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Quantifying the amount and incidence of fog at a mid-altitude site in the Saint Marys Range, Otago, New Zealand

Sarah M. Mager,[1] Alice M. Trevelyan,[1] Peter G. Wilson[2] and Daniel G. Kingston[1]

[1] *Department of Geography University of Otago, PO Box 56, Dunedin, New Zealand. Corresponding author: sarah.mager@otago.ac.nz*

[2] *New Zealand Fish and Game Council, Palmerston North, New Zealand*

Abstract

Occult precipitation describes forms of precipitation that are typically not captured by traditional rain gauges, like fog, and represent a small, but potentially important component of total precipitation through the interception of water droplets onto plant surfaces. Occult precipitation is notoriously difficult to quantify, and there has been debate over the potential contributory role that fog has in the high water yields associated with Otago tussock grasslands. To ascertain how much occult precipitation was occurring as fog and horizontally-driven rain, a passive fog collector was situated over a tipping bucket rain gauge and monitored along with meteorological conditions at a field site in the Saint Marys Range in Central Otago, New Zealand. Over a two-year period fog contributed 32.2 mm, or 1.5% of total precipitation, whereas horizontal rain that formed as a precursor to rain (identified here as frontal fog) contributed 181.7 mm and was equivalent to 8.3% of the total precipitation recorded. Collectively, this occult precipitation contributed 9.7% of the total precipitation, and was more frequent during spring and autumn.

Keywords

precipitation; fog; tussock grasslands; occult precipitation; water yield

Introduction

Fog deposition is widely acknowledged as an important input to hydrological systems, but its quantification is notoriously difficult (Bruijnzeel *et al.*, 2005). The difficulties arise from determining canopy interception (Joslin *et al.*, 1990), its variable occurrence over space and time (e.g., Błaś *et al.*, 2010), and the challenges in comparing results between quantification techniques (e.g., Bruijnzeel *et al.*, 2005). Precipitation inputs that are not captured by rain gauges ('occult precipitation') typically move in the horizontal plane, but may be effectively intercepted by vegetation and potentially contribute up to several hundred millimetres of water per year (Bruijnzeel and Veneklaas, 1998). In New Zealand there is a long-standing debate concerning the importance of fog deposition (see: Davie *et al.*, 2006), particularly on native snow tussocks, which have a high leaf-to-area ratio and are morphologically suitable to fog interception (Holdsworth and Mark, 1990).

Fog interception occurs when water droplets in fog condensate are intercepted by a plant surface. However, the plant surface may also act as condensation nuclei for water vapour, enhancing the formation and coalescence of water droplets (Davie *et al.*, 2006). Globally several biomes are highly adapted to scavenging water vapour from fog, including cloud forests (e.g., Clark *et al.*, 1998), coastal redwood forests (e.g., Dawson, 1998) and hyper-arid regions such as the Namib and Atacama deserts (e.g., Ebner *et al.*, 2001; Oliver, 1995; Cereceda *et al.*, 2002). Plants that are likely to be efficient fog catchers have narrow leaves with high length to width ratios (Ritter *et al.*, 2008; Martorell and Ezcurra, 2007), and therefore tussock tillers are highly suited and effective interceptors of fog water (Davie *et al.*, 2006; Ingraham and Mark, 2000). The interception and coalescence of fog droplets on tussock tillers eventually causes larger water droplets that fall to the ground (Davie *et al.*, 2006). Fog drip is likely to infiltrate to greater depths in the soil than other types of rainfall because the presence of fog in the atmosphere tends to lower the evapotranspiration demand from the soil and the overlying vegetation (Hildebrandt *et al.*, 2007). However, the fog would have to persist for a long time for water to infiltrate beyond the root zone of a plant, so the observations of Hildebrandt *et al.* (2007) may not translate to locations where fog duration is relatively short lived, like Otago.

Fog incidence and deposition rates vary widely between studies and geographic locations with radiative fogs typically producing less water content compared to advective fogs (e.g., sea fogs, frontal fogs) or mountain/orographic fogs, the latter of which produce the most water content (see: Bruijnzeel *et al.*, 2005). Frontal fog forms as an early form condensate in horizontally driven air-masses associated with frontal activity, and is a fine drizzle or mist that occurs as a precursor to rain. Due to the small droplet size, frontal fog is not captured by standard rain gauges and typifies occult precipitation.

The importance of fog deposition in tussock grasslands in the Otago region (Fig. 1, sites 1, 4–7) was investigated by Holdsworth (1981) who reported that interception gains from wind-driven fog could reach as much as 120 mm annually at the most fog-prone sites, equivalent to 9% of runoff. However, fog was largely held as insignificant by McSaveney and Whitehouse (1988), who countered that the high yield from Otago grasslands was complicated by the elaborate networks of bogs and ponds that delay water routing. In a comprehensive review Davie *et al.* (2006) contended that that high water yields from Otago grasslands are determined by very low evapotranspiration rates of snow tussock, due to their ability to restrict their stomata and reduce water loss under water stress, rather than by a dominance of fog interception. Their position was derived on the balance of evidence from a number of studies that examined the transpiration rates from tussock grasslands including weighing lysimeter observations and modelling studies from Glendhu (Lammerlaw Range) and Swampy Summit near Dunedin (Fig. 1, sites 2 and 3) (Campbell 1988; Campbell and Murray, 1990; Fahey *et al.*, 1996; Cameron *et al.*, 1997). In these studies fog deposition was determined to account for only 1 to 2% of net precipitation and not a significant contributor to overall water yield.

The difficulty in resolving the significance (or otherwise) of fog interception versus supressed evapotranspiration is that there are relatively few studies that have examined the evaporation and transpiration rates in New Zealand indigenous grasslands; in particular, how important elevation and site-specific climatic conditions are to the overall significance of fog, as well as what influence species variation might have on transpiration

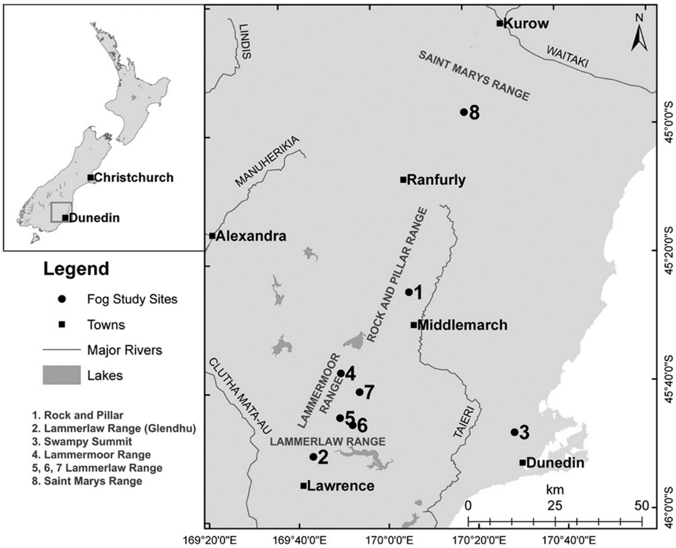

Figure 1 – The location of previous fog studies undertaken in Otago tussock grasslands (labelled as 1–7) and the location of this study in the Saint Marys Range (8)

rates. Holdsworth and Mark (1990) suggested that there may be strong differences in transpiration rates between grass species, as well as significant differences in fog incidence with site location and elevation. Part of the challenge around determining the incidence of fog is that proponents for fog interception have typically undertaken experiments at elevations between 800 to 1200 m above sea level (e.g., Holdsworth and Mark, 1990), compared to the transpiration-advocates whose experimental observations have typically occurred at lower elevations (~ 500 to 700 m above sea level).

Tussock grasslands offer essential hydrological ecosystem services (Mark *et al.*, 2013; Mark and Dickinson, 2008), however, these indigenous grasslands are increasingly threatened by pastoral development, and are now largely restricted to catchment headwaters (Mark *et al.*, 2013). In a region characterised by high water deficits in the growing season, the sustainable management of Otago grasslands, held in conservation estate and private ownership, is essential for good water governance. Although Davie *et al.* (2006) provide compelling evidence to suggest that fog may not be an important component of water yield, the debate is far from settled as to what mechanism drives the high water yield observed from tussock grasslands in Otago.

The objective of this study was to assess the significance, or otherwise, of fog as a portion of annual precipitation in north Otago, in an area characterised anecdotally as having a high incidence of fog. Principally, the focus was on the assessment of the portion of net precipitation attributed to occult precipitation as fog, and whether fog was generated under similar or different weather conditions to rain events.

Methods

A fog monitoring site was installed in the Saint Marys Range, north Otago, at 650 m above sea level (44.96ºS, 170.33ºE) (Fig. 1) in a catchment covered with indigenous snow tussock (*Chionochloa rigida* species) that has been rested from sheep grazing for 13 years. The field site was chosen due to local anecdotal evidence of being fog-prone, its tussock biome, and being at an elevation that could be accessed throughout winter, with only a few snow days per year. Passive, harp-style fog collectors similar to the design of Fischer and Still (2007) were constructed specifically for this study. Fog collectors consist of monofilament fishing line that is strung vertically in four panels offset at 90 degrees. Beneath each panel a PVC gutter directs water drip into a central drain. Four fog collectors were installed at the field site; three were situated over plastic 1 L containers with a 1 cm layer of paraffin oil, which impedes any water loss due to evaporation, and the other fog collector was seated over a TB3 tipping bucket rain gauge that recorded rain events in 10-minute time steps. The fog collectors were strung with 89.7 m of 0.45 mm line with an equivalent collecting area of 404 cm^2 in the vertical plane, and covered with a 0.7 m wide stainless steel lid to reduce admixture with rain. There was some variability in the depth of water collected between the different fog collectors; however, this was only equivalent to a mean monthly difference of 1.04 mm. Regression analysis between the manual fog collectors and the TB3 fog collector showed a strong linear relationship in the amount water intercepted between fog collectors (slope 0.93, goodness of fit r^2 of 0.90), which supports the use of these passive harp fog collectors for collecting consistent amounts of intercepted precipitation in Otago grasslands. Under fog conditions during installation it was observed that fog collected on the monofilament strings, which are a similar dimension to the tussock tillers, so it is reasonable to assume that the measurements from the fog collectors are appropriate for inferring potential interception rates in this environment. A second TB3 tipping bucket rain gauge attached to an automatic weather station was installed 30 m from the fog collector to record rainfall, with a collecting area of 314 cm^2 (aperture diameter of 20 cm) in the horizontal plane. Fog occurs as advected precipitation in the horizontal plane, whereas rain is a vertical deposit, but often occurs tangential to the horizontal plane by wind shear. Under calm conditions, the collecting surface of the rain gauge is equivalent to 78% of that of the fog collector. To directly compare the amount of precipitation recorded by the fog collector in units equivalent to the rain gauge, all data reported from the fog tipping bucket was multiplied by 0.78 to account for the fog collector's larger collecting surface relative to the rain tipping bucket.

The automatic weather station was installed in April 2014 and recorded meteorological observations every 10 minutes, including incoming and outgoing radiation, air and ground temperature, wind speed and direction, and relative humidity. The tipping bucket rain gauge was installed above the ground surface, so that the aperture was 50 cm above the land surface, and approximately two-thirds of the height of the adjacent tussock following the approach of Fahey *et al.* (1996). The fog collector was installed in June 2014, and all instrumentation left on site until July 2016. Data gaps in the time series occurred between 25 September and 9 December 2014 due to a weather station datalogger error, and between 18 January and 17 April 2016 due to a fog collector funnel blockage.

To quantify the amount, intensity and frequency of fog events at the study site the precipitation records for the fog and rain gauges were time-step aligned. Given the windiness of the site it was regularly observed that during rain events, as recorded by the rain gauge, rain was also being intercepted by the fog collector. To account for this, a series of filter steps were used to exclude rain events from the fog record. Firstly, any fog tips recorded concurrently with rain tips were automatically excluded from the fog record. Secondly, any fog tips that occurred within two hours of rain cessation were also excluded from the fog record on the premise that this might be residual rain dripping down the fog collectors. This second rule was adopted for a conservative approach to fog quantification, and potentially excludes post-rain fog events. Thirdly, any fog tips recorded when the air temperature was 0.5°C or less were also excluded from the record and categorised as snow. The most common method for determining snow is to apply a mean daily air temperature threshold, values of which vary from +4 to -1°C and are usually site specific (Harder and Pomeroy, 2014). The snow air temperature threshold used for Saint Marys Range was set at ≤ 0.5°C on the 10-minute time series data. This ensured that all precipitation events categorised as 'snow' had a mean air temperature < 0°C, whereas all other precipitation events (e.g., rain) had a mean air temperature above 1°C. Snow was quantified by any tips recorded by the rain gauge when the air temperature was ≤ 0.5°C and not by the fog collector gauge due to the fog collector's propensity to be an excellent snow accumulator.

Preliminary analysis of the time series data revealed that fog was a regular precursor to rain events, so to establish whether the fog occurred as an isolated event, or as a precursor to rain events, any fog tips that occurred within two hours prior to rain were defined as frontal fog. The distinction here between fog and frontal fog is entirely on its temporal occurrence relative to rain, and is a descriptor rather than suggesting any difference in precipitation form or visibility.

Results

Over the observation period monthly pre-cipitation was highly variable, with lower than normal precipitation recorded regionally from September 2014 to February 2015 and February to April 2016 (NIWA, 2015; 2016) (Table 1). Two large rainfall events were recorded during the study period with 60.8 and 60.2 mm on 28 May 2016 and 3 June 2015, respectively. A large snow fall event was recorded over 15–17 August 2015, depositing 93.1 mm water equivalent depth. These three events account for the higher than usual monthly rainfalls for June 2015, August 2015 and May 2016 (Table 1; Figure 2).

The amount and type of precipitation was highly variable over the observation period (Fig. 2), with fog and frontal fog being recorded in most months. Fog events typically accounted for less than 2.0 mm of precipitation a month and contributed 1.3% of the total precipitation on site. However, in rare instances fog contributed more than 1 mm per event. Three significant fog events were noted during the study period. The first significant event was observed

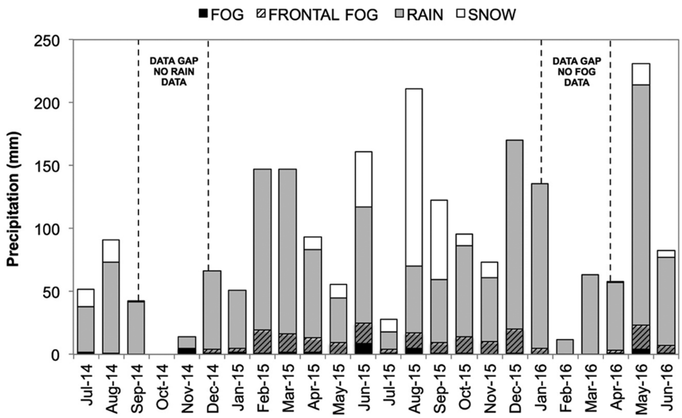

Figure 2 – Monthly precipitation (mm) recorded at St Marys Range from July 2014 to June 2016

Table 1 – Precipitation (mm) of different types recorded at St Marys Range. Due to instrumentation failures some data are calculated from incomplete monthly records. These months are indicated with a percentage of complete days per month, where it is less than 100% complete. n.d. denotes months where there is no data available.

Month	Fog	Frontal fog	Rain	Total	% as fog and frontal fog	% Complete
Jul-14	1.4	0.0	50.4	51.8	2.7	
Aug-14	0.3	0.8	89.6	90.7	1.2	
Sep-14	0.0	0.0	41.8	41.8	0.0	83%
Oct-14	n.d.	n.d.	n.d.	n.d.	n.d.	0%
Nov-14	n.d.	n.d.	n.d.	n.d.	n.d.	0%
Dec-14	0.2	4.1	61.8	66.0	6.4	71%
Jan-15	1.4	3.6	45.6	50.6	9.9	
Feb-15	0.3	19.1	127.4	146.8	13.2	
Mar-15	1.4	15.1	130.2	146.7	11.3	
Apr-15	1.7	11.2	80.4	93.6	13.8	
May-15	0.0	9.2	46.4	55.6	16.6	
Jun-15	8.4	16.5	135.8	160.8	15.5	
Jul-15	0.9	3.1	23.6	27.7	14.7	
Aug-15	4.7	12.5	193.5	210.7	8.1	
Sep-15	0.6	8.7	113.0	122.3	7.7	
Oct-15	0.6	13.7	72.2	81.1	95.4	
Nov-15	0.0	10.4	62.7	73.2	14.3	
Dec-15	0.6	19.8	149.4	169.8	12.0	
Jan-16	0.0	4.7	130.8	135.5	3.5	58%
Feb-16	n.d.	n.d.	11.4	11.4	n.d.	
Mar-16	n.d.	n.d.	63.2	63.2	n.d.	
Apr-16	0.3	3.0	54.3	57.6	5.7	43%
May-16	4.1	19.0	207.6	230.7	10.0	
Jun-16	1.1	6.2	75.3	82.6	8.9	
2015	**20.7**	**143.1**	**1189.4**	**1353.2**	**12.1**	
TOTAL	**28.1**	**180.8**	**1975.6**	**2184.5**	**9.6**	

on 20 November 2014 when 3.9 mm of fog was deposited in the morning from the southeast under warm conditions (17°C) and light winds (1.9 m s^{-1}). The second largest fog event occurred on the morning of 11 August 2015 with 3.9 mm deposited under cold conditions (air temperature of 3.1°C and -0.9°C ground temperature) with light winds (1.5 m s^{-1}) from the northeast. The third largest was 1.6 mm deposited on 5 May 2016 shortly after midnight under mild temperatures (air temperature of 8.7°C and ground temperature of 9.2°C) with strong southerly winds (4.1 m s^{-1}). It should be noted, however, that at the study site occult precipitation also occurs as a fine drizzle as a precursor to rain (what we have called frontal fog), which contributed up to 19.8 mm a month (Table 1). Frontal fog events had a median depth of 6.2 mm in winter and summer, and 11 mm in spring and autumn. Combined, the occult precipitation was 214 mm over the study period, accounting for 9.2% of the total precipitation, of which 8.3% was derived from frontal fog events and the remainder from fog events. The portion of fog and frontal fog at the Saint Marys Range site indicates an annual contribution of 1.5% as fog (20.7 mm), 10.6% as frontal fog (143.1 mm), 65.8% as rain (890.8 mm) and 19.9% (298.6 mm) as snow for the calendar year of 2015.

The higher number of fog and frontal fog days during spring and autumn is consistent with the higher portion of precipitation that occurs as fog and frontal fog during these seasons (Table 2). It appears that fog occurs 2 to 4 times a month, and frontal fog up to 10 times a month, with an overall incidence of 52 fog days (9%) and 83 frontal fog days (14%) over the 580-day observation period (Fig. 3). On some occasions fog was observed (e.g., first thing in the morning) with frontal fog to occurring later on the same day, so the total number of occult precipitation days was 126 (22%) over the 580-day observation period, and 77 of those days had occult precipitation occurring during daylight hours (equivalent to 13% per year). During the two-year observation period 54 discrete fog events were identified in the fog record; of these, 34 were discrete measurements that only recorded fog during one 10-minute time step. For these low intensity events it was not possible to determine duration or intensity as there was no way to determine the lag time between fog initiation and sufficient fog drip into the tipping bucket. The remaining 15 fog events ranged in duration from 20 minutes to 7 hours, with a median intensity of

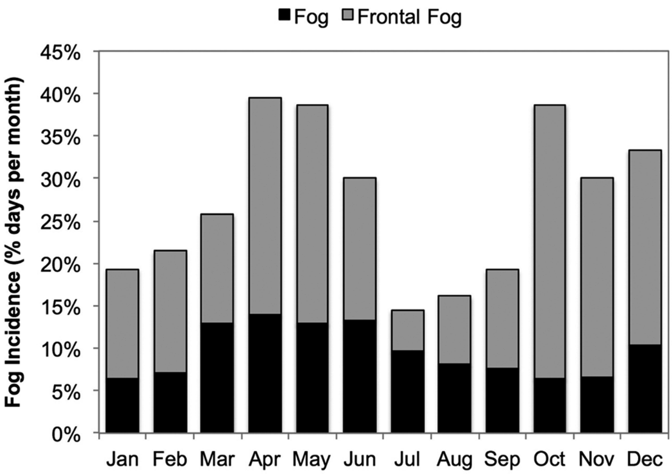

Figure 3 – Incidence of fog and frontal fog in the Saint Marys Range, averaged per month as a percentage of observation days in each month

Table 2 – Seasonally-aggregated median precipitation (and percentage of total precipitation) for different precipitation types as observed at St Marys Range fog monitoring station (July 2014 to June 2016). Units are in mm month^{-1}. Data calculated from four months during each meteorological season except winter, which was calculated from six months (two full winters).

	Fog		**Frontal-fog**		**Rain**		**Total**
	mm	**%**	**mm**	**%**	**mm**	**%**	**mm**
Winter	1.2	2.5	6.2	6.7	76.9	90.9	84.4
Spring	0.6	0.4	9.6	14.3	60.6	85.4	70.8
Summer	0.5	0.2	4.7	7.1	94.6	91.9	99.7
Autumn	1.6	1.0	11.2	10.3	77.3	89.6	90.1

0.47 mm hr^{-1}. By comparison the median intensity of frontal fog was 1.9 mm hr^{-1}.

An analysis of the wind conditions showed that southerlies were the main source of fog, frontal fog and rain (Fig. 4). Fog events originated from both southerly and northeasterly winds, with a mean wind speed of 3.6 m s^{-1}. As expected, wind conditions of frontal fog events were similar to those of the rain events, being dominated by southerly winds with a mean wind speed of 3.6 m s^{-1}; snow and rain events had a mean wind speed of 3.1 m s^{-1}. However, around 20% of fog and 60% of snow originated from the northeast. Frontal fog, rain and snow occurred at any time of the day, but fog was more likely to occur during the morning with the highest frequency of events around dawn (Fig. 5). Fog that formed during the evening, or early morning, was also likely to persist for longer, on average over 1 hour (Fig. 5).

Discussion

Fog, as an isolated phenomenon, was not an important component of precipitation at the Saint Marys Range site contributing only ~1.5% of the total precipitation during the study period. However, the local climatic conditions are strongly advective and associated with frontal activity and frontal fog as a precursor to rain was a common occurrence, contributing ~8.3% of the total precipitation, although the amount was highly variable between months. This rainfall precursor contributed ~10% of monthly precipitation during spring and summer and may be a significant but unaccounted for moisture source in the local water balance.

Previous studies have identified that fog in Otago is often associated with rain events, occurring either before or after rain associated with cold fronts typically sourced from the south and southeast (Fahey *et al.*, 1996; Cameron *et al.*, 1997; Ingraham and Mark, 2000), making the two precipitation types difficult to separate. A lysimeter study in the Lammerlaw Range in the tussock paired experimental catchment at Glendhu (Fig. 1, Site 2) identified 41 instances when fog occurred over a 18-month period, of which 30 events contributed less than 0.2 mm of occult precipitation (Campbell and Murray, 1990). Two larger events were observed, associated with significant rainfall, with occult deposition rates of 1.4 mm and 2.3 mm. Despite the occurrence of occult precipitation, and validation that tussock plants are able to intercept fog, it accounted for only ~1% of total precipitation. The lysimeter experiment was replicated at Swampy Summit (Fig. 1, Site 3) by Fahey

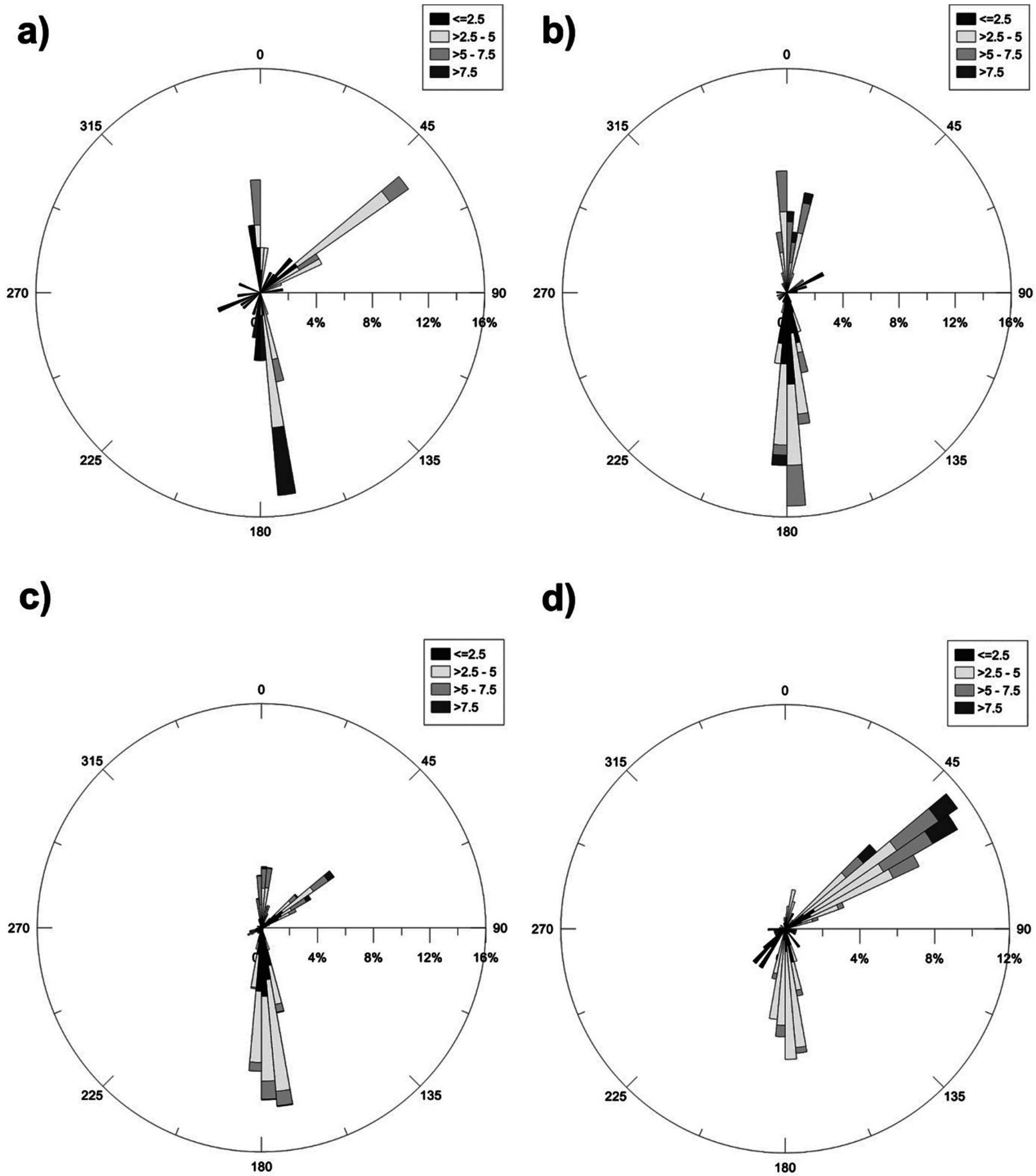

Figure 4 – Wind direction and speed (m s^{-1}) at Saint Marys Range fog monitoring station for period July 2014 to June 2016. Time series analysis used to determine type of precipitation shows that for this site precipitation is almost exclusively associated with southerly winds with only episodic events from the northeast. a) fog, b) frontal fog, c) rain, and d) snow

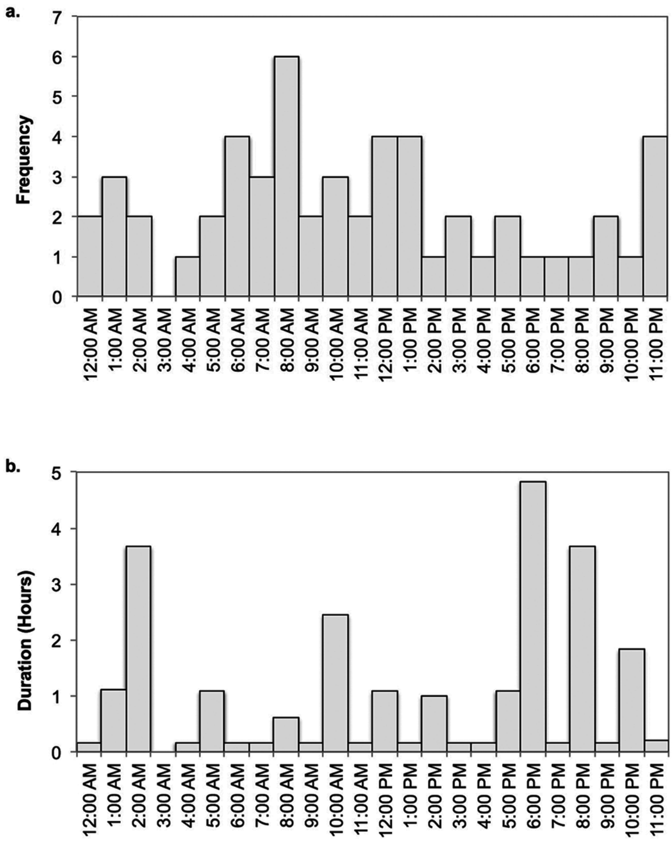

Figure 5 – a) Time of day (New Zealand Standard Time) of fog observed and b) duration in hours of fog events initiated at different hours of the day (excludes fog events where no duration could be determined, i.e., only one timestamp measurement). Data determined from 54 fog events observed over a two-year period (July 2014 to June 2016)

et al. (1996) who identified 40 days of fog incidence over a three-year period, contributing 70 mm of occult precipitation. Despite being a fog-prone site, the data from Swampy Summit suggests fog incidence is only 3.8%, and contributes < 2% to total precipitation. By comparison, the study site in the Lammerlaw Range (Site 2, Fig. 1) had 41 fog events over 18 months, equivalent to a fog incidence of 7.5%. Despite the same instrumentation being used at both locations, occult precipitation only contributed 1 to 2% of total precipitation, although fog incidence varied between sites. By comparison, the Saint Marys Range site had a slightly higher number of fog days (52), equivalent to a fog incidence of 9%, but there was no difference in the contribution of fog to overall precipitation. The percentage of precipitation occurring as fog was 1.5% and is consistent with the portion reported at both Swampy Summit and Site 2 in the Lammerlaw Range (Cameron *et al.*, 1997; Fahey *et al.*, 1996; Campbell and Murray, 1990).

Our results diverge from the previous observations at Swampy Summit and the Lammerlaw Range (Sites 3 and 2) by attributing an additional 8.3% of total precipitation occurring as frontal fog prior to rainfall. On average, frontal fog was detected in the 40 minutes prior to the initiation of rain, and was not detected in a traditional tipping bucket train gauge. When frontal fog deposition and fog deposition are combined, the total occult precipitation contribution at the Saint Marys Range site is equivalent to 9.7% of the total precipitation observed over the 580 observation day record. For the calendar year 2015, occult precipitation contributed 164 mm (Table 1), which is similar to the observations of Holdsworth and Mark (1990) who attributed ~120 mm a year as interception gains in the fog-prone sites of the Lammerlaw Range (Fig. 1, Site 5), and this estimation includes frontal fog.

The frontal fog phenomenon

The type of fog that occurs in Otago will vary depending on local conditions, with advective fog common on the coastal fringe (e.g., Swampy Summit) and radiative fog during meteorological temperature inversions. Analysis of the fog incidence at the Saint Marys Range site showed that fog is associated with southerlies and northeasterlies, but that occult precipitation is mostly a frontal fog phenomenon. Frontal fog is a particular subset of the advective fog formation processes and typifies occult precipitation, rather than being a discrete meteorological phenomenon. Isotopic work by Ingraham and Mark (2000) supports this observation, that fog events at three sites in Otago (Sites 1, 2 and 3 on Fig. 1) were produced from the same weather patterns and the same moisture sources as rainfall. From our study, we concur that the bulk of the occult precipitation is from the same origin as rainfall. Frontal fog contributed 8.3% of the total precipitation recorded at the Saint Marys Range site, whereas non-frontal fog contributed only 1.1% of total precipitation. These are equivalent to mean annual deposition rates of 0.02 mm d^{-1} and 0.24 mm d^{-1} for non-frontal and frontal fog, respectively, which are considerably less than the mean annual rainfall rate of 2.03 mm d^{-1} recorded at the site.

The median event fog deposition rate (excluding the single-tip fog events) was 0.47 mm hr^{-1}, which is higher than the rate of fog deposition for Swampy Summit (Cameron *et al.*, 1997) where cloud-water deposition rates ranged from 0.02 to 0.26 mm hr^{-1} with a median rate of 0.05 mm hr^{-1}. Similarly, Holwerda *et al.* (2006) reported fog deposition rates of 0.11 mm hr^{-1} under rain-free conditions and 0.24 mm hr^{-1} under rainy conditions in Puerto Rican cloud forest. Both of these studies were characterising cloud-water deposition rates. The deposition rates at the Saint Marys Range are likely to be much lower than 0.47 mm hr^{-1} as there was no way to ascertain the lag time between the initiation of fog and accumulation of droplets on the fog collector. The occult precipitation that occurred as frontal fog had even higher intensity rates compared to the fog events, with a median of 1.87 mm hr^{-1}. However, the higher deposition rate is due to the relatively short duration of frontal fog, typically in the 40 minutes prior to the onset of rain.

The difference in the attribution of occult precipitation as a portion of total precipitation reported at the Saint Marys Range site compared to Swampy Summit is largely due to the different collection techniques and their associated errors. Cameron *et al.* (1997) reported a divergence in the fog deposition rates between the lysimetric calculations and the forward scattering spectrometer used to determine water content and then model the fog deposition rate using aerodynamic modelling. These two approaches were only consistent in their estimated fog deposition when rates exceeded 0.15 mm hr^{-1}, with the lysimeter often reporting negative values below this threshold. Determining the portion of deposition that occurs as fog in lysimetric methods requires solving a water balance equation so that all of the uncertainty in the measured components is lumped into the estimated fog deposition rate. Although the weighing lysimeters have a low error component with an estimated detection limit of 0.05 mm (Campbell, 1988), and are a robust method for determining transpiration rates, the method does not directly measure fog interception and may be problematic for quantifying fog deposition (Davie *et al.*, 2006). In our study, 35% of the occult precipitation events (fog and frontal fog) occurred at an intensity below 0.15 mm hr^{-1}, and 31% of the occult precipitation events had a water depth equivalence less than 0.25 mm, which suggests that if a weighing lysimeter approach had been used these events might not have been detected. These low intensity events are not a significant contributor to the overall water balance of the catchment, and account for only a tiny portion of the overall precipitation that occurs at the site, but the incidence of fog does potentially alter the evaporation rates and suppress transpiration.

Fog contribution to water yield

On the basis of this study, it appears that occult precipitation comprising fog/frontal fog is dominated by the latter and contributes ~10% of the total precipitation at our field site. This alone, however, is insufficient to account for the high water yields typically associated with tussock grassland catchments. The bulk of the runoff generated in these tussock catchments is more likely due to the low transpiration rates of tussock plants. However, these transpiration rates, as well as direct evaporation from the ground and from plant surfaces, are controlled by vapour gradients (Campbell, 1989). Therefore, even if fog does not significantly wet the ground surface, the presence of fog may reduce transpiration by reducing the water vapour diffusion gradient between the atmosphere and plant leaves (Ritter *et al.*, 2008). However, the reduced transpiration rates during fog are likely to be short lived, because the mean duration of fog at the Saint Marys Range site is only 1.1 hours. Reduced transpiration rates also occur in tussock grasslands under high vapour gradients (e.g., Campbell, 1989) because under high water stress the furling of tussock tillers effectively closes the tussock stomata reducing water loss. The combined effects of variable transpiration rate, fog incidence, duration and interception are more likely to explain the high runoff, rather than any one process acting in isolation.

Regardless of the processes involved, tussock grassland catchments typically produce high water yields, and a reduction in tussock cover will likely reduce the amount of water generated for downstream use. Since 2010 in the Glendhu Experimental Catchment in the Lammerlaw Range (Site 2, Fig. 1), there has been a systematic decline in water yields in the tussock control catchment, concomitant with the increased spread of manuka and *Coprosma* species on the northeastern slopes (Fahey and Payne, 2015). Although the attribution for this decline in water yield is unclear, it is suggested that the shift from tussock grasslands to woody species may be linked to less conservative water use by the woody species (Fahey and Payne, 2015). In terms of future land management this suggests that the loss of tussock grasslands to other land covers will have a detrimental effect on runoff generation, and in the semi-arid regions of Otago such a loss of water may be economically significant.

There are many limitations to the work here, including the use of passive fog collectors. Passive fog collectors' efficiency is affected by wind, with a propensity to collect rain under windy conditions so that they are not specific to fog under conditions where fog and wind-driven rain occur concurrently (Bruijnzeel *et al.*, 2005). To account for this potential admixing of fog and rain, the data record was filtered to exclude any detection of fog that occurred at the same time step as rain and excluded any fog that occurred after rain, and in this respect the amount of occult precipitation that occurred could be underestimated. The intensity rates for fog and frontal fog reported in this study are also likely to be an overestimation, as we were not able to account for the time lag between the occurrence of fog and sufficient liquid volume of water produced to run off the strings into the tipping bucket sensor. In our study we used only one automated rain gauge so it was not possible to determine a measure of uncertainty associated with the rainfall measurements. The estimations of snow are also subject to over catch on fog collectors, so any snow on the fog collectors was filtered out from the dataset. Standard rain gauges may under or over-estimate snow, depending on the meteorological conditions. Another potential limitation is the low elevation of the study site, compared to international montane fog studies (see: Bruijnzeel *et al*., 2005). It is likely that if the collectors were situated higher up the catchment there may have been a greater portion of occult precipitation collected, although there would be additional altitude challenges with more snow and higher wind speeds blowing rain onto the passive fog collectors.

Conclusions

At a study site in the Saint Marys Range occult precipitation contributed 164 mm of the total precipitation of 1353 mm for the calendar year of 2015, compared to 1189 mm from rain. Over a two-year period occult precipitation from fog and frontal fog contributed 9.6% of total precipitation. Fog accounted for 1.5% of total precipitation, whereas frontal fog that occurred prior to rain events contributed 8.3% of total precipitation. This study supports previous observations that occult precipitation in Otago is most commonly associated with frontal activity largely from the south and southeast.

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