THE SURFACE REFLECTANCE OF SNOW TUSSOCK

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ABSTRACT

A series of albedo measurements taken over native snow tussock yielded a mean daily value of 0.20. Tussock albedo was observed to exhibit strong diurnal variation under clear sky conditions; the observed zenith angle dependence was found to be higher than taller crops such as corn. The observed zenith angle/albedo relationship was used to investigate annual and latitudinal variation in clear sky tussock albedo values. An analysis of tussock albedo dependence on atmospheric transmissivity revealed a noticeable decrease in albedo under overcast, low cloud conditions. It was estimated that these effects could amount to changes of up to ±15% of net radiation in the middle of the day at a mid-latitudinal site.

INTRODUCTION

The reflectance, or albedo, of a surface is of fundamental importance in determining the amount of energy available for evapotranspiration, convective heat transfer, heat conductance into the soil, as well many other physical and biological processes. It is well known, for example Sellers (1965), that the albedo of vegetated surfaces varies on daily and seasonal time-scales in response to variation in the nature of the incoming solar radiation (e.g. incidence angle, spectral qualities, ratio of diffuse to direct radiation) and the nature of the surface (e.g. roughness, leaf area index, soil moisture status, plant senescence).

Knowledge of surface albedo (both the magnitude and the spatial and temporal variability) is important in many climatological applications such as estimation of evapotranspiration rates (Fitzharris, 1974), modelling urban climates (Please et al. 1976), and more recently in modelling land surface processes in general circulation models (GCMs). In 1974, Fitzharris pointed out that the albedo of typical New Zealand vegetation associations such as tussock grassland and beech forest were almost unknown. To a large extent, this observation is still true today, and it is somewhat ironic, given the relative simplicity of albedo measurements, that GCM modellers include better knowledge of the surface albedo (including diurnal and seasonal variations) amongst the priority areas for improving models of land surface processes (Verseghy, pers. comm. 1991).

Alpine grass or snow tussock (*Chinochloa rigida*) is a significant landcover in many New Zealand watersheds, particularly in catchments east of the main divide which experience low and variable precipitation regimes. There are several interesting features of tussock which may have implications for seasonal and diurnal variation in albedo. The dominant feature of tussock is its stiff, narrow, rolled leaves or tillers. These tillers spread out from a clumped base to form a cone shape from 30 cm to 100 cm in height. This structure minimizes shading, and permits radiation to easily penetrate the canopy. Another feature is the existence of dead material at leaf ends. This material increases during the dry season, the proportion of green leaf matter decreasing with increasing moisture stress. Pollock (pers. comm., 1977) found that during clear days, tussock leaves increased their amount of leaf roll in response to diurnal moisture stress within leaves. Leaf roll has the potential to decrease the area exposed to radiation by 20-30%. According to Redman (1973), reduction of surface area by leaf roll should increase plant reflectivity. However, the random orientation of leaf surfaces within a tussock canopy is likely to reduce the significance of this effect.

The objective of this note is to publish results of albedo measurements made over snow tussock during a two month period in 1977. Due to the relatively short period of measurement, plant-related seasonal effects were unable to be addressed. However, data were obtained which document diurnal variation in tussock albedo in response to changes in solar elevation, as well as changes in albedo in response to changing cloudcover. These results were previously unpublished (Brown, 1977) and not widely available.

DATA COLLECTION

Daily values of incoming and reflected solar radiation were obtained from March 19 to April 27, 1977 over a dense stand of snow tussock near the summit of Flagstaff (66 m) approximately 10 km northwest of the city of Dunedin. The site was located at 45.8°S 170.5°E in a water catchment area for the city of Dunedin free from agricultural-induced modifications of the vegetation cover.

Incident and reflected global short-wave radiation were measured by an upward and downward-facing Kipp and Zonen pyranometer mounted on a standard surveying tripod. The inverted sensor was attached to the end of an arm extending approximately 1.0 metre beyond the centre of the tripod. The arm was oriented toward the north to reduce the effect of instrument shadow. It was estimated from a method outlined in Slatyer and McIlroy (1961) that instrument mountings and their shadow occupied less than 1.0% of the effective reflecting surface. The downward-facing sensor was mounted 1.0 metre above ground level which gave an integrated recording of reflected solar radiation over 28 m^2 of tussock. Output from the two instruments were fed to a chart recorder and daily mean albedo values obtained by planimetery. This procedure produced an integrated daily mean albedo value.

RESULTS

Over the period of measurement, 28 values of mean daily tussock albedo were obtained which ranged from 0.12 to 0.26. The mean value was 0.20 with a standard deviation of 0.04. Scott et al. (1968) reported a mean albedo value for tall fescue tussock of 0.26. However, this represents the mean of only two spot measurements, while the date, time and location of the measurements are not given. Greenland (1971) took measurements of tussock albedo at solar noon on four different occasions at Cass, Canterbury, to determine if there was any seasonal change. The results suggested little seasonal change with a mean albedo value of 0.14. It is probably not appropriate to compare the results of these spot measurements with the integrated daily values obtained in this study since the latter take into account diurnal variation in solar elevation as well as changes in the properties of the incoming solar radiation. The observed mean daily tussock albedo value of 0.20 agrees well with published mean albedo values for tall grasses (Table 1).

Variation of Tussock Albedo with Solar Elevation

Under clear sky conditions, many natural surfaces exhibit a diurnal trend in albedo that

TABLE 1: MEAN ALBEDO VALUES FOR TALL GRASSES.

Type	Albedo	Source
30 cm high Pangola grass	0.19	Lin-sien-Chia (1967)
High Standing grass	0.20	Budyko (1958)
Savannah grasses	0.23	Oguntoyinbo (1970)
Snow tussock	0.20	Brown (1977)

typically follows an exponential relationship of the form

$$\alpha_c = a_0 e^{bZ} \qquad (1)$$

where α_c is the instantaneous clear sky albedo, a_0 represents a 'crop factor' coefficient, and b is a coefficient describing the rate at which albedo changes with changing zenith angle, Z (Arnfield, 1975). This phenomenon occurs because many natural surfaces exhibit anisotropic reflection at lower solar elevations, and in the case of vegetation, because sunlight is able to penetrate the canopy more effectively at higher solar elevations. Numerous investigators (e.g. Monteith and Sceicz, 1961; Davies and Buttimor, 1969; Kalma and Badham, 1972) have noted asymmetry in the diurnal trend, with afternoon albedo values higher than their morning equivalents. The most plausible explanations for this are plant response to diurnal moisture stress (Davies and Buttimor, 1969), and diurnal change in the spectral quality of global radiation (Nkemdirim, 1972).

Only two of the 28 days of albedo measurements were clear days suitable for investigating the diurnal response of tussock. Albedo values were computed for each hour, and are shown plotted in Figure 1 against the corresponding value of solar zenith angle. There was no evidence of significant diurnal asymmetry in the Flagstaff tussock albedo data. However, it was unlikely the tussock underwent any moisture stress during these two days as the soil was wet during the entire field period.

Figure 1 also shows the results of clear sky tussock albedo measurements made at Cass, Canterbury, by Greenland (1971). These agree

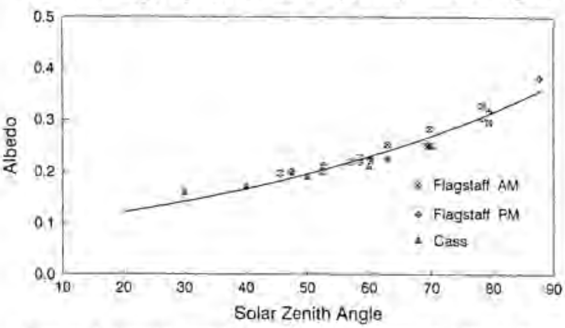

Figure 1. Zenith angle dependence of tussock albedo from measurements made at Flagstaff, Otago (Brown, 1977) and Cass, Canterbury (Greenland, 1971).

well with the Flagstaff values. A nonlinear least-squares regression technique following Marquardt (1963) was used to fit equation (1) to the pooled data in Figure 1. This yielded 0.088 for a_0 and 0.016 for b ($r^2 = 0.93$). According to Arnfield (1975), b increases with surface roughness. Table 2 shows typical values of b for various surfaces including tussock, which shows that tussock behaves as a much 'rougher' surface than its physical height might suggest. One can conclude from this that tussock is particularly effective at trapping radiation via multiple reflections within the canopy at higher solar elevations.

TABLE 2: VALUES OF *b* FOR VARIOUS SURFACES

Surface	$b \times 10^2$
Bare soil	0.826
Short grass	1.063
Cornfield	1.206
Tussock	1.600

As outlined by Arnfield (1975), the above observed relationship between tussock albedo and solar zenith angle allows one to investigate the effect of seasonal and latitudinal variation in zenith angle on clear sky tussock albedo. Standard equations from Sellers (1965) were used to compute the half-day length for a given latitude and time of year. Eqn. (1) was then integrated numerically over the half day length to obtain a mean daily albedo value assuming a symmetrical diurnal response. A cosine weighting function was applied to weight albedo values according to variation in incoming solar radiation i.e. a low weight was given to early morning and late afternoon albedo values where the amount of incoming solar radiation is a small fraction of that received during the middle of the day. Seasonal and latitudinal variation in estimated mean daily albedo is shown in Figure 2 for latitudes 35°S, 46°S and 55°S, along with the minimum (midday) daily value of clear sky tussock albedo for 46°S. The latitudinal effect is most noticeable in the winter months, but it is unlikely to have a significant impac on the surface energy balance because of the smaller amounts of incoming solar radiation at this

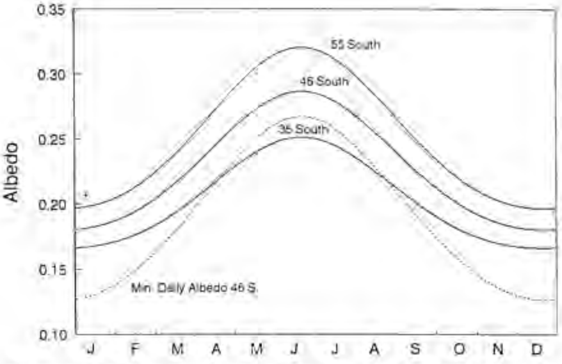

Figure 2: Estimated annual and latitudinal variation in mean daily clear sky tussock albedo based on the zenith angle dependence observed in Figure 1. Estimated minimum daily albedo value (at solar noon) is also shown for 46°S.

time of the year. In contrast, the diurnal effect (manifested by the difference between the average and minimum daily albedo curves for 46°S) is at a maximum in summer when incoming solar radiation is at a maximum. The potential implications of this effect on the surface energy balance are addressed later. The estimated summer minimum tussock albedo value of 0.13 agrees well with a value of 0.127 obtained by Greenland (1971) at solar noon on January 29, 1967.

It should be noted that Figure 2 is only intended to demonstrate the potential sensitivity of tussock albedo to zenith angle variation. The curves are not proposed for applied use as they are based on only three days of measurements made in the late-spring and autumn when diurnal moisture stress was unlikely. Albedo measurements clearly need to be made over a longer period to examine potential sources of variation in b and a_0 related to plant factors such as diurnal moisture response, and seasonal variation in green leaf material.

Nkemdirim (1972) pointed out that with a complete cloudcover, the sky becomes the effective radiating surface which has the effect of decreasing the diurnal range in albedo and the daily mean. Arnfield (1975) also found that cloudcover decreased the dependence of albedo on zenith angle. More recently, Hay and Darby (1984) showed that surface albedo decreased in response to the increased component of diffuse short-wave radiation associated with the eruption of El Chicón in April 1982. In this particular case, the negative feedback effect of the decrease in albedo was sufficient to compensate for the reduction in incoming total short-wave radiation.

Equipment was not available to measure diffuse radiation at the tussock albedo measurement site. The mean daily transmission coefficient (or transmissivity) was therefore used as an index of the proportion of diffuse radiation following Nkemdirim (1972). The transmissivity, T_r, was computed by dividing the daily total global short-wave radiation received at the surface by the daily total solar radiation incident at the top of the atmosphere. T_r is an index of the amount of scattering and absorption going on in the air column, and depends on numerous variables such as clouds (amount, type, thickness) optical air mass thickness, aerosols (concentration and size distribution) and precipitable water. It was assumed that the ratio of diffuse to direct beam radiation will follow some form of inverse proportional relationship to T_r.

Albedo values are shown plotted as a function of T_r in Figure 3. Ignoring one outlier, a curvilinear relationship of the form

$$\alpha = 0.021 + 0.049 \log_e T_r, \quad T_r > \sim 5\% \quad (2)$$

was found to explain 72% of the variance (compared to 61% for a linear relationship). Figure 3 shows that the effect of transmissivity on tussock albedo is strongest for transmissivities lower than about 30%. According to data in Haurwitz (1948, Table 4) on the average transmission coefficients of overcast skies for various cloud types, this threshold corresponds to the change from cirriform and altiform clouds to stratiform clouds. Clearly more data are needed in the 20-40% transmis-

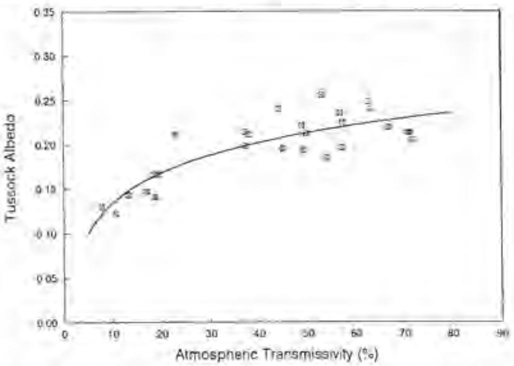

Figure 3: Observed dependence of mean daily tussock albedo on mean daily atmospheric transmissivity.

TABLE 3: INPUT VALUES USED IN ENERGY BALANCE MODEL.

	Summer	Winter
Latitude	46°S	
Day	January 1	June 15
Atmospheric Pressure	1015 mb	
Dust particle concentration	$0.2/cm^3$	
Mean diurnal air temperature	15°S	5°C
Relative humidity	62% clear (82% cloudy)	
Precipitable water	14 mm	
Wind speed	5 m/s	
Soil thermal diffusivity	$0.0037\ cm^2/s$	
Soil heat capacity	$0.59\ cal\ cm^{-3}\ °C^{-1}$	

TABLE 4: ESTIMATED EFFECT OF ZENITH ANGLE- AND CLOUD-INDUCED CHANGES IN TUSSOCK ALBEDO ON THE SURFACE ENERGY BALANCE (ΔRN COMPUTED AT MIDDAY).

	Summer			Winter		
	ΔRN (%)	ΔT_{max} (°C)	ΔET (mm)	ΔRN (%)	ΔT_{max} (°C)	ΔET (mm)
Clear	14.8	0.9	0.45	-6.9	-0.2	-0.04
Overcast	5.8	0.1	0.7	9.3	<0.05	<0.005

Note: Changes computed with respect to a constant albedo of 0.23.

sivity range to confirm the relationship proposed in eqn. (2). However, it seems reasonable to conclude on the basis of Figure 3 that significant diffuse radiation-induced reduction in tussock albedo is likely to be limited to conditions with a complete cover of stratiform cloud.

Significance of Albedo Variation

The significance of the above sources of variation in tussock albedo were evaluated by running a surface energy balance model following Fitzharris (1974). The model is based on Outcalt (1972) and is similar to that described by Fitzharris (1974). The main difference is that cloudcover effects on incoming solar radiation and outgoing long-wave radiation were parameterized following Hauritz (1948) and Sellers (1965) respectively. A complete tussock cover was assumed with soil at field capacity (surface wet fraction equal to 1.0). In the overcast cases, a 10/10 layer of stratus was assumed, and the relative humidity was increased by 82%. The model input values used followed Fitzharris (1974) and are summarized in Table 3.

To evaluate the potential importance of seasonal and diurnal variation in albedo due to zenith angle, the model was run for midsummer and mid-winter clear sky conditions. In one version of the model, tussock albedo was assumed to have a fixed annual mean value of 0.23 (from Figure 2). In the other, diurnal variation in albedo was described by

$$\alpha_c = 0.088e\ 0.016Z \qquad (3)$$

To investigate the importance of the reduction in tussock albedo under overcast conditions, the model was run with the assumed clear sky annual mean of 0.23, and a constant overcast value of 0.14 which corresponds to the mean tussock albedo value observed for transmissivities < 20%. The difference in the model output was compared on the basis of the % change in net radiation at solar noon (ΔRN), the difference in maximum surface temperature (ΔT_{max}), and the change in total evapotranspiration during daylight hours (ΔET) (Table 4).

The results indicate that in all cases except clear sky conditions in summer, the changes in net radiation due to albedo variation were less than ±10% of the net radiation computed assuming a fixed annual mean tussock albedo of 0.23. Under summer clear sky conditions, the zenith angle effect produced a 15% increase in the midday value of net radiation which had a more noticeable impact on the surface temperature regime and evapotranspiration.

It should be pointed out that these effects are relatively small compared to the impact of changes in variables such as slope and azimuth. Also, the above simple energy balance model ignores important aspects of the evapotranspiration process such as varying stomatal and soil resistances which are likely to exert a more profound effect on the surface energy balance during summer months. However, the cumulative effect of diurnal variation in albedo, say over an entire summer, may be an important consideration. This effect would need to be investigated by more sophisticated surface climate models.

SUMMARY AND CONCLUSIONS

Measurements of incident and reflected global short-wave radiation taken over native snow tussock from March 19 to April 27, 1977, yielded a mean daily albedo value of 0.20. During clear days, tussock albedo was observed to exhibit strong variation with solar elevation. The observed zenith angle dependence of tussock albedo was found to be higher than taller crops such as corn, which implied tussock was very efficient at trapping incoming solar radiation at higher sun angles. The zenith angle/albedo relationship was used to investigate annual and latitudinal variation in clear sky tussock albedo values. This yielded an estimated mean annual clear sky tussock albedo of 0.23. An analysis of tussock albedo dependence on atmospheric transmissivity showed it to decrease noticeably in overcast, low cloud conditions when transmissivity was less than 30%.

An investigation of the importance of these sources of albedo variation on the surface energy balance showed that provided a representative annual mean value of albedo was selected, maximum effects (for a mid-latitudinal site) were typically less than ±10% of net radiation in the middle of the day. The largest effect was encountered during clear mid-summer days when net radiation was increased by close to 15% in the middle of the day. The use of a simple energy balance model ignores the cumulative effects of diurnal variations in surface albedo. It would be instructive to investigate these further with some of the more sophisticated land surface process models being used in GCM simulations (e.g. Verseghy, 1991).

At a more local level, it is clear that work still needs to be done to assess the significance of important sources of variability in tussock albedo not addressed in this study such as seasonal variation in plant green leaf matter, moisture stress, and plant factors such as density and height.

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