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Synoptic Influences on Snow Accumulation on Glaciers East and West of a Topographic Divide: Southern Alps, New Zealand

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Abstract

Understanding relationships between snow accumulation and synoptic climatology is important for assessing the way in which future climate variability will impact on glacier mass balance. However, few studies have as yet examined these relationships. Variability in snow accumulation on mid-latitude glaciers is strongly influenced by atmospheric circulation, orography, and redistribution of snow by wind. Very little is known about these processes in the New Zealand Southern Alps, where it is assumed that west-facing glaciers receive higher snow totals. However, few measurements are available to test this hypothesis. These processes were investigated over a 21-day period in winter 2008 on glaciers located west (Franz Josef Glacier) and east (Tasman Glacier) of the Main Divide of the Southern Alps. We directly measured snow accumulation and considered how it was affected by synoptic weather regime and location with respect to the Main Divide. Both glaciers received ~75% of their snowfall during troughing regimes, which are characterized by strong westerly quadrant winds bringing humid air masses from the Tasman Sea over the Southern Alps. The Franz Josef Glacier site received ~30% more snow than the Tasman Glacier site, but wind deflation meant that by the end of the study period, net snow accumulation was similar at both sites. Blocking synoptic regimes resulted in a reversal of prevailing westerly flow, generating strong downslope winds at Franz Josef Glacier and snow loss.

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Introduction

Understanding how synoptic weather systems influence snow accumulation is of increasing interest to the glaciological community (Romolo et al., 2006; Jansson et al., 2007), especially since climate warming will likely result in changes to atmospheric circulation patterns (Mullan et al., 2001; IPCC, 2007). Because atmospheric circulation exerts a primary control on processes influencing accumulation on glaciers—snowfall, wind redistribution of snow, avalanching, and ablation—synoptic control is likely to be strong. It is already clear that synoptic variability affects snow accumulation on annual and decadal time scales in continental climates (Grundstein, 2003; Romolo et al., 2006), and that glacial ablation is strongly affected by synoptic conditions (Hay and Fitzharris, 1988; Neale and Fitzharris, 1997; Cutler and Fitzharris, 2005). However, little is known about the impact of synoptic conditions on glacial accumulation.

Relationships have been found between large-scale atmospheric circulation and glacier mass balance. For example, advance and retreat of Scandinavian glaciers have been linked to phase changes of the North Atlantic Oscillation (McCabe et al., 2000; Nesje and Dahl, 2000; Nordli et al., 2005). In western North America the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have been correlated to both glacier fluctuations (Walters and Meier, 1989; Hodge et al., 1998), and to North American snowpack variability (McCabe et al., 2000; Jin et al., 2006). Similarly in New Zealand, ENSO has been related to the advance and retreat of glaciers in the Southern Alps (Fitzharris et al., 1997; Chinn et al., 2005). Embedded within these glacier-atmospheric circulation relationships are changes to frequencies in synoptic weather systems. Improved understanding of how synoptic weather systems manifest in snow accumulation on glaciers will assist in prediction of glacier behavior with climate change.

The distribution of snowfall in New Zealand is affected by the presence of the Southern Alps. Henderson and Thompson (1999) found that orographic processes result in higher precipitation on the western side of the Main Divide, with maximums (~10 m a^{-1}) recorded at elevations of 600–1700 m a.s.l. Recent work by Kerr (2009) suggests that there may also be a secondary or subsidiary precipitation maximum on the eastern side. However, both these studies suffer from a lack of direct measurement at elevations greater than 2000 m a.s.l.

Accurate measurement of snow accumulation in high alpine catchments is problematic (Barry, 1992). Automatic weather stations, precipitation gauges, and stakes are prone to burial by large snowfall in mountain regions. As a result a number of studies utilize accumulation/mass balance proxies rather than direct measurement (Fitzharris et al., 1997; Grundstein, 2003; Romolo et al., 2006). Success in snow measurement has been gained by utilizing ground penetrating radar (Machguth et al., 2006; Dunse et al., 2009), but this technique has yet to gain full success in New Zealand (Nobes and Owens, 1995). Therefore, limited data means that we are currently unable to assess how snow accumulation patterns vary across the Southern Alps, and therefore cannot assess how such patterns may change in the future.

Models are increasingly useful for understanding how glacier mass balance varies in response to climate (De Woul and Hock, 2005; Hock et al., 2009). Energy balance or degree day models are

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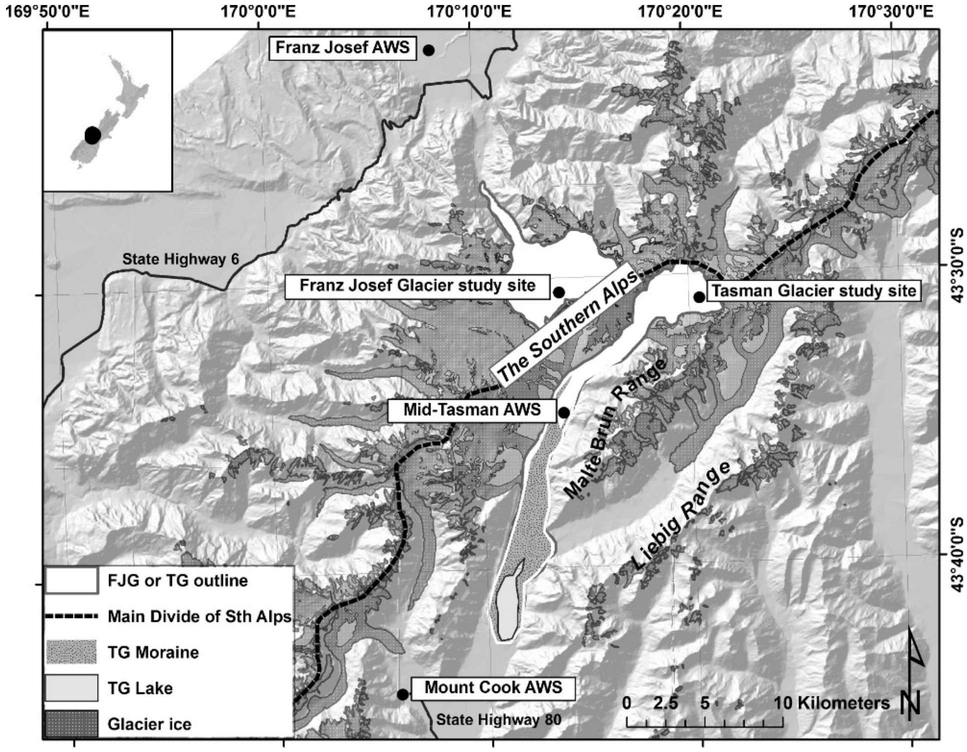

FIGURE 1. Location map of the Tasman Glacier (TG) and Franz Josef Glacier (FJG) study sites in relation to the Main Divide of the Southern Alps, and location of other automatic weather stations (AWSs) utilized in the study.

relatively good at simulating ablation (Hock, 2005), but they rarely consider snow accumulation processes in much detail. Orographic processes are usually included by calculating accumulation as a function of elevation (Oerlemans, 2001; Anderson et al., 2006). Large-scale orographic gradients, potential effects of preferential deposition, wind redistribution, or avalanching are not often included, although it is acknowledged that this approach is simplistic (Hodgkins et al., 2005; Machguth et al., 2006). Models that do account for snow transport by wind (Lehning et al., 2008; Mott et al., 2008) and gravitational processes (Dadic, 2008) exist, but are computationally expensive and are not used widely in accumulation studies.

In this paper, we use an empirical approach to investigate the impact of synoptic-scale climate systems on snow accumulation at two glacier sites during winter in the New Zealand Southern Alps. The specific objectives of this study are to: (1) quantify temporal patterns of total and net snow accumulation, at daily and synoptic time scales, by simultaneous direct measurement; (2) compare temporal patterns of measured snowfall across the precipitation gradient, that is, west and east of the Main Divide; (3) interpret results in relation to the passage of different synoptic weather systems; and (4) evaluate whether a simple, standard accumulation model can capture synoptic-scale variability in snow accumulation.

Study Site

The New Zealand Southern Alps form a 700-km-long, ~2500-m-high barrier to dominantly westerly atmospheric circulation, intercepting air masses of both temperate and subtropical origin. Rapid passage of weather systems over the New Zealand landmass means that a variety of synoptic situations can occur over a short time period (Sturman and Tapper, 2006). Franz Josef Glacier is located on the western flank of the Southern Alps (43°30′S, 170°14′E), covering an area of ~35 km^2, while the Tasman Glacier at ~95 km^2 is situated immediately on the eastern side of the range (43°30′S, 170°20′E) (Fig. 1).

The accumulation area of the Franz Josef Glacier is approximately 7 km in width, 3 km in length, has a low surface slope angle, and covers an area of ~25 km^2, approximately 70% of the total glacier area. It has a northwest aspect and is 25 km from the coastline. It is therefore directly exposed to prevailing westerly air flow from the Tasman Sea. The Southern Alps flank the southeast border of the glacier, and ice descends steeply from the accumulation area into a narrow valley, terminating at ~300 m a.s.l. The Tasman Glacier accumulation area is smaller at approximately 3.5 km wide, 5 km in length, and covering an area of ~16 km^2 (excluding tributaries flowing into the glacier below the equilibrium line). The accumulation area comprises only approximately 20% of the total glacier area. The Main Divide of the Southern Alps borders the west and north of the Tasman Glacier accumulation area, with the Malte Brun Range flanking the east and south. This glacier has a broad, gently sloping tongue, which descends southwards, terminating at 700 m a.s.l. into a rapidly growing lake. The lower 10 km of the glacier tongue is debris covered, thereby reducing melt rates on this lower part of the glacier (Purdie and Fitzharris, 1999).

Data and Methodology

SNOW ACCUMULATION MEASUREMENT

Study sites were established and field measurements undertaken during the austral winter of 2008. The Franz Josef Glacier study site (FJG) was established on 14 July, and measurements conducted over 24 days until 7 August. The Tasman Glacier study site (TG) was established on 17 July, and measurements conducted over 21 days, which were concurrent with the FJG site (Fig. 1). Both study sites were set up at approximately 2300 m a.s.l., on relatively flat snow surfaces in the center of the accumulation areas. Sites were chosen to be at least 100 m away from topography (ridges/depressions), which could potentially influence snow deposition patterns.

The FJG site was located in the Davis Snowfield (Fig. 2). There are no spatially comprehensive winter snow accumulation measurements for FJG. Previous net accumulation measurement shows that an area in close proximity to the winter site has recorded near average net accumulation (Purdie et al., 2010). The TG site was located close to a previous long-term mass balance measurement point (Chinn, 1994). Like at FJG, there have been no previous measurements of winter snow accumulation at high spatial resolution. However, a net accumulation survey in 2008 (Purdie et al., 2010) recorded a point nearby with lower than average net accumulation (Fig. 2).

At each study site four snowboards (0.4 m $\times$ 0.4 m) with central poles (2 m) were installed at 1 m intervals in a linear array aligned perpendicular to prevailing westerly flow (Fig. 3). Snowboards are a standard method for snow accumulation measurement (New Zealand Mountain Safety Council, 2008) and have been used to determine percentage under-catch for other precipitation gauges (Barry, 1992). However, a degree of under-catch is still likely, particularly during light snowfall accompanied by strong winds.

Each of the four snowboards in the array was used to measure accumulation at different time scales. For the purposes of this paper, results are presented from two of these boards: the 'total-board,' at which net snow accumulation was measured on a daily basis, and which allowed measurement of snow loss as well as gain; and the '24 hour board' at which daily snowfall was measured at 0900 hrs. Each time the 24 hour board was measured it was subsequently cleared of snow and repositioned on the snow surface. For each measurement, four separate depth measurements were made in each quarter of the boards and averaged (Fig. 3). Snow surface density was measured daily at the 24 hour board. Density was measured by weighing a 250 mL sample (taken with a Snowmetrics RIP 2 cutter) of fresh surface snow on a digital scale. Comparison of measurement between adjacent boards found snow depths to be within $\pm$10 mm. Relative measurement errors are estimated as depth ($\pm$5%), mass ($\pm$0.5%), and volume ($\pm$2.5%), equating to a total relative measurement error of $\pm$8%.

SNOW ACCUMULATION MODELING

Standard accumulation models, which predict snow accumulation using an elevation/temperature–based approach, have been found to provide effective estimates of snow accumulation on glaciers on seasonal and annual time scales (Oerlemans, 2001; Braithwaite et al., 2002; Anderson et al., 2006). Here we evaluate the usefulness of such models at a synoptic scale, by applying the model from Anderson et al. (2006). In this model, snow accumulation occurs on the glacier when precipitation occurs at a nearby low-elevation weather station and air temperature on the glacier is estimated to be below a snow/rain temperature threshold. A threshold of 1 °C was determined by best-fit modeling in New Zealand accumulation models (Moore and Owens, 1984; Barringer, 1989). Air temperature at the glacier site is calculated by applying a locally measured temperature lapse rate (-5 °C km^{-1}) to temperature measured at the low-elevation weather station (Anderson et al., 2006). A precipitation factor is applied to the low-elevation precipitation total, to account for orographic processes. For FJG, a precipitation factor (1.41) was empirically derived (Anderson et al., 2006) and for TG a precipitation factor of (1.46) was derived on the basis of interpolation of precipitation gradient maps (Henderson and Thompson, 1999).

Modeling was conducted using two configurations. The first model run (M1) utilizes the model parameters outlined above and is forced with hourly temperature and precipitation data from an automatic weather station (AWS) at Franz Josef (80 m a.s.l.) or Mount Cook (765 m a.s.l.) village for the FJG or TG site, respectively. These AWSs are owned and operated by the National Institute of Water and Atmospheric Science (NIWA). The second model run (M2) uses modified model parameters, including temperature lapse rates, based on AWS data measured at the low-elevation weather stations run by NIWA and AWSs installed at glacier study sites (see following section for AWS details). For M2, precipitation input data for each site are modified to better reflect regional variations in precipitation. This is done by combining precipitation from weather stations using distance weighting. A new measured precipitation factor is also applied to the distance-weighted precipitation. This derives a daily precipitation total for each site that is a reflection of precipitation recorded on both sides of the Southern Alps. For both model runs, hourly modeled precipitation is summed daily to enable comparison with daily (0900 hrs) measured snow accumulation.

SYNOPTIC CLASSIFICATION AND LOCAL CLIMATE

To assess the influence of synoptic type on snow accumulation, each day during the study was categorized as one of three synoptic regimes (troughing, zonal, or blocking; Fig. 4). Daily synoptic weather types were supplied by NIWA and classified according to the scheme of Kidson (2000). Kidson utilized 40-year NCEP/NCAR data to identify 12 different weather types for New Zealand, which were further categorized into zonal, troughing, or blocking regimes. Troughing regimes are characterized by frequent troughs and frontal systems crossing New Zealand, zonal regimes typically have high-pressure systems north of New Zealand with zonal flow to the south, and blocking regimes are characterized by high-pressure systems being more prominent in the south, stalling or slowing the passage of approaching weather systems (Kidson, 2000). Since their development, Kidson indices have been applied to studies of air pollution (Appelhans, 2009; Baldi et al., 2009), climate change (Lorrey et al., 2007; B. Mullan, personal communication), drought patterns (Salinger, 2009), and marine biodiversity (Dunn et al., 2009).

Meteorological variables were measured and compared between the glacier study sites. Temporary AWSs were set up at each site, ~4 m from the snowboard array, recording hourly temperature, humidity, and wind speed and direction (Fig. 3). Each site had a catch precipitation gauge (150 mL capacity) in case of liquid precipitation. Riming of AWS sensors occurred during storms, and both stations periodically required excavation and repositioning on the snow surface. Manual recordings (temperature, humidity, wind speed, and barometric pressure) were made daily at 0900 hrs at the sites with a Kestrel 4000 pocket weather tracker. Upper-level wind directions were determined by tracking cloud movement with a compass and used to confirm synoptic-scale flow. The degree of wind transport was categorized using the blowing snow scale from the New Zealand Mountain Safety Council (2008), which records snow transport as nil, light, moderate, or intense.

In addition data from an AWS situated on the mid–Tasman Glacier (1110 m a.s.l.), and data from the two low-elevation AWSs run by NIWA were used to consider local-scale climate variability. Data from the latter two were used to calculate the modified temperature and precipitation lapse rates for M2, and force both model runs.

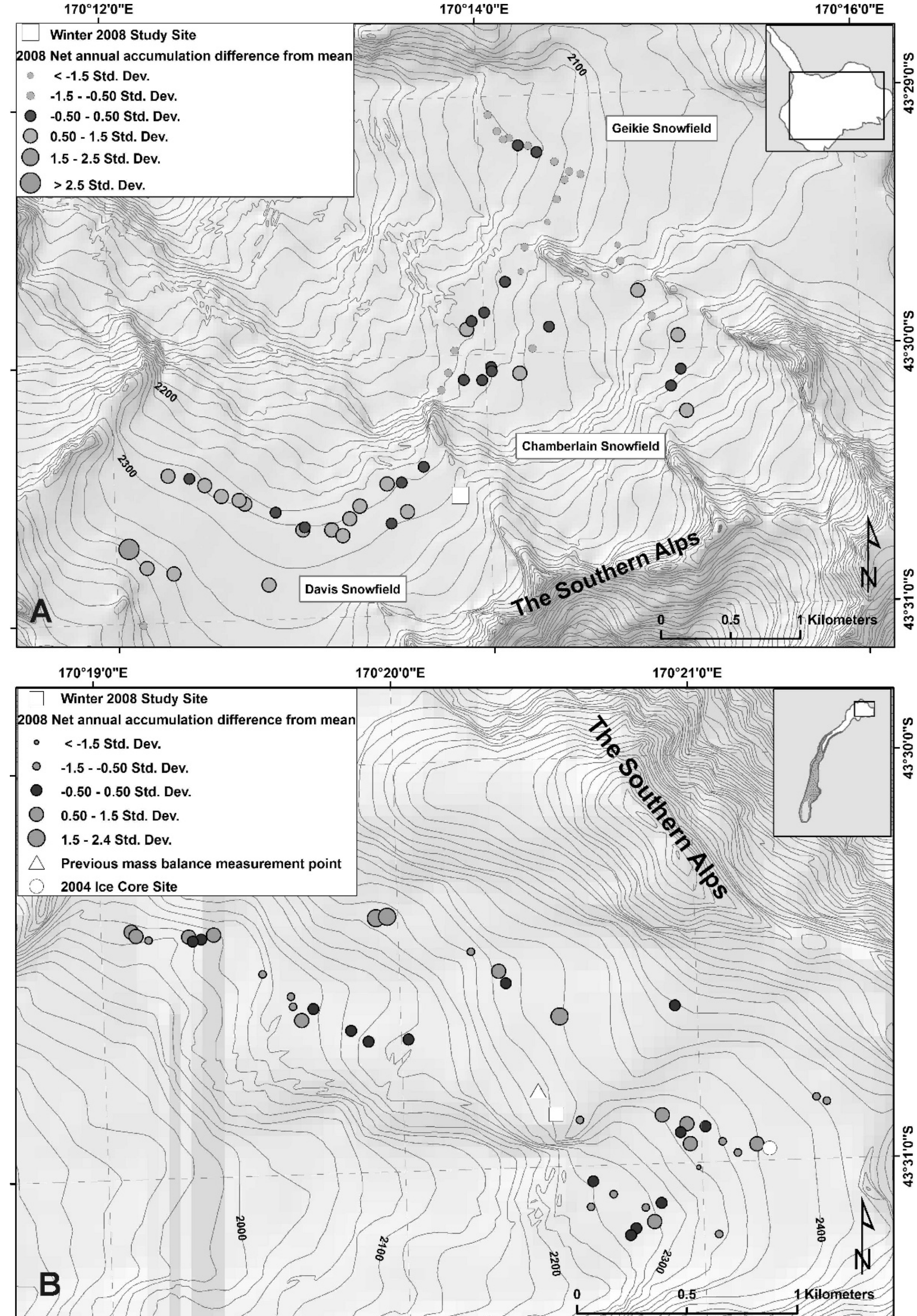

FIGURE 2. The Franz Josef Glacier (A) and Tasman Glacier (B) accumulation areas, showing the location of the winter study sites in relation to previous net accumulation measurement.

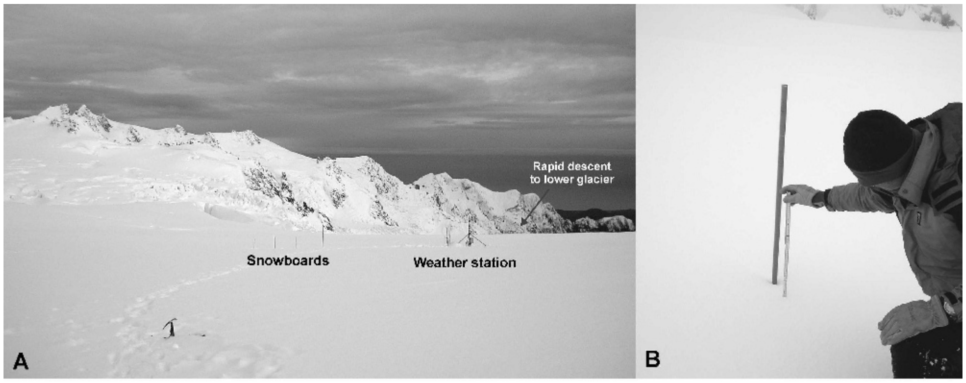

FIGURE 3. (A) Site layout at Franz Josef Glacier showing the four snowboards and automatic weather station. Photo taken looking to the southwest. (B) Snow depth measurement. The solid wooden ruler is easily inserted through the snow down to the wooden board. The central poles ensure relocation of boards after each snowfall.

Results

SYNOPTIC VARIABILITY IN SNOW ACCUMULATION

Direct observations and the absence of any liquid catch in the rain gauges at the study sites indicated that all precipitation received during the study period at both sites was solid. Snowfall events occurred on 15 of 24 days at FJG, and 14 of 21 days on the TG (Table 1 and Fig. 5). During the period of concurrent measurement, FJG received more snow on 56% of the days when snow occurred, and under all synoptic regimes.

In order to determine the extent to which the 24-day study period was representative of mid-winter conditions in other years, daily Kidson synoptic types from 14 July–8 August for the previous 50 years (1958–2007) were compared to those occurring during this study. The long-term (1958–2007) average frequency of twice daily (00UTC, 12UTC) Kidson synoptic weather types shows that during this time of year, troughing is most frequent and zonal conditions occur the least (Table 1). During the study period, troughing was more frequent than mean conditions, but still within one standard deviation of the long-term mean. Twenty-three of the previous 50 years also experienced higher frequencies of troughing (e.g. 1962, 1965, 1985, and 1986). In terms of the wider synoptic picture, of the 50 years of record, 21 years experienced similar regime frequency to 2008; the remaining 29 deviated from the mean by more than 1 standard deviation (e.g. 1970, 1974, and 2003). The regime frequency in the study period is therefore inferred to be reasonably representative of synoptic conditions of this mid-winter period.

A comparison of daily meteorological variables during the different synoptic regimes shows that zonal conditions were generally warmer and less windy during the study (Fig. 6). Troughing was associated with westerly quadrant winds, cooler temperatures, high humidity, and low pressure at both sites, with wind speeds higher at FJG. Blocking resulted in a reversal of normal wind direction (easterly quadrant winds dominated) and cold, humid conditions were recorded on TG. Low humidity, cold temperatures and strong downslope winds were recorded at FJG during these periods.

Of the 263 ± 21 mm water equivalent (w.e.) of daily snow accumulation recorded at FJG during the study, 77% occurred during troughing, 19% with blocking, and less than 10% during zonal conditions (Table 1). Likewise, at TG the majority of snowfall (76%) occurred during troughing regimes, with blocking conditions contributing the remainder. The later start date at TG meant that only two days of zonal flow were measured, and no snow accumulation was recorded on those days. Troughing conditions were in place over 50% of the time, and was the most persistent synoptic regime, sometimes lasting for five or more days.

By the end of the concurrent study period the western, FJG site had received 74 ± 6 mm w.e. (29%) more gross daily snowfall than the TG site, east of the Main Divide. However, on six occasions there was <2 mm w.e. difference in daily snow accumulation at both sites, which was below estimated measurement accuracy. On three occasions, when snow was recorded at both sites, the eastern glacier site recorded more snow accumulation (Fig. 5), in particular, on 28 July, when wind direction recorded at the site was from the northeast, and 12 mm w.e. more snow was recorded at TG in comparison to FJG. Excavation of a snow pit at the total boards indicated that at the end of the study, net accumulation was 231 ± 18 mm w.e. at FJG (indicating a loss of 22 ± 2 mm w.e.), and 217 ± 17 mm w.e. at TG. The net total at TG was 38 ± 3 mm w.e. more than the daily cumulative measurement (179 ± 14 mm w.e.). This difference between cumulative and net accumulation at TG could be influenced by a lack of density data recorded below 300 mm in the TG pit, due to weather and time constraints, or an indication that the total board at TG received more snow than the 24-hr board, which was not detected by depth measurements due to compaction. So overall, difference in net accumulation between the two sites was very small at only 14 ± 1 mm w.e. (6%).

REDISTRIBUTION OF SNOW BY WIND

During the study period, snow transport by wind was a regular occurrence, with 9 out of 24 days categorized as having 'moderate' or 'intense' snow transport. During intense transport it was difficult to determine how much snow was actually precipitating and how much was remobilized. Quantifying loss of snow is complex as changes to snow surface height can be a combination of wind deflation and compaction. In calm conditions, a reduction in snow surface height is expected due to snow compaction and settling (Dewalle and Rango, 2008), and during fine, calm weather, the snow surface height at the total board was measured to decrease by 10–20 mm per day. Density measurements of fresh (or surface) snow were taken on a daily basis, but a full density profile was only completed at the end of the study to determine overall net accumulation. Reductions in snow surface height, in terms of water equivalent, are therefore estimated by first subtracting potential surface reduction due to compaction, and increasing the estimated error (±2 mm w.e.) to account for the uncertainty in compaction rates.

Intense snow transport occurred during a SE storm on 30 July (Figs. 4 and 6). At FJG wind speeds up to 30 m s^{-1} were recorded before the wind speed sensor failed. By 0900 hrs on 31 July there had been a reduction in snow surface height (recorded at the total board) at FJG of 195 mm (Fig. 5), equating to 16 ± 3 mm w.e. On the eastern (windward) side of the Southern Alps at TG, the

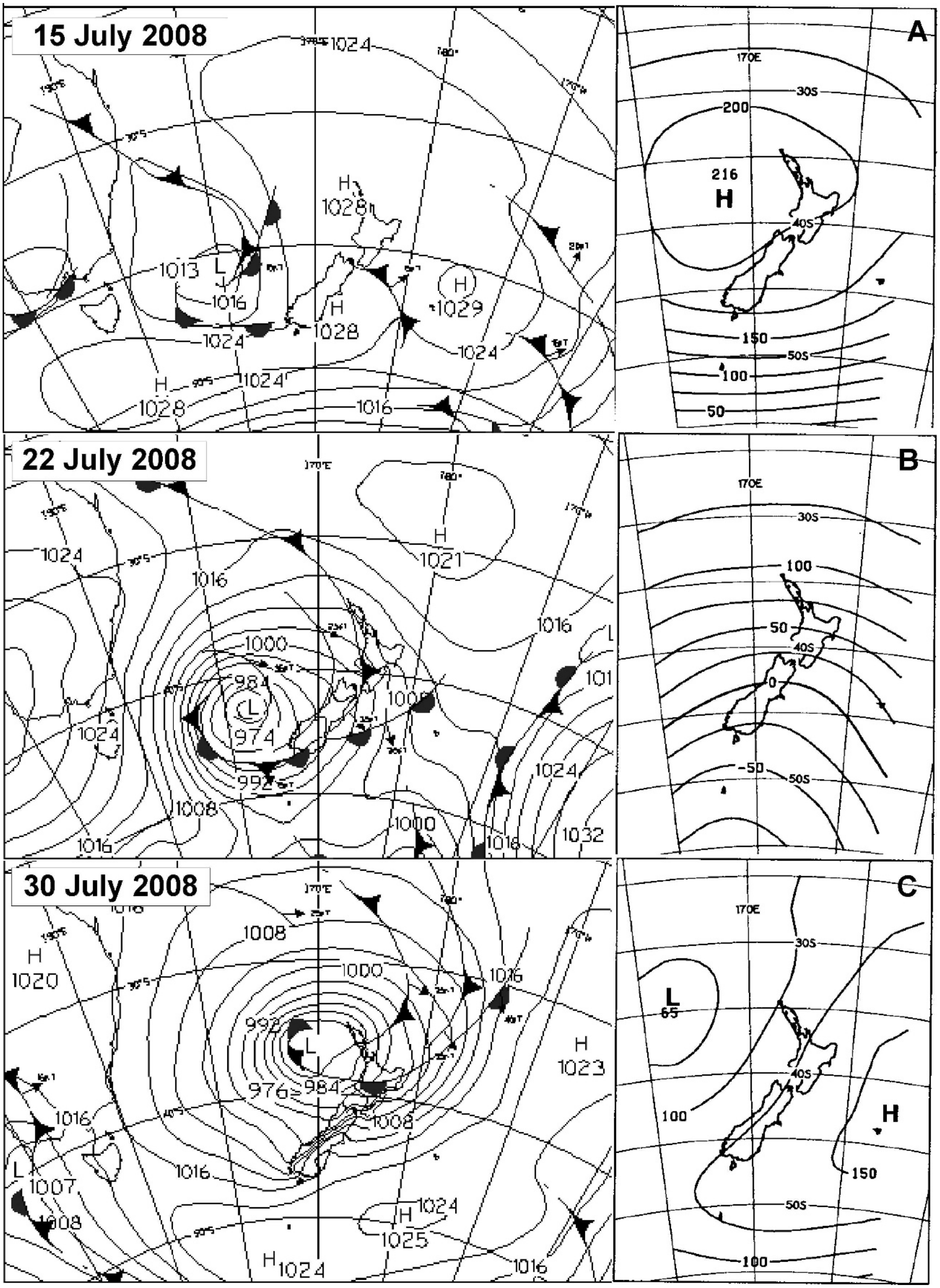

FIGURE 4. Examples of (A) zonal flow (15 July), (B) troughing (22 July), and (C) blocking (30 July) regimes at 00UTC during the study period. Synoptic analysis charts provided by Metservice, and Kidson diagrams from Kidson (2000).

TABLE 1

Snow accumulation measured at the 24-hr snowboard in relation to synoptic frequency, including the long-term synoptic average.

Synoptic regime			Franz Josef Glacier snow accumulation		Tasman Glacier snow accumulation	
Regime	% this study	% 1957–2008	Measured (mm w.e.)	% total	Measured (mm w.e.)	% total
Troughing	54	38	202	77	136	76
Zonal†	20	28	10	9	0	0
Blocking	26	34	51	19	43	24
Total snow all regimes (mm w.e.)			263 (24 days) 253 (21 days)		179 (21 days)	
Average measured density of fresh snow (kg m^3)			161		162	

† Simultaneous measurement was conducted during troughing and blocking regimes, but only two days of zonal flow were recorded at TG in comparison to five at FJG.

reduction in snow surface height, during the same storm, was only 56 mm (8 ± 2 mm w.e.) (Fig. 5).

Although occasionally blowing from the SE, wind directions recorded at the TG site during the storm tended to come from N-NE-E directions, and at times, a W direction, with gust speeds also reaching 30 m s^{-1}. Lower down the glacier, the mid-Tasman AWS recorded winds from the S-SE with a maximum average hourly wind speed of 11 m s^{-1}. This indicates a degree of localized wind turbulence at the TG site. So although snow was observed blowing down and away from the accumulation area at FJG during this storm, it is likely that turbulence resulted in redeposition of transported snow at the TG site.

Under troughing or zonal regimes snow surface changes were small (≤3 mm w.e. per day), and not beyond that which can be accounted for by compaction alone. However during blocking regimes, total snow surface reduction at FJG was 30 ± 4 mm w.e., and despite an additional 16 ± 1 mm w.e. of snow falling, there was an overall reduction in snow depth of 14 ± 3 mm w.e. during this synoptic type. At TG, although 16 ± 3 mm w.e. of snow surface reduction was recorded, there were still gains of 32 ± 3 mm w.e., giving a positive total during the same synoptic conditions.

Sublimation can also result in snow loss, depending on temperature, humidity, and wind speed (Liston and Sturm, 1998; Wever et al., 2009). However, sublimation was not thought to be an important process during this study, as periods of snow surface height reduction corresponded with high humidity (>90%) and observed, extensive wind transport. Increases in snow density from wind packing (Sato et al., 2008) could account for some of the loss in snow surface height, but not of the magnitude of reductions recorded.

CALCULATING MODEL PARAMETERS

Local climate data measured at the sites enabled the assessment and modification of standard model (M1) parameters, including temperature lapse rates, snow/rain thresholds, and precipitation factors (Table 2).

During the study, measured temperature lapse rates between low-elevation AWSs and glacier study sites were highly variable on

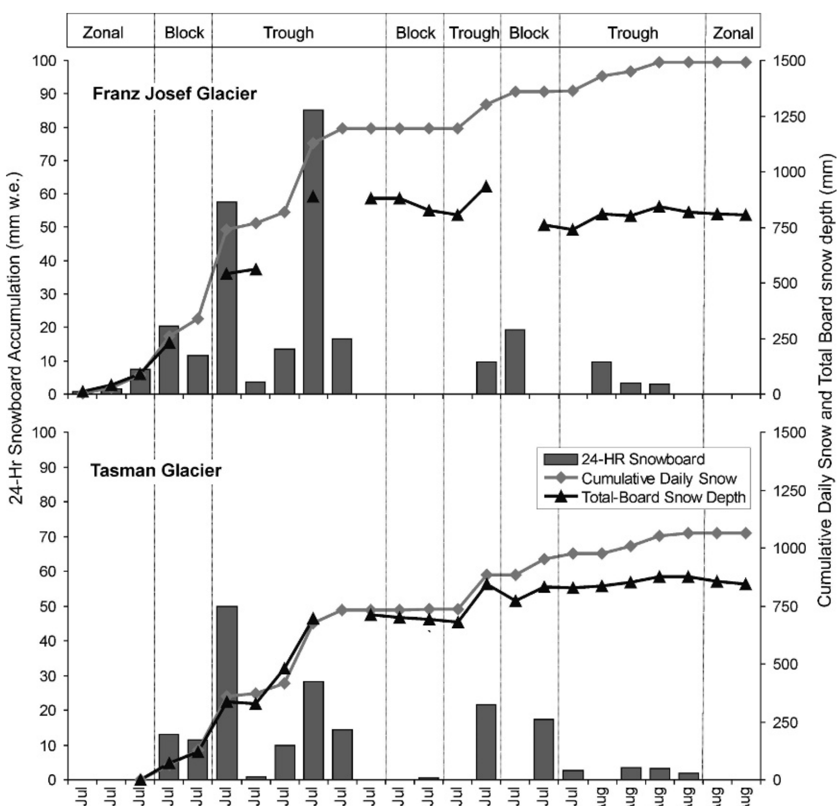

FIGURE 5. Daily measured snowfall recorded at 24-hour snowboard, cumulative daily snow, and snow depth at the total board (gains and losses) on Franz Josef and Tasman Glaciers. The study period is divided into synoptic regimes as per Kidson (2000). Snow was measured at 0900 hrs and assigned to the previous day as per standard meteorological convention.

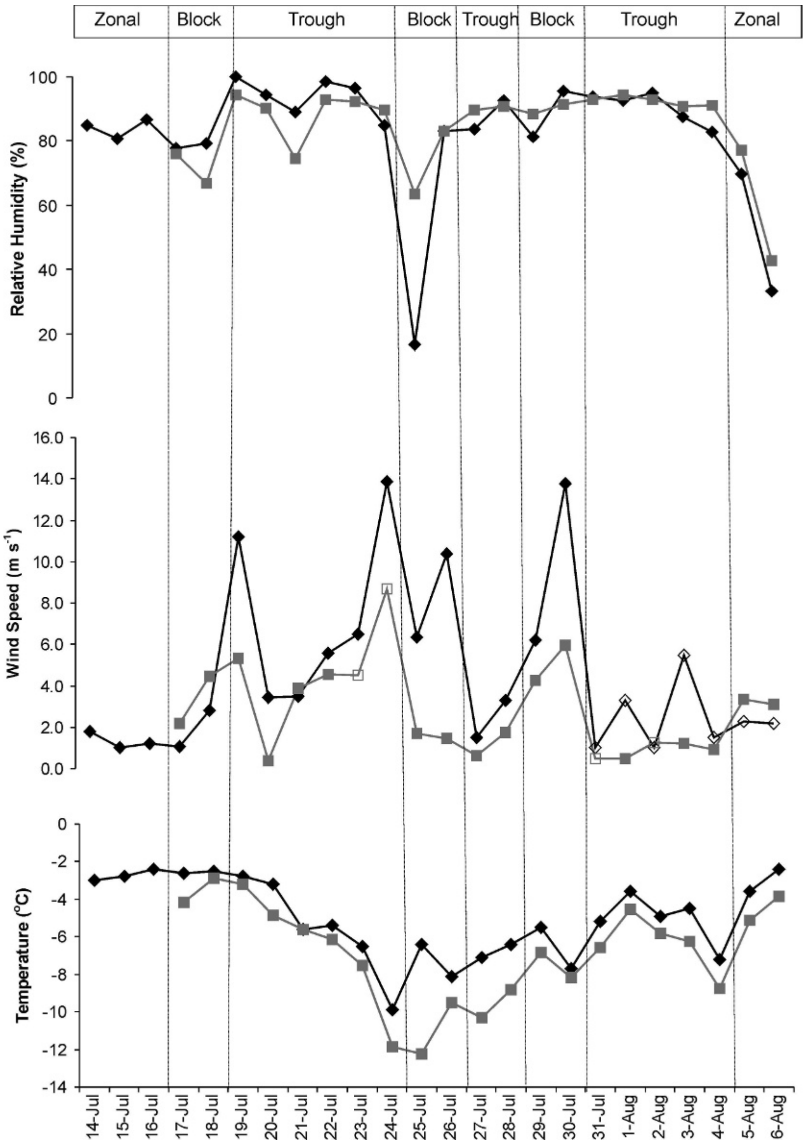

FIGURE 6. Average daily meteorological variables measured at the FJG (dark gray) and TG (light gray) study sites under different synoptic regimes.

an hourly scale, ranging from 0.1 to -10 °C km^{-1}, but had an average over the whole study period of -5.5 °C km^{-1} and -5.7 °C km^{-1} at FJG and TG, respectively. These values are similar to previously measured lapse rates in these catchments by Anderson et al. (2006) and Ruddell (1995) of -5.0 °C km^{-1} and -5.4 °C km^{-1}, respectively. At FJG lowest average rates (-4.3 °C km^{-1}) occurred during zonal flow, with near-average lapse rates during troughing and blocking. At TG blocking produced the lowest average lapse rates (-4.7 °C km^{-1}), troughing near average rates, and zonal the highest (-6.8 °km^{-1}), although only two zonal days were measured at TG. Longer-term temperature monitoring on Tasman Glacier has found that throughout the course of a year, temperature lapse rates between Mount Cook AWS and mid-Tasman AWS vary seasonally, with lowest rates (<-4 °C km^{-1}) occurring in winter and highest (>-9 °C km^{-1}) in summer.

Although temperatures at TG remained below zero throughout, positive temperatures were recorded on occasion at FJG, including 4 °C during snowfall on 20 July. Snowfall during this event was light, lasting for ~1–2 hours, and only resulting in 35 mm w.e. snow accumulation. Even so, this demonstrates that applying a 1 °C snow/rain temperature threshold will result in underestimation of snow accumulation. Kienzle (2008) conducted sensitivity analysis of snow/rain temperature thresholds in Alberta, Canada, finding a mean threshold of 2.6 °C. Likewise, measurement at mid-Tasman AWS in winter 2007 recorded snow accumulation events when air temperature was ~2–3 °C. Therefore a higher snow/rain threshold of 2.5 °C is used in M2.

Measured average precipitation factors between the glacier study sites and lowland AWS over the course of the study period were 1.51 and 1.36 for FJG and TG, respectively. However, on a

TABLE 2

Model parameters utilized by the initial (M1) and modified (M2) model run based on data measured during the study period.

Model parameter	M1	M2
Temperature lapse rate		
Franz Josef AWS—FJG Site	-5.0° C km^{-1}	-5.5 °C km^{-1}
Mt Cook AWS—TG Site	-5.0° C km^{-1}	-5.7 °C km^{-1}
Snow/rain threshold	1 °C	2.6 °C
Precipitation factors and weightings ( )		
Franz Josef AWS–FJG	1.41	1.51 (0.64)
Mt Cook AWS–TG	1.46	1.36 (0.26)
Mt Cook AWS–FJG	n/a	1.92 (0.36)
Franz Josef AWS–TG	n/a	1.07 (0.74)

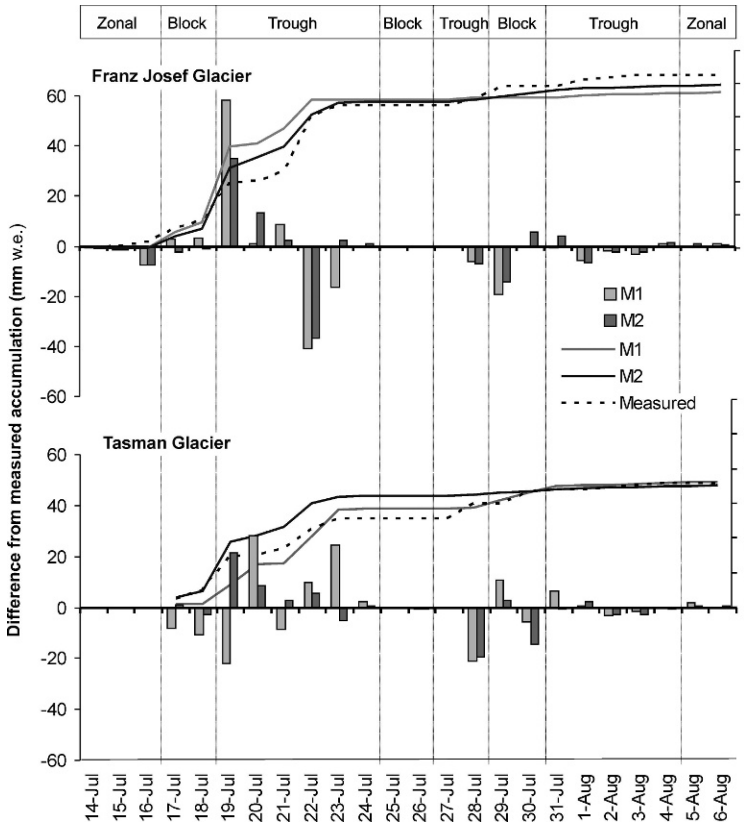

FIGURE 7. Difference between modeled and measured snow accumulation (bars) and cumulative modeled and measured snow accumulation (lines) at the study sites with a simple accumulation model.

per storm basis, factors could be highly variable, often ranging from 0.7 to 3.9 and in some cases being >30 or <1 (i.e. the lowland weather station received more precipitation than the glacier). These average precipitation factors measured during the study were applied to the M2 model run (Table 2). Franz Josef AWS is actually closer to the TG site than Mount Cook AWS, so with the change to distance weighting precipitation from both low-elevation AWS in M2, more weight is given to precipitation recorded at the western AWS when calculating snowfall for TG. It is important to note that these modified model parameters are based on measurement made during this study. Measurement during other seasons (e.g. spring, autumn) may result in variations in snow/rain temperature thresholds and precipitation factors. Despite this, comparing results from M1 and M2 provides opportunity to identify which model parameters are most sensitive over short temporal scales, and whether tuning a simple model to site parameters actually provides noticeable improvement.

COMPARISON OF MEASURED AND MODELED SNOW

Comparison between measured snow accumulation at FJG with a standard accumulation model (Anderson et al., 2006) found that by the end of the simulation, both M1 and M2 had underestimated total snow accumulation by 27 mm w.e. and 15 mm w.e., respectively (Fig. 7), although the difference in M2 is below the estimated measurement error of ±21 mm w.e. Simple linear regression between modeled and measured snow accumulation gave a correlation coefficient of $r^2 = 0.59$ for M1 and 0.70 for M2. On a daily basis results are variable. Both model runs underestimate accumulation during the first period of zonal flow. Orographic precipitation is not considered explicitly by the model, and although a precipitation factor is applied that accounts for some difference between low-elevation AWS and the glacier accumulation area, the factor is held constant under all synoptic regimes. On occasions <1 mm precipitation was recorded at the low-elevation Franz Josef AWS, yet >50 mm snowfall was recorded at the top of the glacier, suggesting the precipitation factor needs to be synoptically adjusted. M2 produced improved results for the first period of blocking (least windy), but there is still a large difference between modeled and measured precipitation with the blocking event at the end of July, although this was an exceptionally windy storm. During troughing both simulations overestimate (19th) and underestimate (22nd) snow accumulation. On the 23 July, large improvement is seen with M2, as a frontal system moved east across the Southern Alps, ceasing to rain at Franz Josef township, while rain continued at Mount Cook village. Overall, the largest differences between measured and modeled (either run) precipitation occurred during troughing, when differences exceed 50 mm w.e. for M1 and 30 mm w.e. for M2. Best model performance (least difference) in either run was during zonal flow.

Simulation at the TG site also showed variable quality on an event-based scale (Fig. 7), but noticeable improvement was gained on some days by the additional precipitation data from Franz Josef AWS used in M2, with $r^2 = 0.31$ and 0.79 for M1 and M2, respectively. The cumulative difference between modeled and measured precipitation with either run was very small (3 mm w.e.), with M1 slightly overestimating and M2 underestimating cumulative snow accumulation. Consequently the difference in both simulations falls well below the estimated accuracy of the manual measurement (±14 mm w.e.). On 28 July, large difference exists between modeled (either run) and measured precipitation at TG. This snowfall was accompanied by very light winds (<2.5 m s^{-1}) from NE-NW directions, meaning that wind redistribution cannot account for the difference. Temperature, both modeled and measured, was below zero, so neither the temperature lapse rate nor the snow/rain threshold can account for the difference. In other words, the local nature of precipitation means that it is difficult to simulate all events using lowland weather station data and a precipitation factor, even using values that are specifically tuned for the glacier in question.

Discussion

SNOW ACCUMULATION AND SYNOPTIC REGIME

This study aimed to simultaneously quantify snow accumulation on glaciers east and west of the Southern Alps in order to gain better understanding of relationships between synoptic weather systems and snow accumulation processes. As expected, the western and predominantly windward site on the Franz Josef Glacier recorded more snow accumulation than the eastern, predominantly lee, site on Tasman Glacier. But by the end of the study, there was little difference in net accumulation between the two sites, attributed at least in part to wind deflation.

During the study period, some of the largest snowfalls occurred with northwesterly conditions during troughing regimes, and both sites received >75% of their total measured snowfall during troughing events. The largest difference in snow accumulation east and west of the Southern Alps occurred under blocking conditions, which resulted in snow loss from FJG during strong southeast winds. On a regional scale, blocking is not necessarily associated with strong winds (Kidson, 1994), but in this case, the stalling of low-pressure systems east of the South Island resulted in large pressure gradients, generating very strong downslope winds west of the Southern Alps. Zonal circulation occurred least during the study period, and also resulted in the least snow accumulation.

New Zealand's maritime climate means that snow accumulation can occur year-round, but seasonal shifts in freezing levels result in the majority of snow accumulation occurring during winter and spring. As this study was conducted during winter, a question remains about relationships between synoptic weather systems and spring snowfall patterns. Synoptic frequencies in the New Zealand winter are similar to those occurring in spring, with larger differences to frequencies in the autumn and summer seasons (Kidson, 2000). Although it would have been desirable to undertake this experiment over a whole year, results from this winter survey, in terms of proportions of snow accumulation received under different synoptic regimes, still provides some insight into the potential impact that a change to synoptic frequency during the accumulation season could have to snow accumulation on glaciers.

Variation in synoptic frequency is driven by changes in atmospheric circulation patterns (Sturman and Tapper, 2006). In New Zealand, ENSO/Interdecadal Pacific Oscillation (IPO) phases have been linked to anomalous southwesterly (El Niño, negative ENSO, positive IPO) and northeasterly (La Niña, positive ENSO, negative IPO) circulation anomalies (Salinger et al., 2001). La Niña (El Niño) conditions in the Pacific are associated with a reduced (increased) frequency of troughing regimes and higher (lower) frequency of blocking circulation in New Zealand (Kidson, 2000). On longer time scales, increased troughing frequency was identified as an important factor associated with cooling and increased precipitation in New Zealand during the Little Ice Age (Lorrey et al., 2008). The recent negative phase shift in the IPO (Folland, 2008) indicates that the Southern Alps are likely to become warmer and receive less precipitation in future years than they did between 1977 and 2001 (Salinger et al., 2004).

Associations between synoptic frequencies, atmospheric circulation, and snow accumulation demonstrated in this and other studies are important on longer time scales. During the last few decades, glacier advances in Patagonia have been linked to increased westerly circulation and reduced blocking events, associated with positive IPO (negative ENSO) phases, whereas an anti-phase relationship exists between New Zealand and tropical Andean glaciers (Fitzharris et al., 2007). Similar relationships are evident worldwide. For example, increased troughing synoptic regimes have been associated with higher rates of snow accumulation in the Peace River Basin, Canada (Romolo et al., 2006), and on the northern Great Plains, U.S.A. (Grundstein, 2003). Similarly, positive phases of the NAO have resulted in increased winter accumulation on western Norwegian glaciers (Nesje et al., 2000; Nordli et al., 2005), and an inverse mass balance response is seen between Wolverine Glacier, Alaska, and South Cascade Glacier, Washington, U.S.A., in association with phase changes of the Pacific Decadal Oscillation (PDO) (Josberger et al., 2007). In conclusion, one must consider the role of regional (synoptic-scale) climate variability and its affect on mass balance when considering the future response of temperate glaciers, as the direction of change may enhance or buffer the anticipated negative mass balance of glaciers.

MODELING SNOW ACCUMULATION

While there are a number of complex snow accumulation models available (Liston and Elder, 2006; Lehning et al., 2008) which would likely improve snow accumulation estimation on glaciers, neither the meteorological input data (i.e. multi-level wind speeds from alpine catchments) to drive these models, nor the detailed accumulation measurements to calibrate and validate these models exist, except for a few specialized studies (Liston and Sturm, 1998; Mott et al., 2008; Dadic et al., 2010). Many of the worlds regions suffer from paucity of data—for example, South America (Popovnin et al., 1999), China (Sakai et al., 2009), and the Himalaya (WGMS, 2008). Therefore our data provided an opportunity to evaluate the ability of a simple snow accumulation model to capture synoptic-scale variability.

Troughing synoptic regimes accounted for ≥75% of measured snow accumulation during the winter study period. However, the largest difference between modeled and measured precipitation also occurred during troughing regimes, which were most frequent (Fig. 7). Total snow accumulation during blocking regimes was underestimated, with largest difference coinciding with snow accumulation during high winds. Simulation of snow accumulation under zonal flow was most successful, although it is important to note that this synoptic regime occurred least frequently, and overall contributed least to total snow accumulation.

Model performance was better at the eastern (TG) site, where after 21 days there was only a small (2%) difference between measured and modeled snow accumulation. It is likely that wind redistribution of snow was a factor in performance at the western FJG site, with biggest discrepancies between modeled and measured snow accumulation often associated with strongest wind speeds. Wind redistribution not only potentially removed snow from the site (e.g. 19 July), but also enhanced deposition (e.g. 22 July).

The importance of redistribution and preferential deposition of snow by wind has been quantified on complex glaciated terrain in the European Alps (Liston and Sturm, 1998; Lehning et al., 2008; Mott et al., 2008; Dadic et al., 2010). Interaction between wind dynamics and topography tend to result in increased snow deposition on lee slopes and reduced deposition on exposed slopes (Liston and Sturm, 1998). Strong downslope (SE) winds under blocking conditions resulted in significant loss of snow from the FJG site, but during the same period the TG site recorded both wind deflation and deposition, with complex topography resulting in turbulence, generating winds contrary to the general synoptic flow.

Aside from wind transport, event-scale variability in precipitation factors between low-elevation weather stations and high-elevation sites means that accurate snow accumulation estimation cannot be achieved by using a single precipitation factor. Applying a range of precipitation factors based on synoptic regime may provide improvement. Likewise, increasing precipitation input data to include a larger number of surrounding weather stations (especially at high elevation) would better capture regional precipitation patterns.

During this study, cold winter temperatures at the low-elevation AWS meant that the model was not very sensitive to choice of lapse rate, or snow/rain temperature thresholds. In the New Zealand Southern Alps, snow accumulation can occur year-round, with some of the largest snowfalls in spring, when warm moist air masses cross the Tasman Sea and intercept the mountain range. On Tasman Glacier, temperature lapse rates between low-elevation AWS and glacier AWS have been found to vary seasonally, with largest rates during summer and smallest in winter. Kienzle (2008) recorded seasonal variations in snow/rain temperature thresholds in Alberta, Canada, with mean monthly maximums (~5 °C) occurring in winter, and minimums (0 °C) in summer. How such thresholds vary in the Southern Alps is unclear, but during the study, snowfall occurred at the FJG site when the temperature was 4 °C. So although these two model parameters did not account for inaccuracies during this winter simulation, such may not be the case if the study were repeated in spring.

In the absence of increased meteorological observation allowing application of higher order models, this study demonstrated that a simple snow accumulation model did provide reasonable approximation of cumulative snow accumulation, but still failed to capture event-scale variability. Interestingly, there was only small cumulative improvement by tuning model parameters specifically to the sites (M2), thus highlighting the difficulty in utilizing input data measured at low-elevation weather stations to estimate snow accumulation at a single point on a glacier. Utilizing more precipitation input data, and gaining a better understanding of precipitation relationships between low-elevation meteorological sites and glacier catchments under varying synoptic flow is essential to improve snow accumulation simulation. The challenge is to find ways to refine models without large increases to input data and computational requirements.

Spatial variability in snow accumulation on glaciers is important to both accurate mass balance measurement and modeling (Fountain and Vecchia, 1999; Jansson and Pettersson, 2007). This study has demonstrated links between synoptic frequencies and snow accumulation, but in order to be applied to the glacier as a whole, an assessment of how snow accumulation is spatially distributed on these glaciers is essential and is part of ongoing research (Purdie et al., 2010).

Conclusions

Synoptic flow type was found to influence snow accumulation patterns during winter at two glacier study sites in the New Zealand Southern Alps, with troughing regimes accounting for over 75% of recorded snowfall. Although only 8 km apart, the predominantly windward, Franz Josef Glacier site received ~30% more snow accumulation than the Tasman Glacier site, lee of the Southern Alps. However, wind deflation meant that after 21 days, net accumulation at both sites was similar. A simple accumulation model estimated snow accumulation to within 8% of measured values, but large discrepancies occurred from day to day. Improvement could be gained by using a more complex snow accumulation model, but as yet in New Zealand (and other parts of the world), insufficient data exist to force such models.

Only capturing a short time-period during winter, this research needs to be extended for longer time periods and to other regions. If such relationships between synoptic frequency and snow accumulation are shown to hold over longer time scales, then expected future changes to atmospheric circulation patterns and synoptic frequency, in particular, a decrease in troughing, would lead to more negative mass balance on glaciers in New Zealand. Similar outcomes may also be likely on other maritime glaciers (e.g. Patagonia, Norway, Alaska) where the position of winter storm tracks are influenced by regional-scale climate variability.

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