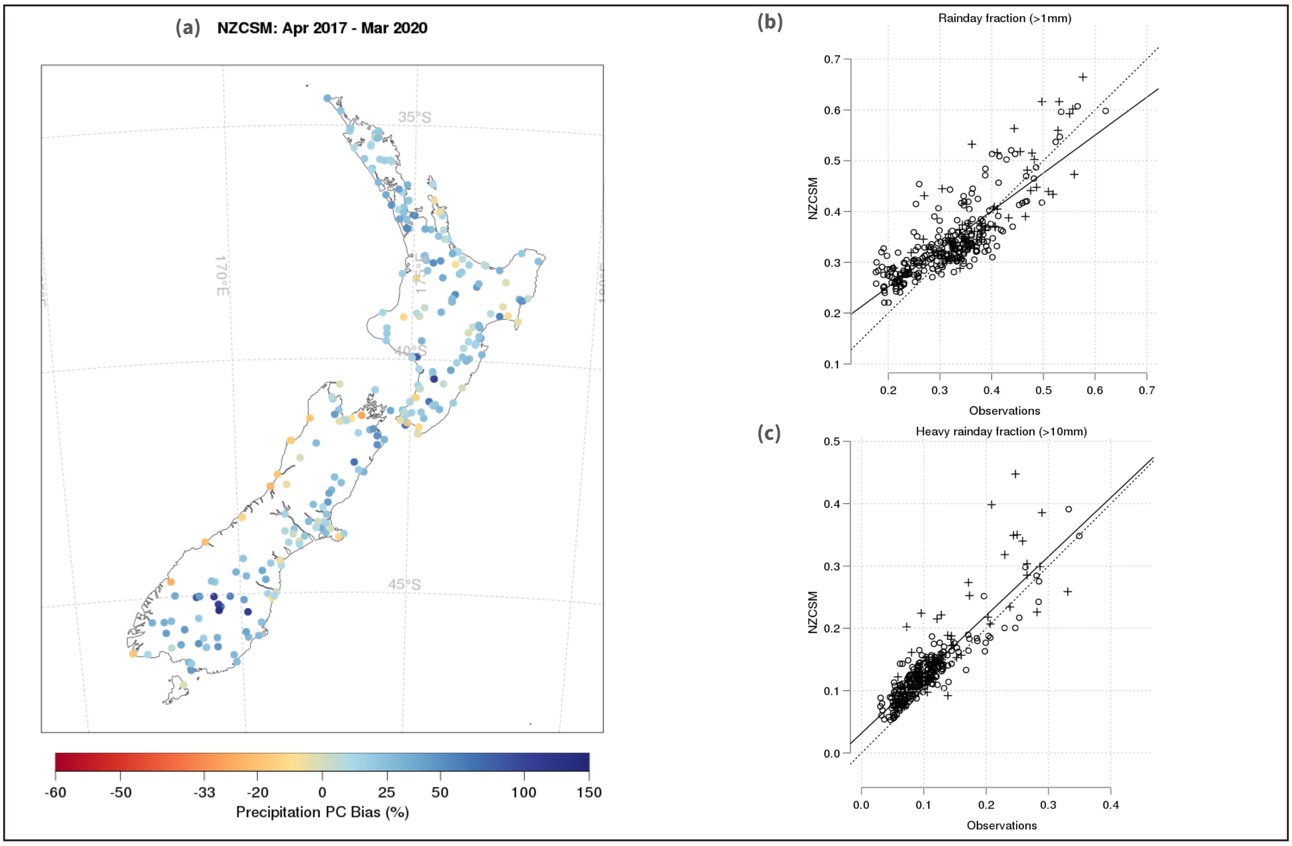


**Figure 2:** Comparison of total precipitation from NZCSM to observed rainfall at selected sites: (a) percent bias in total precipitation (n=267), (b) rainday (daily totals > 1mm) fraction and (c) heavy rainday (daily totals >10 mm) fraction, with sites > 500 m a.s.l. (n=51) shown as crosses. SIN sites are not included in the precipitation comparison, as the observations are unreliable during winter due to freezing.

percentage differences comparatively large. The fraction of heavy-rain days (daily totals >10 mm) in NZCSM is consistent with observations (Figure 2c). The higher fraction of rain days (daily totals >1 mm) in NZCSM at drier sites indicates too frequent light rain in NZCSM, a pattern often seen in numerical weather prediction model output (Blacutt et al., 2015).

### *3.2 Snow cover duration*

The pattern of simulated mean annual snow cover duration (SCD) illustrates the stark contrast between snow cover in the North and South Islands (Figure 3). SCD greater than 1 or 2 months is widespread within the South Island, even outside the Southern Alps, while significant snow cover is limited to the tops of the ranges in the Lower North Island. MODIS observations show similar patterns (Figure 4c, d) but with longer SCD in low elevation areas within Fiordland and the West Coast (Figure 4e). The simulations show longer SCD in some of the more eastern mountain ranges in Otago and Southland, particularly the Takitimu and Remarkables/Hector Mountains, as well as areas within the Nelson Lakes and Kaikōura Ranges. It is likely that small values of SCD across patchy areas in Coastal Otago, Fiordland and the West Coast are a result of cloud shadows that appear to be often misclassified as partial snow cover within MODIS products. This feature is quite apparent in the North Island as a low bias in SCD in areas outside the main ranges (Figure 4f). Within the North Island, the spatial patterns of snow cover are represented well by the model, albeit being more clearly defined by topography compared to MODIS. Note that east of Mt Ruapehu (area of maximum SCD at centre top of Figure 4b), a large area has been masked as water (grey colouring) due to spurious inland water points within MODIS.

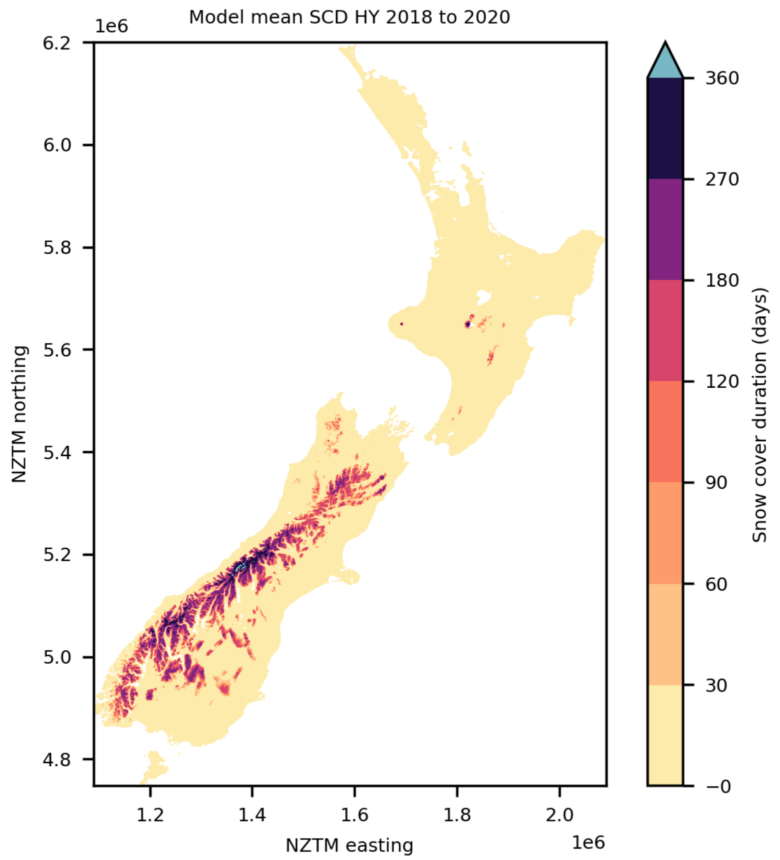


**Figure 3:** Annual mean simulated snow cover duration (SCD), 1 April 2017 – 30 March 2020.

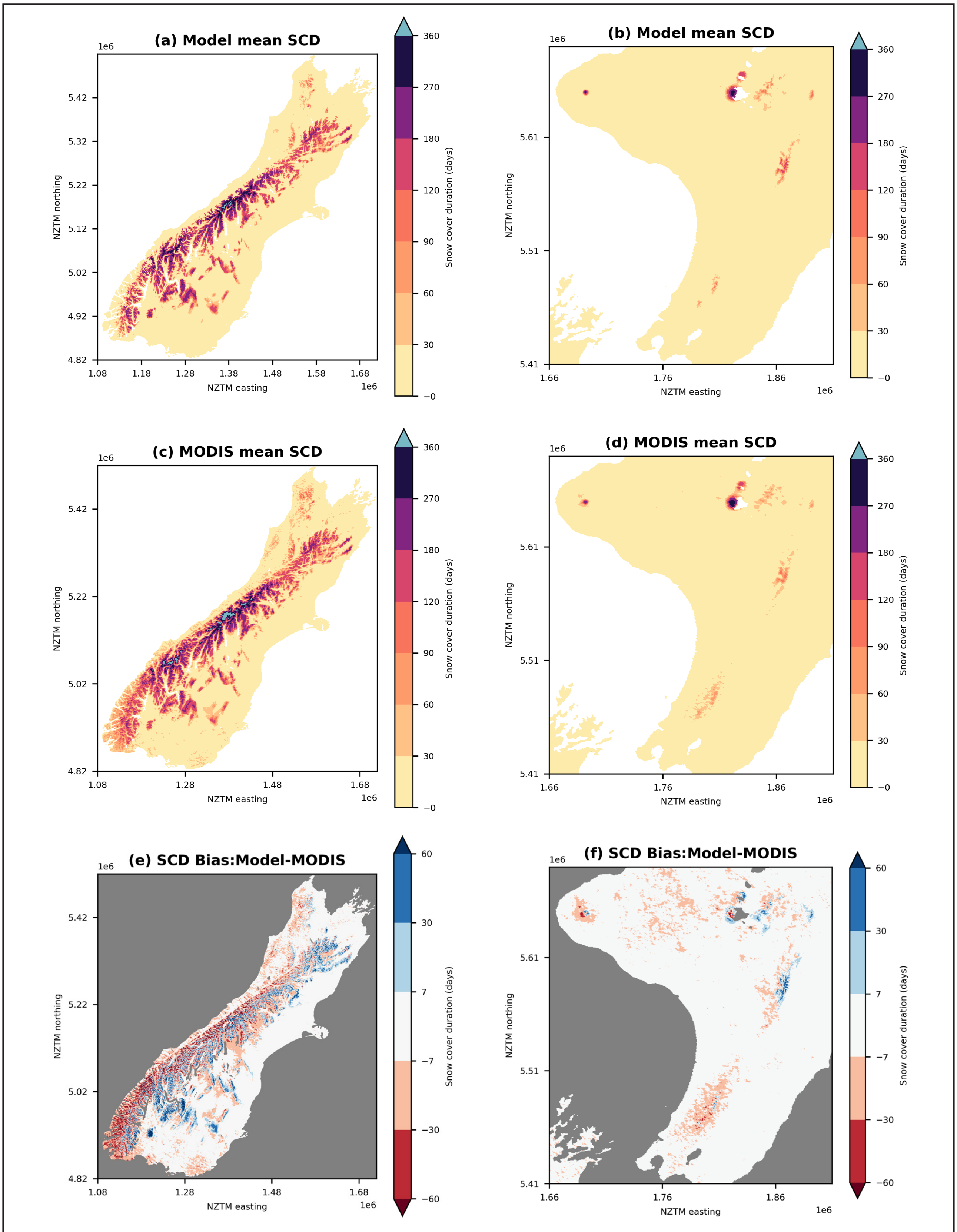


**Figure 4:** Comparison of simulated and observed annual mean SCD for the South and North Islands of NZ, for hydrological years 2017-18 to 2019-20.

**Table 2:** Snow cover duration statistics for Default and Sensitivity runs and for different SWE thresholds.

| Model options | SWE threshold (mm w.e.) | Mean SCD *(all points weighted equally)* (days) | Mean bias *(all points weighted equally)* (days) | MAE *(all points weighted equally)* (days) | SCD macro-averaged in 200m elevation bin (days) | Bias of SCD macro-averaged in 200m elevation bins (days) |
|---|---|---|---|---|---|---|
| MODIS | - | 21.7 | - | - | 200.4 | - |
| Default run | 30 | 15.0 | -6.69 | 9.14 | 195.3 | -5.1 |
| | 5 | 21.3 | -0.32 | 9.18 | 205.2 | 4.8 |
| Sensitivity run | 30 | 10.2 | -11.50 | 11.88 | 183.0 | -17.4 |
| | 5 | 15.1 | -6.60 | 9.04 | 192.7 | -7.7 |

The average SCD bias across all points is 6.69 days with mean absolute error (MAE) < 10 days for default options (Table 2). To better understand the sensitivity of the results to model parameters and analysis threshold, the SCD was calculated using both 30 and 5 mm w.e. SWE thresholds for both Default (Tacc = 1 °C, Tmelt = 0 °C) and Sensitivity (Tacc = °0 C, Tmelt = -1 °C) runs. When a 5 mm w.e. threshold is used to define snow cover from the simulations, SCD increases and the mean bias is close to 0 days. The Sensitivity run with a 5 mm w.e. threshold shows very similar bias and error as the default settings, while the Sensitivity run with 30 mm w.e. threshold has much shorter snow cover than observations. Further discussion is made after elevational patterns of SCD are presented.

Closer inspection of a 30 km x 30 km domain reveals a pattern of ragged edges within MODIS SCD, while the model closely follows the contours of the topography (Figure 5). This pattern is an artefact of the reprojection from the sinusoidal grid that MOD10A1 is distributed on. Over New Zealand, the nominal 500m sinusoidal pixels are distorted into parallelograms with a diagonal of 2 km running ENE – WSW. When this distorted grid is resampled to a regular 250m grid with nearest neighbour to retain the integrity of the data, the MODIS

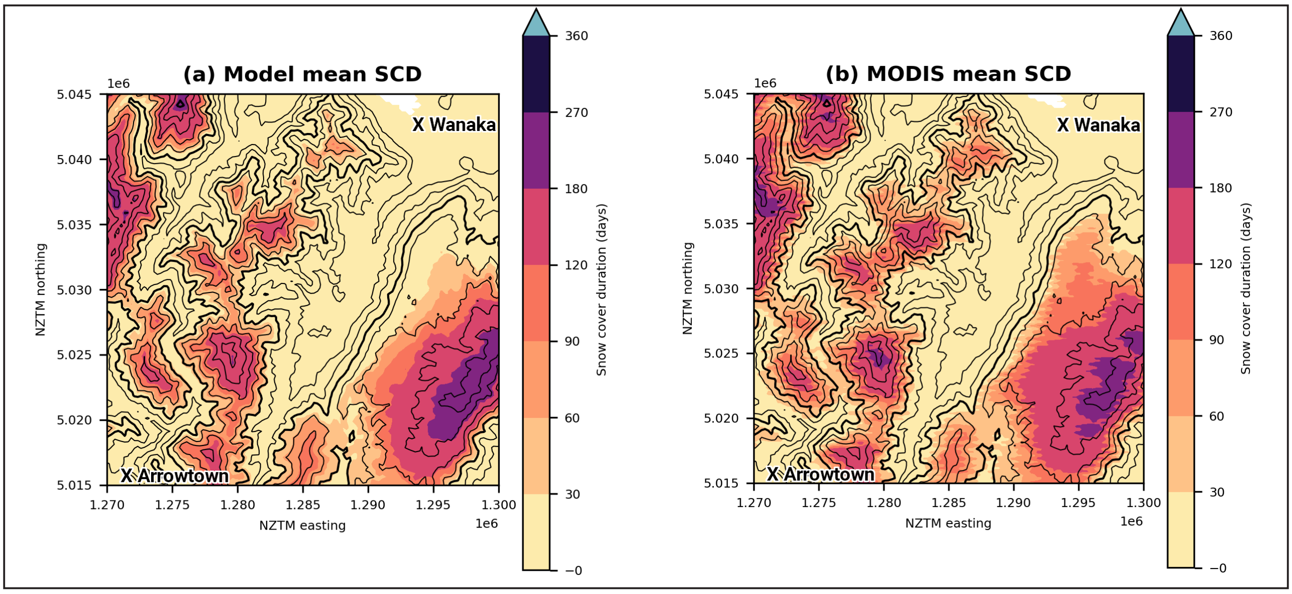


**Figure 5:** Detailed view of simulated and observed mean SCD for 30 km x 30 km domain centred on the Cardrona Valley for hydrological years 2017-18 to 2019-20. 200 m elevation contours are shown for reference, with 1000 m contour bolded.

data is smeared across elevation bands, principally in the longitudinal direction. In complex topography, this smearing results in signal from high-elevation areas with snow cover being smeared to lower elevations. Future work should look to process the MODIS data from swath direct to an NZTM grid to avoid such artefacts.

The relationship between elevation and SCD across the South Island shows the expected positive relationship in both the model and MODIS (Figure 6a, b). Under 800 m, < 30 days snow cover dominates in both model and MODIS (Figure 6a,b), with the model showing very little snowpack with longer SCD. The mode of MODIS SCD shows a non-linear relationship to elevation. From 1000 to 1400 m the SCD increases rapidly from < 30 days to > 120 days, then increases more slowly, reaching 210-240 days between 2000 and 2200 m. Above this, the mode of SCD jumps to > 360 days, indicative of areas of permanent snow. The mode of model SCD is consistent with the MODIS SCD mode in most bins, though has a more linear relationship to elevation, resulting in larger SCD simulated between 1800 and 2200 m. Figure 6c shows that, between 1000 and 1500 m, MODIS has a more pixels with SCD between 40 and 150 days, while the model has more pixels with no snow cover. Between 1500 and 2000 m, there is a broad range of SCD in MODIS that is well represented by the model, except for a tendency to underestimate the small area with the longest SCD. These points include areas with permanent snow and glaciers that show up in MODIS as a subtle peak in SCD > 360 days above 1600 m (Figure 6b). This feature is not seen in the model SCD as SWE is reset to 0 at the beginning of simulations (1 April), so permanent snow areas below 2200 m show up as SCD of 330 to 360 days (Figure 6a). Between 2000 and 2500 m, areas of permanent snow create a bi-modal distribution of SCD in MODIS observations, which is also apparent in the model distribution, albeit shifted to longer SCD (Figure 6c).

The sensitivity of the results is illustrated by the elevation profile of mean SCD. While a 5 mm threshold shows a smaller mean bias compared to the 30 mm threshold for the Default run (Table 2), this is only because it is closer to the MODIS observations over the large area of land below 1000 m elevation, while overestimating SCD at most elevations (Figure 6d). To give a better representation of the fit, the SCD bias can be macro averaged by elevation bins (i.e. by equally weighting mean bias over each 200 m elevation bin). When macro averaged, the two thresholds give similar results, with the 5 mm w.e. threshold showing a positive bias and the 30 mm w.e. threshold a negative bias (Table 2), in agreement with visual assessment of mean SCD in Figure 6d. The Sensitivity run with the 5 mm w.e. threshold shows a similar fit to the Default run, while Sensitivity run the 30 mm w.e. threshold produces average SCD that is much shorter than observations at all elevations (Figure 6d) and a large negative macro-averaged bias (Table 2). Aside from the changes in bias, the spatial patterns of SCD are similar in all model analyses (not shown). We note the purpose of this analysis is to illustrate the sensitivity of the results, rather than selecting a 'best' simulation. A better simulation of snow would be made using an ensemble snow model, once the model parameter space has been evaluated at sites where the meteorology and snowpack dynamics are well known. This would allow a more robust validation against observation and potential for assimilating snow covered area in the future.

In contrast to simulations using NZCSM as input, simulations using daily gridded climate observations as input show much shorter snow cover duration than MODIS observations, and large areas of negative bias across most of the areas with snow cover (Appendix A). While a thorough diagnosis of the reasons for poor model performance with gridded observations is beyond the scope of this paper, it is likely that both air temperature and precipitation biases along with model parameter errors lead to the underestimation of snowfall, and therefore to a reduced length of snow cover. In addition, the extra

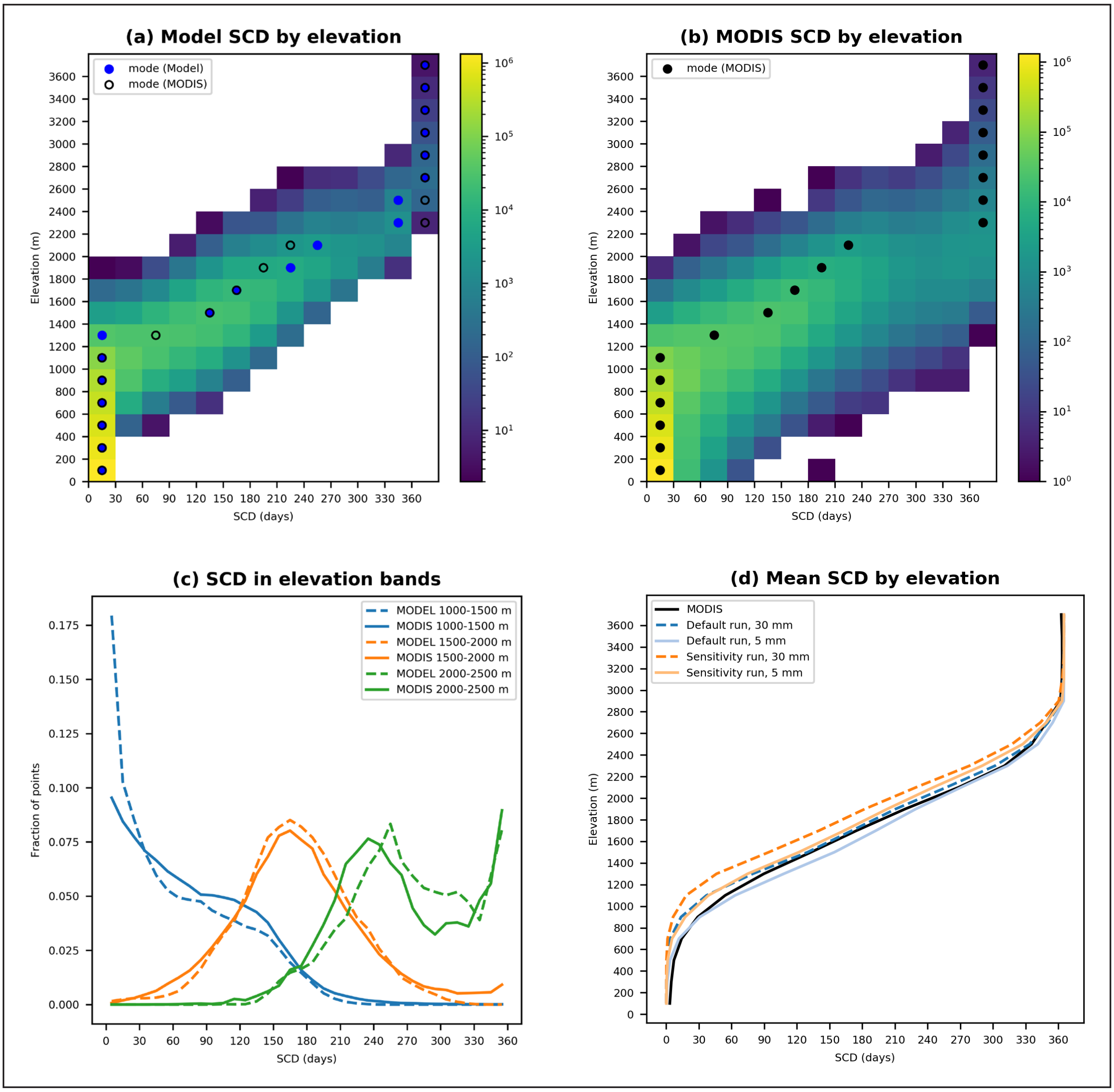


**Figure 6:** 2D histogram of (a) simulated (Default run) and (b) observed annual mean snow cover duration (SCD) for New Zealand in 200 m elevation bins and 30-day SCD bins. Note the log scale of bin frequency in panels (a) and (b). The mode for each elevation bin is shown as points. (c) simulated (Default run) and observed SCD distribution in 500 m elevation bins (d) mean SCD for Default and Sensitivity runs with 30 and 5 mm w.e. SWE thresholds.

step to convert the input data from daily to hourly will also introduce uncertainty. The poor performance of the model with daily gridded climate observations highlights the need for a thorough investigation of model parameter ranges and sensitivity at sites with observed meteorology and snow storage, to disentangle uncertainties in model parameters and climate input. While the snow model is sensitive to air temperature, it is encouraging that both the Default and Sensitivity run with NZCSM input are closer to the MODIS observations than those using gridded daily climate observations, giving confidence that the combination of snow model parameters and climate input are producing a more reasonable simulation of snow cover.

### *3.3 Seasonal evolution of snow covered area and snowpack water storage*

Figure 7 shows the seasonal progression of snow covered area (SCA) across New Zealand. The time of peak SCA varies widely in both model and MODIS (from June through September) and depends on the occurrence of low-level snowfall events. During winter, the model SCA is very sensitive to the threshold used to define snow cover from SWE (compare Figure 7a and 7b), and this may contribute to the generally lower modelled values of SCA in winter. A low threshold of 5 mm w.e. produces similar snow covered area as MODIS in the early season, whereas the early season peaks in SCA are too low for a threshold of 30 mm w.e.. Through spring, the timing and rate of depletion of MODIS SCA is well captured by the model with most areas being snow free by the end of December, and the model SCA is less sensitive to the threshold chosen. While the extent of individual low-level snowfall events is not always captured by the model (e.g. July 2017-18), the occurrence of most significant accumulation events through each season are captured. The interannual variability is also well matched between the model and MODIS, with 2017-18 having lower SCA early and later in the season, 2018-19 peaking earlier than other years, and 2019-20 peaking later and remaining higher later into the spring and summer.

We present snow storage values here to compare with previous studies but also to highlight the sensitivity to model settings and provide some insights into the relationship between simulated snow cover and storage. The simulated snow storage (Figure 8) shows a smoother increase and decrease through the season than SCA. In the default simulation, storage increases throughout winter to peak around 1 September at 14 to 15 $km^3$ w.e.. The Sensitivity run shows a very similar pattern, but with peak of storage around 9 $km^3$ w.e.. For context, the long-term average monthly total rainfall for the South Island is 25 to 30 $km^3$ (Henderson et al., 2011), so the peak storage simulated here approaches half one months total precipitation. The total seasonal snow storage is much smaller than the total stored in glaciers (42.1 $km^3$ +/- 8.4 $km^3$ w.e. in 2019; Carrivick et al., 2020), but large compared the annual mass changes (+1.2 to -3.4 $km^3$ w.e.; Salinger et al., 2019) over the last few decades.

Published estimates of the total seasonal snow storage are scarce and show a large variation in magnitude. Fitzharris and Garr (1995) provided an early estimate of peak total

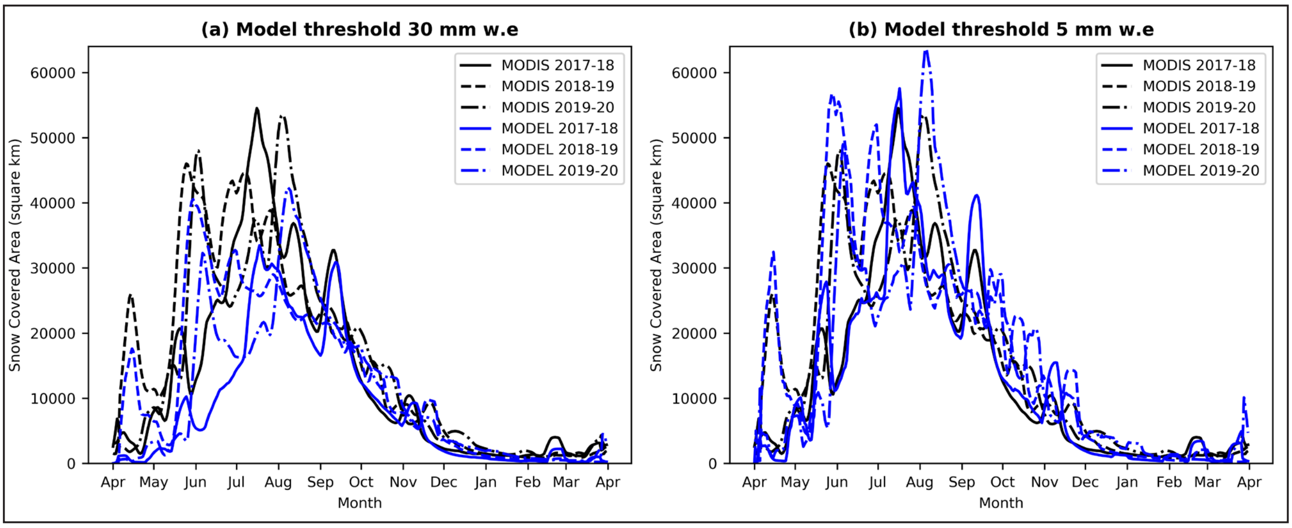


**Figure 7:** Seasonal progression of simulated and observed SCA across New Zealand using different SWE thresholds for classifying modelled grid points as snow covered. Both timeseries are smoothed with 11-day rolling mean.

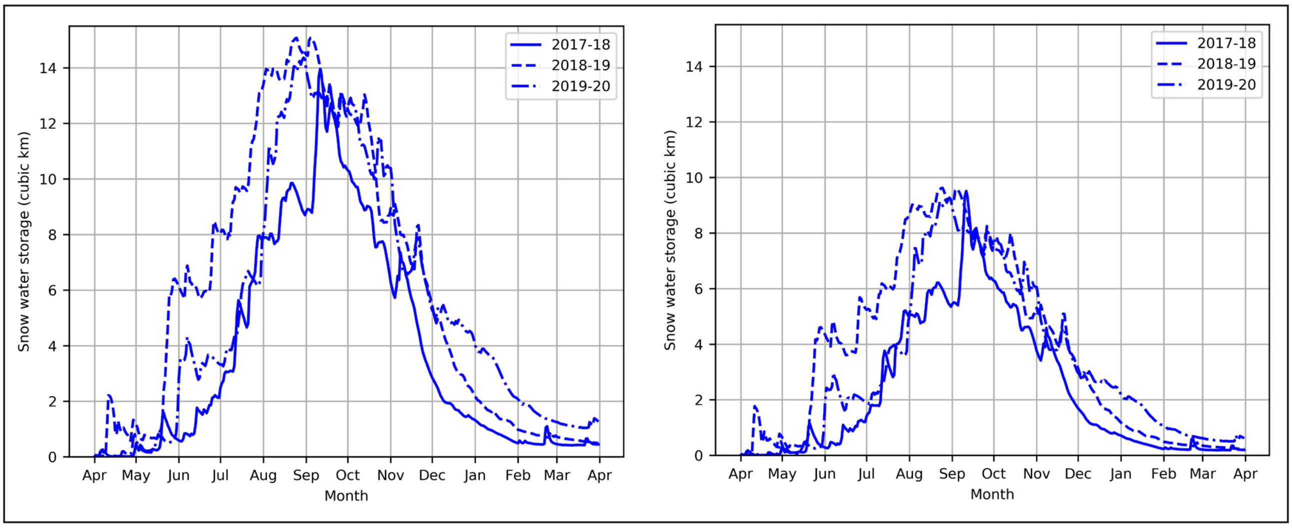


**Figure 8:** Progression of simulated seasonal snow water storage across New Zealand for (a) Default run, and (b) Sensitivity run.

snow storage for the major hydroelectric catchments from Manapouri to Tekapo at around 6 km³ w.e. during October. The NZ water accounts (Henderson et al., 2011) estimate year-to-year changes in snow storage across New Zealand on 1 July of -4 to +2 km³ w.e., which is similar to the differences in 1st July values presented here. The tables associated with the most recent NZ water accounts (Griffiths et al., 2021) estimate mean total snow storage increases by 9.5 +/- 2.9 km³ w.e between 1 April and 30 September, though we note that some melt of permanent snow will be included in these values. The mean value of AMJ storage change (5.1 +/- 2.1 km³ w.e.) in the NZ water accounts is half that first reported by Fitzharris (2004) who put total snow storage on 1 July at 10.8 +/- 3.2 km³ (mean value between 1994-95 and 2000-01) for the South Island only. NZ Water Accounts storage values on 1 September for the years presented here are 7.8, 7.7 and 8.3 km³ w.e., respectively, with less accumulation occurring during April, May, June (AMJ) (mean of 3.3 km³ w.e.) than July, August, September (JAS) (mean of 4.7 km³ w.e.). The smaller values obtained from the Sensitivity run are more congruent with the NZ water accounts numbers, while the Default run is closer to the values in Fitzharris et al. (2004). Given the general overestimation of precipitation by NZCSM across areas to the east of the main divide, the values simulated with NZCSM input are likely to be an overestimate, but will depend on (i) how this is balanced by underestimated precipitation in western areas and (ii) to what extent model parameter uncertainty is compensating for input data biases, given the good fit of SCD. Given the similar fit of Default and Sensitivity runs to MODIS SCD (for a range of plausible SWE thresholds), further data beyond MODIS observations should be used as validation of future simulations of snow storage (e.g. satellite snow depth, *in-situ* SWE measurements). More detailed analysis of snow cover and snow storage in major catchments is possible using these results but is beyond the scope of paper.

Total storage depletes rapidly through spring, indicating widespread melt, then slows through summer, particularly in 2019-20 where significant snowfall in December prolonged the storage of snow through summer. To investigate this further the total simulated storage in different elevation bands within the South Island is shown for each month through spring (Figure 9). The slowing rate of total melt during summer in the model is a function of the increase in the average elevation of the remaining snowpack. At the start of spring, most storage lies between 1200 and 2400 m elevation, with the mode around 1600 m. This pattern is caused by the interaction of increasing snow storage and decreasing land area with elevation. Only 0.75% of land in the South Island (~1100 km$^2$) is > 2000 m elevation, and only 0.05% (~70 km$^2$) is > 2500 m. Through spring the average elevation of the storage increases as lower elevation snow melts and higher elevations continue to accumulate snow (e.g. compare 1 Sept and 1 Oct at 1400-1600 m and 1800-2000 m). By 1 December the average elevation of storage lies around 2000 m, and most storage below 1600 m is depleted within the model.

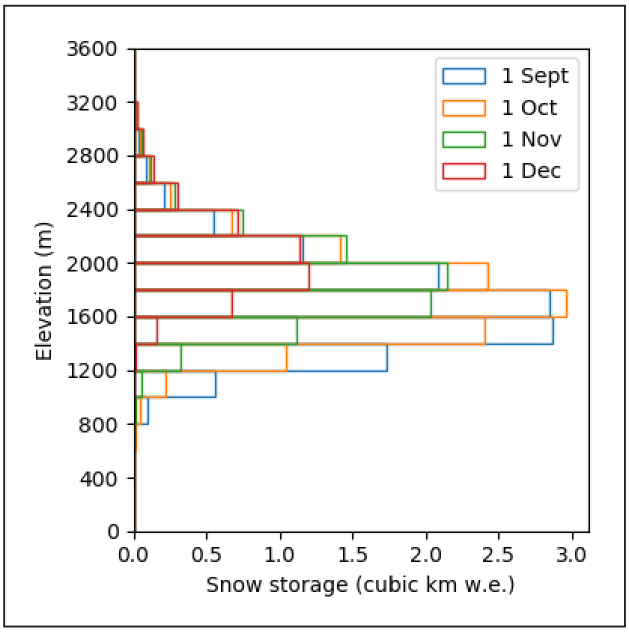


**Figure 9:** Progression of total simulated snow storage for the South Island during spring in 200 m elevation bins. Data are averages from the three years.

## 4. Limitations and directions for future research

This work has many limitations that centre on the accumulation of uncertainties from each step in the model process. Firstly, it is apparent the NZCSM fields used as input meteorology contain systematic biases that would ideally be bias-corrected before snow simulations were performed. The fact that the model shows a good fit to the observed snow cover duration dynamics suggests that snow model parameters may be acting to counter or mask the biases in NZCSM input. Future research should work to separate the uncertainties in snow model parameters and input data. Validation of precipitation in alpine areas continues to be problematic as direct validation of winter precipitation is limited to 3 sites with solid precipitation measurements and large spatial and temporal variability. Additional rainfall sites at low elevations within mountainous areas that are not in the National Climate Database may be useful for further validation.

Secondly, the snow model is a relatively simple model that reduces the many physical processes controlling the rate of snow accumulation and melt into a few tuneable parameters. Here we use a limited range of parameters, but future work should look to assess the range of appropriate model parameters using independent datasets such as meteorological and snow information from high-altitude weather stations (e.g. Porhemmat et al, 2020; 2021). A thorough assessment of the model parameters should also assess parameter transferability between sites and include comparison to more sophisticated snow models to diagnose what processes may be responsible for poor model performance. A better understanding of parameter ranges will aid in assessing the reliability of simulations with different input data in areas without climate observations. Snow simulations at SIN sites could also be used as validation of NZCSM precipitation if observed air temperature is used as model input and model parameters are properly constrained. These point simulations would also be useful in assessing snow storage estimates using NZCSM input. Ensemble model techniques may also be useful in capturing uncertainty (in e.g. catchment average snowpack storage) and enabling assimilation of satellite derived snow information (e.g. Alonso-González et al. 2021). Model parameters will need to be more tightly constrained to avoid compensating for input biases when assimilating.

Thirdly, the comparison of simulated SWE to MODIS NDSI involves transfer functions that are largely unknown.

These functions can introduce large uncertainty at times, e.g. the sensitivity of simulated SCA to the SWE threshold during winter. While we know that MODIS does detect fractional snow cover within a pixel, the model has no explicit or implicit fractional snow cover, and the effect of a simulated fractional snow cover on the comparison to MODIS has not been assessed. Future work should look to resolve the relationship between snow depth, SWE, SCA and MODIS NDSI using more sophisticated snow models and new remote sensing products (e.g. Deschamps-Berger et al., 2020) that enable snow depth to be retrieved at finer spatial scales. This work could include directly simulating fractional snow cover area using sub-grid snow depth parameterisations (e.g. Clark et al, 2011) to compare to MODIS fractional snow cover area (Alonso-González et al. 2021). Future simulations may also benefit from explicit simulation of 2D snow processes such as mass transport by wind (preferential deposition and redistribution) and gravity (avalanches).

Perhaps the most significant limitation of this work is the short length of the simulations. The observed variability of SCA over the 20-year MODIS record is much greater than that over our 3-year study period[2]. Therefore, we would expect much greater variation in the timing and magnitude of snow cover and snow storage over longer simulations. When improved gridded near-surface meteorological products such as high-resolution reanalysis datasets are available, longer model simulations in concert with direct analysis of MODIS snow cover (e.g. Redpath et al., 2019) will enable a much greater understanding of interannual variability and trends in seasonal snow cover. Alternatively, efforts to improve gridded observational products such as VCSN may improve the ability to use these products for reliable simulation. Improvements being investigated include higher spatial and temporal resolutions (500 m and hourly, respectively), better mean rainfall surfaces for interpolation, and/or the inclusion of data from rain gauges outside the National Climate Database (i.e. from regional councils and other providers).

## 5. Conclusions

While three years of simulation are insufficient for an authoritative climatology, they can inform future work to improve the estimation of seasonal snow at national scale by allowing a first detailed analysis of snow cover duration patterns in relation to remote sensing snow cover and estimate of the seasonal cycle of total storage of water within New Zealand's seasonal snowpack. While surface meteorology fields from NZCSM forecasts are generally colder and wetter than observations, we find them a reasonable input for simulating seasonal snow with simple snow model at national scale, particularly in comparison to simulations using gridded daily climate observations as input. The interannual variability in seasonal snow covered area patterns is captured by the NZCSM meteorology, including the most significant snowfalls in each season, thus, NZCSM output could be used to develop near-real time or forecasted state of the snowpack solutions. Biases against MODIS SCD are found in some areas, particularly to east of main divide where modelled snow cover persists longer than observed, likely due to the general wet bias in the NZCSM total precipitation east of the main divide. On average, we find a good fit to MODIS SCD with elevation, though the model is more tightly constrained to elevation. Between 1000-2000m, the model shows a correct pattern of SCD, except for a tendency to underestimate the longest duration snow cover. At lower elevations, the model has a greater proportion of grid points with very short SCD compared to MODIS. This underestimation of MODIS SCD at lower elevations could stem from model errors or from artefacts of the MODIS snow cover processing for New Zealand. It is likely that model parameters are compensating for biases in NZCSM and exacerbating potential biases in gridded observed climate data, but it is difficult to disentangle input data and model parameters uncertainty using MODIS observations at this scale. The model SCD and SCA is very sensitive to SWE threshold within the winter accumulation season, and caution is

[2]*https://www.otago.ac.nz/surveying/potree/pub/mrc/projects/snotago/modis-snow-cover; retrieved 5 Aug 2021.*

warranted when validating snow storage estimates solely on MODIS observations. Nonetheless, the simulations provide a useful view of the patterns of snow cover across New Zealand as well as highlighting the need for more nuanced use of MODIS observations and alternate remotely sensed products to directly validate and/or derive appropriate relationships between MODIS observations and model simulations.

Over the three years of simulations, the peak seasonal snow storage occurs around 1 September, following the period of peak snow covered area, which varies between June and September. While substantial uncertainty still exists, the estimated total seasonal snow storage is a similar order of magnitude as half the long-term average monthly total rainfall for the South Island. Longer simulations are likely to reveal substantial interannual variability in this storage, based on the observed variability of MODIS SCA over the last 20 years.

Future work should look to independently address uncertainties in meteorological input data, snow model parameters (including accumulation, melt and sub-grid snow processes), and relationships between snow depth, SWE, SCA and MODIS NDSI to inform future estimates of snow cover and water storage. Alongside this, efforts to evaluate ensemble modelling efforts and assimilation of remotely sensed snow information will lead to more reliable estimates of snow storage and melt across New Zealand, which will benefit end users interested in future mountain climate, snow hazards and streamflow from alpine areas.

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## Appendix A: Snow simulations using gridded observations as input

As a comparison to simulations using NZCSM meteorology as input, further simulations were performed for the South Island domain using Virtual Climate Station Network (VCSN) data as input. The methods used were identical to the NZCSM simulations, with the addition step to transform the daily VCSN data to hourly fields. This was undertaken following Clark et al. (2009) with hourly air temperature obtained by fitting a sine function to daily minimum and maximum air temperature and hourly precipitation created from daily total precipitation using random cascade method.

Maps for snow cover duration (SCD) show that the VSCN simulations produce much shorter duration snow cover than observed (Figure A1, A2). As with the NZCSM input, the results depend on the SWE threshold chosen, but the smaller SWE threshold (5 mm w.e.) does not resolve the issue that not enough snow accumulates at most elevations, particularly moderate elevations (1000 to 2000 m) and areas in the east (Figures A3, A4). A timeseries of snow-covered area (Figure A5) shows some low-level snowfalls in the VCSN simulations, but the total area is much lower than observed. While a thorough diagnosis of the reasons for poor model performance is beyond the scope of this paper, it is likely that both air temperature and precipitation biases along with snow model parameter errors lead to the underestimation of snowfall and therefore to a reduced length of snow cover. The extra step to convert the input data from daily to hourly will also introduce uncertainty.

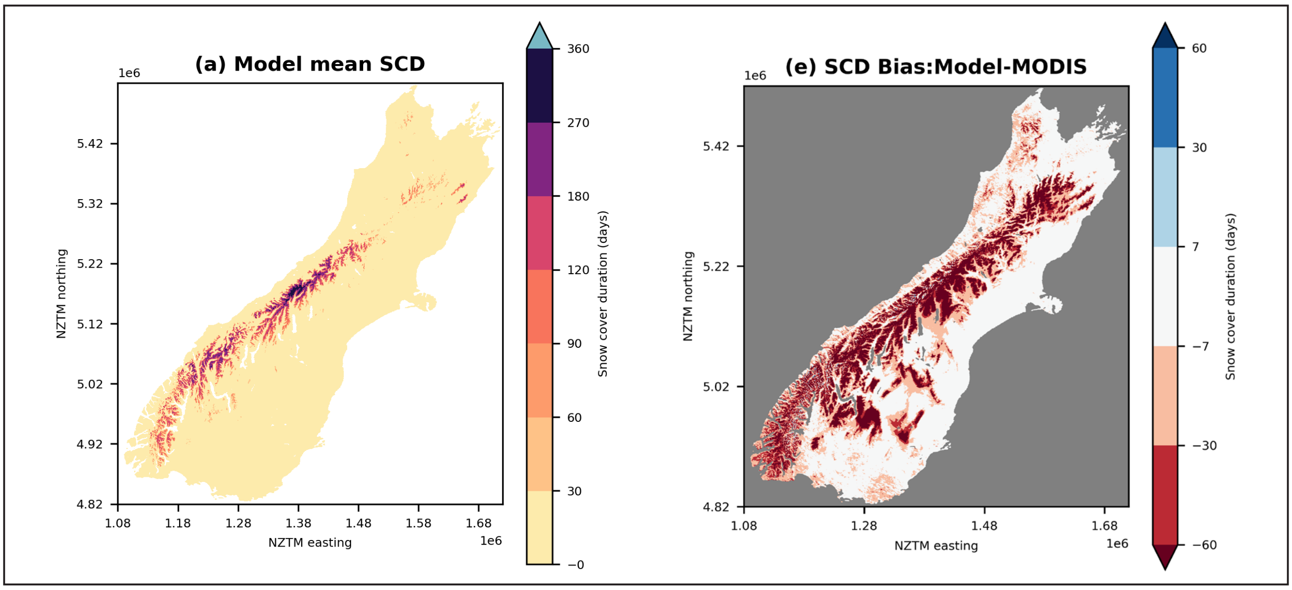


**Figure A1:** As for Figure 4a, e but for simulations using VCSN as input (30 mm SWE threshold).

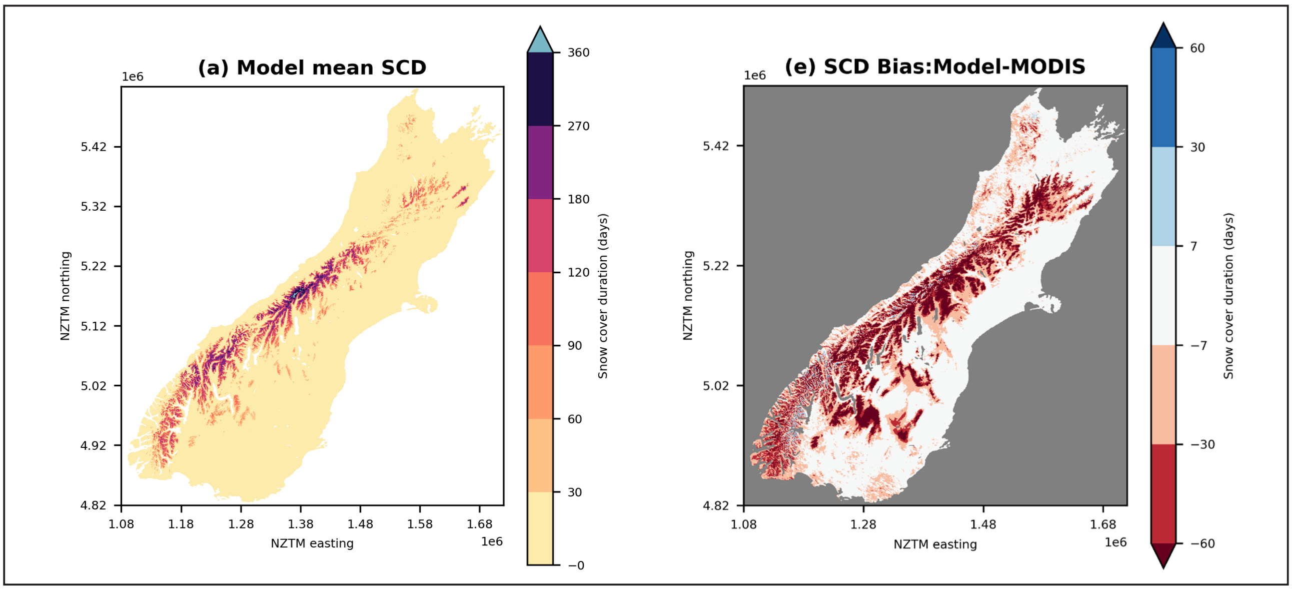


**Figure A2:** As for Figure A1 but for 5 mm SWE threshold.

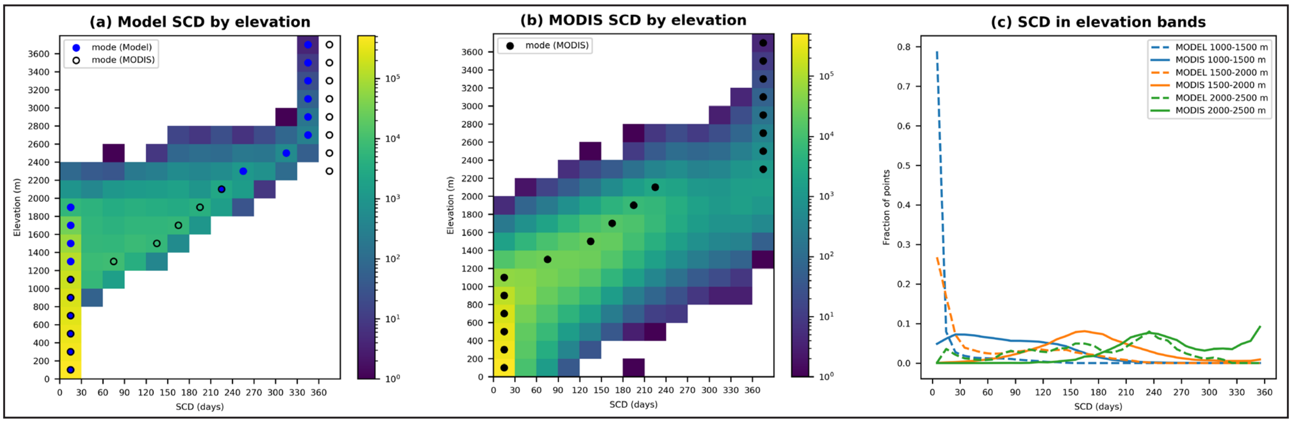


**Figure A3:** As for Figure 6 but for South Island simulations using VCSN as input (30 mm w.e. threshold).

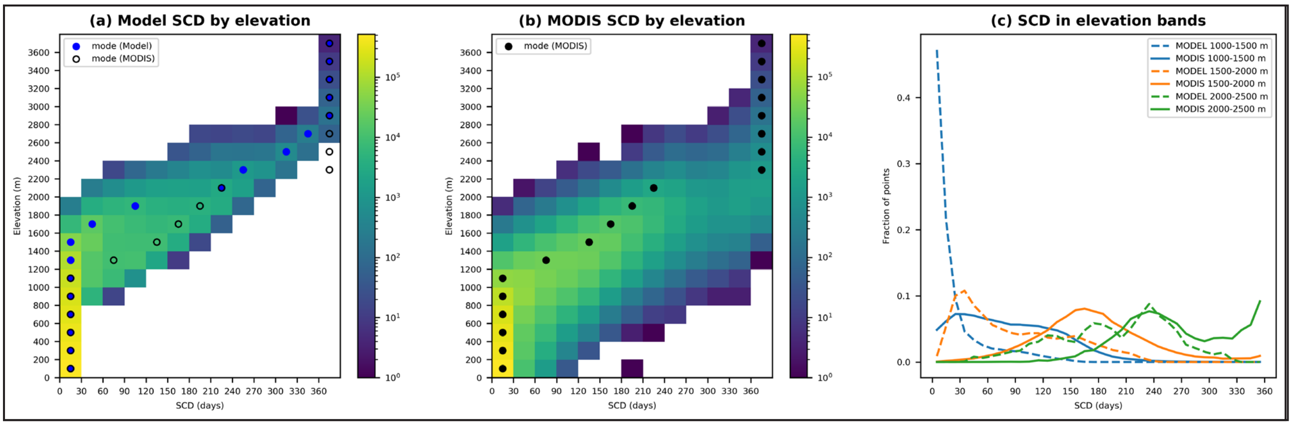


**Figure A4:** As for Figure A3 but 5 mm w.e. threshold.

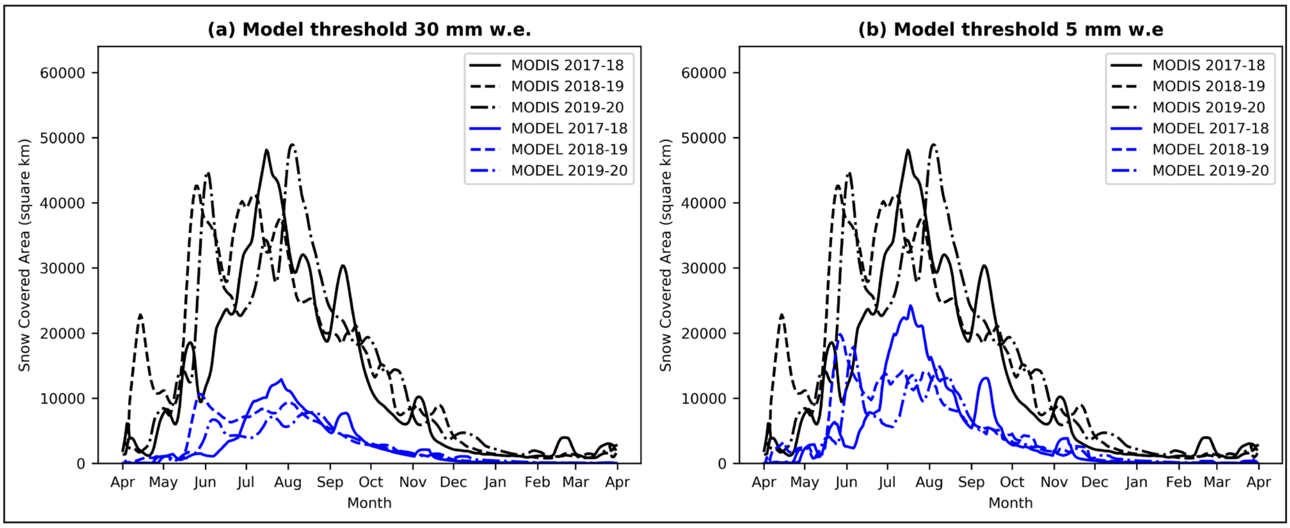


**Figure A5:** As for Figure 5 for South Island simulations using VCSN as input.

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