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RESEARCH ARTICLE

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Quantifying rainfall and cloud water interception in upland forests of Norfolk Island

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Abstract

The higher elevation (>200 m ASL) forests of Norfolk Island are regularly immersed in the clouds and scientific and anecdotal evidence suggests that in addition to rainfall, water is likely to be collected as cloud droplets are intercepted by the forest canopy. This water is likely to be important for the local hydrology and ecology, yet it has never been quantified. To address this, a field measurement campaign was established to measure hydrological inputs to the forest floor at two elevated (290 and 310 m ASL) forest sites in the Norfolk Island National Park over a 524-day period. Instrumentation included throughfall and stemflow measurement systems and recording rain gauges in the open in nearby clearings. Sites exhibited very high stem density and basal area and delivery of water to the forest floor was dominated by stemflow because of the funnelling characteristics of the dominant palm and pine trees. Both sites showed similar hydrological behaviour with stemflow and throughfall of around 48% and 32% of total atmospheric inputs, respectively. Stemflow contributions of 48% far exceed observations from the literature on cloud-affected ecosystems which are typically less than 10%. Rainfall rarely occurred in the absence of low-level cloud and some cloud immersion events lasted for many days with hydrologic inputs continuing for extended periods despite rainfall not being observed in the open. Cloud water interception accounted for approximately 20% of total water input at both sites which is equivalent to 25% extra water on top of rainfall measured in the open. From an island-wide perspective, the calculated additional hydrological input is only small due to the limited spatial extent of upland forest; however, the additional water is likely to be very important to local hydrological processes and the unique plants, insects and animals which inhabit the upland forests of Norfolk Island.

KEYWORDS

fog, forest hydrology, island water resources, stemflow, throughfall

1 | INTRODUCTION

Small island nations represent more than one-quarter of the countries on Earth and their freshwater resources are being put under increasing pressure due to a warming climate, changing rainfall patterns, sea level rise, and increasing population (Holding & Allen, 2016; Post et al., 2018; Spellman et al., 2021; Welsh & Bowleg, 2022). There is a strong consensus that the impacts of climate change will have substantial consequences on small islands as adaptation options are often lacking (IPCC, 2023). There are ~1000 populated islands in the Pacific Ocean and many of these have been identified as being particularly vulnerable as their water supplies are often restricted to rainwater and groundwater (Weber, 2007; White & Falkland, 2010).

Amongst these Pacific Islands is Norfolk Island which is located in the subtropical latitudes of the south-west Pacific Ocean (−29.03, 167.95). The island is a remnant of a volcano and covers an area of 35.7 km^2. Like many other Pacific islands, water security on Norfolk Island is becoming an increasing concern. Changes in rainfall patterns (Jovanovic et al., 2012, McGree et al., 2019) over the last 50 years have been having a profound impact on the water balance of Norfolk Island. A water balance analysis of the island between 1915 and 2020 (Hughes et al., 2022) found that mean annual rainfall between 1970 and 2020 was 11% lower relative to the 1915 to 1969 period, with the largest decreases occurring during autumn and winter and a slight increase occurring during the summer months. Over the same comparison periods modelled recharge to groundwater decreased by 27% and modelled streamflow and surface runoff combined decreased by 57%. This study also found an increase in variation in annual rainfall.

With the increasing vulnerability of the island's water supplies a comprehensive analysis of the island's water balance (Hughes et al., 2022; Petheram et al., 2020) and the options available to increase the resilience of the local community to extended dry periods was undertaken (Petheram et al., 2022). The assessment included measurements of water infiltrating into the soil, surface runoff, groundwater storage, water used by vegetation and water used by participating households. While rainfall is the key process that drives recharge and groundwater supply, Petheram et al. (2020) noted that there is some anecdotal and scientific evidence from Norfolk Island and other oceanic islands that interception of moisture from low-level clouds and sea fog may be occurring (Bruijnzeel et al., 2005; Domínguez et al., 2017; Juvik et al., 2011; Prada et al., 2009; Pryet et al., 2012; Rigg et al., 2002) but noted that it was beyond the scope of their assessment to quantify this input.

The highest point on Norfolk Island is Mt Bates at 319 m ASL and the cloud base is regularly observed down to heights of 200 m ASL (see analysis in following sections). Low cloud is a common weather phenomenon on Norfolk Island due to the ready supply of moisture from maritime areas and slight orographic uplift provided by the island. The higher elevation or upland forests of the island provide the ideal surface by which to intercept passing clouds, particularly the stands of Norfolk Island pine (*Araucaria heterophylla*) with their tall form and scale-like leaf structure. In fact, a study of cloud water interception beneath a single Norfolk Island pine in Lana'i (Hawaiian archipelago) (Ekern, 1964) showed the interception of cloud water from passing clouds and subsequent dripping of water through the forest floor (throughfall) could add at least 762 mm y^{-1} to the total water input when compared to a nearby open area with no trees. Also in Lana'i, Juvik et al. (2011) found extremely high contributions of cloud water interception of between 901 and 2883 mm y^{-1} beneath Cook Pine trees (*Araucaria columnaris*) in exposed areas along an elevation gradient. In other oceanic island studies in the Galapagos archipelago, Domínguez et al. (2017) measured cloud water interception across 2 years on San Cristobel Island and reported cloud water interception rates of 480 mm y^{-1}, or 21% of total water input in the first year and 276 mm y^{-1} or 9% of total water input in the second, and Pryet et al. (2012), working on Santa Cruz Island undertook measurements at an elevated site over 75 days and reported that cloud water interception was 20% of total water input. Much of the research into cloud water interception has been undertaken in tropical montane cloud forests and the review of much of this work is presented by (Bruijnzeel et al., 2011). This review reports cloud water interception rates commonly over 100 mm y^{-1} and as high as 1300 mm y^{-1}.

Given the potential additional water inputs to be gained from cloud water interception, this study aimed to undertake a scientifically designed field measurement campaign to quantify how much additional water reaches the forest floor in forested areas on Norfolk Island. While much of the original forest cover of the island has been modified (Invasive Species Council and TierraMar, 2021), there are remnant pockets of forest, protected national park areas and commercial plantations. Of particular interest to this study is the difference in cloud water interception of mature upland Norfolk Island pine stands versus cleared areas. These wetter and high-elevation forests also support a number of endemic and threatened species which may rely on the extra source of moisture from passing clouds for their survival (Director of National Parks, 2010). The unique ecosystems of the higher peaks of Norfolk Island may also be at increasing risk with changing climate as has been documented for other nearby Pacific Islands (Auld & Leishman, 2015). Examples of these species include: land snails (Neuweger et al., 2001), orchids (Zimmer et al., Submitted), ferns, mistletoes and other epiphytes (Mills, 2007) and insects (Moore, 1985; Otte & Rentz, 1985), all of which are far more prevalent in moist areas.

The canopy water balance for a forest, in terms of partitioning of precipitation inputs, can be represented by the following equation:

$$P_g + P_c = E_w + T_f + S_f, \quad (1)$$

where the left side of Equation (1) represents the combined inputs of water to the forest from rainfall (P_g) and cloud water interception (P_c) while the right side of the equation includes evaporation losses from the canopy, known as interception loss or wet canopy evaporation (E_w), throughfall (T_f) which is water that makes it to the forest floor by falling directly through or dripping off the canopy vegetation, and stemflow (S_f) which is water that runs down the stems to the forest floor. This study aims to close the canopy water balance and quantify the potential additional water provided by cloud water interception with the aim of better understanding the potential importance of this extra source of water for local hydrology and ecosystem functioning.

2 | MATERIALS AND METHODS

2.1 | Site characteristics

The selection of measurement sites was undertaken with the aim of choosing forest stands that occurred within the zone that experiences regular cloud immersion. Analysis of Bureau of Meteorology data on cloud base heights from the nearby Norfolk Island Aerodrome (Station 200 288) showed that cloud was commonly observed at elevations less than 250 m ASL. After an extensive ground survey, two forest sites were selected and each of these was paired with a nearby cleared site where rainfall could be measured in the absence of forest canopy (Figure 1). The close proximity of sites was a requirement to avoid any influences of spatial variability in rainfall across Norfolk Island (Stow & Dirks, 1998).

The first forest site will be referred to as the Summit site and is located at an elevation of 290 m at a distance of ~300 m to the SSW of the summit of Mt Bates (the highest point on Norfolk Island at 319 m ASL). The Summit site has a SE aspect with a slope of 30°. The Summit site was paired with a clearing formed by a landslip 200 m to the S. This site will be referred to as the Landslip site and was at an elevation of 270 m (Table 1). The second site is referred to as Mt Cross and is located at an elevation of 310 m ASL at a distance of 200 m to the E of Mt Bates summit. The Mt Cross site has a S aspect with a slope of 25°. The Mt Cross site was paired with a site at a picnic area 400 m to the SE. This site will be referred to Palm Glen and is at an elevation of 210 m.

At each site a 20 × 20 m plot was established and within this plot the diameter of all trees with a diameter at breast height (DBH) of greater than 10 cm was recorded. Trees were also identified as being either Norfolk Island pine, Norfolk Island palm (*Rhopalostylis baueri*) or other species. The slope of each plot was also measured so that the plot area and forest structure statistics could be expressed in horizontal surface units. Measurements of leaf area index (LAI) for the two sites were also taken using a plant canopy analyser (LAI-2000, Li-Cor, Nebraska). Other studies of LAI in coniferous forests have shown that the LAI-2000 underestimates actual LAI because coniferous foliage is not broad and flat and tends to form clumps around stems (Deblonde et al., 1994; Gower & Norman, 1991; Stenberg et al., 1994). The underestimation is typically corrected by applying a factor related to the ratio of the total projected needle area to shoot silhouette area. For four species of conifer Gower and Norman (1991) reported an average correction factor of 1.57 (range 1.49–1.67) and this correction factor has been applied in this study. The leaf area index (LAI) of Summit and Mt Cross sites was 6.85 and 6.94, respectively.

The evergreen Norfolk Island pines dominate the forest stands and have a single upright trunk with tiered branching and a pyramidal shape. At both sites the Norfolk Island pines reached heights of 45 m and the first branches of mature trees began at a height of about 10 m giving a canopy depth of 35 m. Mature trees were often observed to have extensive communities of epiphytes and mosses in the canopy. The understorey of the forest, which was dominated by palms, reached to a height of 10 m.

The Summit site represented a very dense forest stand with more than 85 stems >10 cm DBH in the 20 × 20 m plot (Table 2) and stem density of 2454 stems ha^{-1}. There were 30 Norfolk Island pines on this small plot and nine of these had a DBH > 50 cm. The Norfolk Island pines represented 84% of the total site basal area of 151 m^2 ha^{-1} (Table 2); this is a very high basal area estimate by international standards. Norfolk Island palms accounted for 52% of the stems on the plot but only 10% of the total basal area. The average palm DBH was 12.0 cm and the range in DBH was small (10.0 to 15.7 cm). Other tree species represented just 6% of the total basal area.

The Mt Cross site had a lower stem density (1545 stems ha^{-1}) and basal area (90 m^2 ha^{-1}) but the basal area (Table 2) is still considered high. Norfolk Island pines represented only 32% of the stems but 71% of the basal area. Palms dominated the stem count (41%) and were very consistent in DBH (average 13.8 cm, range 10.3 to 15.7 cm). Palm density was about half that at the Summit site. Other tree species had more representation at the Mt Cross site but still only accounted for 18% of the site basal area.

2.2 | Weather observations

A weather station was installed at the Landslip site to record wind speed and direction, air temperature and humidity, atmospheric pressure (WXT536, Vaisala, Uppsala, Sweden) and solar radiation (SP-110, Apogee Instruments, Utah). In addition to these measurements, the weather station also was fitted with equipment to detect the presence (not amount) of cloud. These sensors included a camera (DS-2CD2085G1-I, Hikvision, Hangzhou, China) for visual checks using hourly images and three leaf wetness sensors (PHYTOS 31, Meter, Pullman). The leaf wetness sensors were installed at different angles (0, 45 and 90°) underneath a 0.4 × 0.4 m cover which excluded rainfall meaning that any wetness detected was due solely to passing cloud. The weather station was controlled by a data logger (CR1000, Campbell Scientific, Utah) and sensors were sampled at 15 s intervals with average, total, maximum, and minimum values recorded at 15 min intervals.

Additional observations of cloud base elevation and rainfall were sourced for the study period from the Bureau of Meteorology station at Norfolk Island Aerodrome (Station 200 288, 112 m ASL). Rainfall data used in long-term analysis spanned from August 1939 until the end of February 2023. Cloud-base height observations provide an insight into cloud characteristics over the island and the regularity at which forests may be immersed in cloud. Cloud-base height above the aerodrome has been measured by the Bureau of Meteorology at a

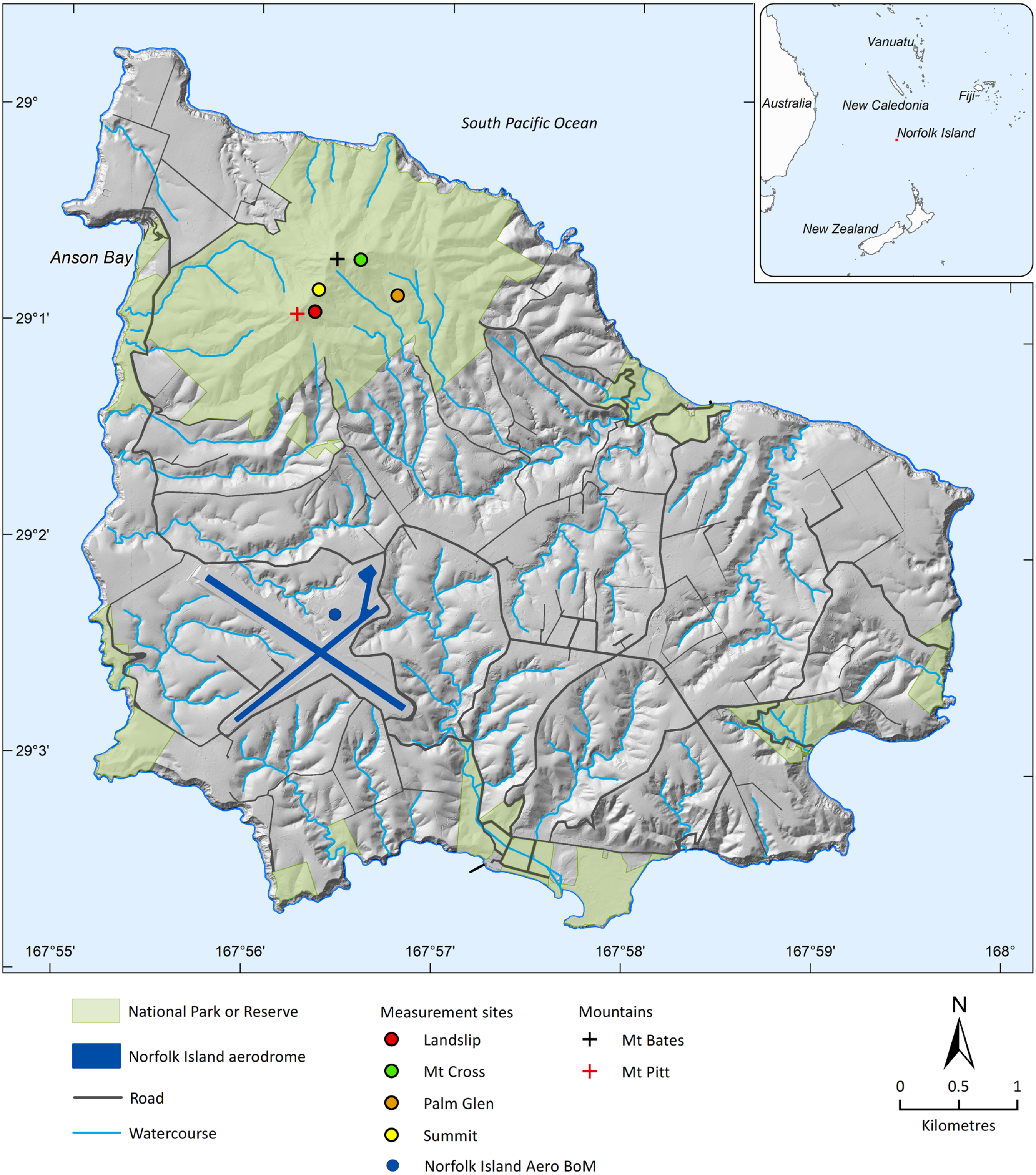

FIGURE 1 Map showing the location of the Summit and Mt Cross forest sites and Palm Glen and Landslip clearings where rainfall observations were made in the open. The two highest peaks, Mt Bates (319 m ASL) and Mt Pitt (318 m ASL), and the location of the Bureau of Meteorology station at the Norfolk Island Aerodrome (200288) are also shown. The inset shows the location of Norfolk Island in the Southwest Pacific.

30-min interval since November 2002 using a ceilometer. For analysis in this study ceilometer data from the commencement of 2003 to the end of February 2023 were used. Gaps in the cloud-base height data of less than 8 h were filled using linear interpolation. 75% of all data gaps were less than 3 h in duration. Days with larger gaps were excluded from any analysis.

TABLE 1 Selected sites for field studies and associated elevation, geographical location, slope, aspect and vegetation type.

Site	Elevation	Latitude, longitude	Slope	Aspect	Veg type
Summit	290 m	−29.0139, 167.9387	30°	SE	Forest
Landslip	270 m	−29.0156, 167.9384	20°	E	Cleared
Mt Cross	310 m	−29.0115, 167.9423	25°	S	Forest
Palm Glen	210 m	−29.0142, 167.9456	15°	SSW	Cleared

Note: The Summit site was paired with the Landslip site and the Mt Cross site was paired with the Palm Glen site.

TABLE 2 Stand characteristics for the Summit and Mt Cross forest sites. Statistics are for all stems >10 cm DBH and the vegetation is classified as either Norfolk Island pine, Norfolk Island pine, or other mixed tree species.

Site	Type	Plot stems (count)	Plot stems (%)	Stem density (stems ha^{-1})	Plot basal area (m^2)	Plot basal area (%)	Basal area (m^2 ha^{-1})
Summit	Norfolk pine	30	35	866	4.4	84	127
	Norfolk palm	44	52	1270	0.5	10	15
	Other trees	11	13	318	0.3	6	9
	Total	**85**	**100**	**2454**	**5.2**	**100**	**151**
Mt Cross	Norfolk pine	18	32	497	2.3	71	64
	Norfolk palm	23	41	634	0.3	11	10
	Other trees	15	27	414	0.6	18	16
	Total	**56**	**100**	**1545**	**3.3**	**100**	**90**

2.3 | Canopy water balance

2.3.1 | Rainfall

Rainfall was measured in the open at the Landslip and Palm Glen sites using a system of throughfall troughs identical to those installed at forest sites. These trough systems are described in full in section 2.3.2. The trough systems were utilized rather than standard rain gauges to facilitate direct comparison of results and avoid differences in observations which relate to measurement technique. A single set of three throughfall troughs was established in the open at each site at a height of ~1 m. Troughs were installed at angles of ~5° to minimize splash-out effects. As an additional backup, rainfall was also measured using a standard 0.2 mm tipping bucket rain gauge (TB3, HyQuest Solutions, Sydney, Australia) at the Landslip site.

2.3.2 | Throughfall

Forest canopy coverage can be quite variable making the measurement of throughfall complicated. Other forest studies have used roving gauges (e.g., Jetten, 1996; Shuttleworth, 1988) or large numbers of rain gauges (e.g., Hölscher et al., 2004; Holwerda et al., 2006) to account for this variation but this was not feasible in this study due to the remoteness of the location and requirement for long-term observations. Following the approach of McJannet, Wallace, and Reddell (2007a) we deployed a series of trough systems at each site. At each of the forest sites, two sets of throughfall troughs were established. Each set of troughs consisted of 3 × 5 m long × 0.12 m wide PVC gutters (Typhoon, Marley, Auckland NZ) which drained to a single 1 m long collection trough and then into a central reservoir. Troughs were covered with 20 × 20 mm mesh to minimize collection of leaf litter and debris and troughs were attached to steel posts at a height of about 1 m above the forest floor. The horizontal collection area was determined by accounting for the installation angle of each trough. The throughfall collection area of each system was ~1.9 m^2 which is equivalent to about 60 standard rain gauges. An example of a set of throughfall troughs installed at Mt Cross is shown in Figure 2.

The central reservoir was fitted with a mesh filter and water drained from the reservoir and into a tipping bucket flow gauge (6506H, Unidata, Perth, Australia). These tipping buckets had a factory calibration of 0.13 L tip^{-1} which produces a throughfall measurement resolution of about 0.07 mm tip^{-1}. Several studies have shown that the tip volume of tipping buckets increases with increasing flow rate (e.g., Niemczynowicz, 1986; Shimizu et al., 2018) and, as such, a custom dynamic calibration was undertaken in the laboratory under controlled flow conditions. The experimental design and results of this dynamic calibration are presented in Data S1. The calibration process revealed that using the 6506H tipping bucket with a fixed calibration would have resulted in a 20% underestimation of true flow volume at the highest flow rates. The dynamic calibration curve was applied to 1-min counts of tip rates which were recorded using an event logger (Hobo Pendant, Onset Corporation, Massachusetts).

2.3.3 | Stemflow

The forest at both the Mt Cross and Summit sites was dominated by Norfolk Island pines and Norfolk Island palms, (94% of the basal area at Mt Cross and 82% at the Summit site, more details below)

FIGURE 2 Photo showing the layout of throughfall troughs and stemflow collars beneath the canopy at the Mt Cross site.

therefore these two species were targeted for stemflow measurements. At each forest site eight Norfolk Island Pine trees and four Norfolk Island palms were selected to cover the observed range of stem sizes. Each selected tree was fitted with a collar made from Clear Vinyl Tubing (CVT) with an internal diameter of 32 mm. A hose length capable of reaching around the entire stem was split longitudinally using a custom-built cutter and then an uncut length (~0.5 m) was fixed to the stem using duct tape. The two sides of the split section of the tube were then attached to the tree in an upward spiralling direction using only silicone sealant. This seal was checked and replenished regularly to maintain a seal with the stem. Once all collars were fitted to selected trees, they were connected using a network of 40 mm PVC tubing with the pines and palms plumbed together separately. A central line from each set of stems was then run into a covered 70 L reservoir and from the reservoir the water drained to a tipping bucket flow gauge. Figure 2 shows stemflow collars installed on trees at the Mt Cross site.

The Norfolk Island pine trees drained to a tipping bucket with a 1 L tipping volume (TB1L, HyQuest Solutions, Sydney, Australia) while the Norfolk Island palms drained to the same model (0.13 L tip^{-1}) of tipping bucket as the throughfall gauges (6506H, Unidata, Perth, Australia). The 1 L tipping bucket was dynamically calibrated in the laboratory based on flow rate using the approach presented in Data S1. The calibration process showed that using the TB1L tipping bucket with a fixed calibration would have resulted in a 13% underestimation of flow at the highest flow rates. Tip rates of both stemflow systems were recorded using an event logger (Hobo Pendant, Onset Corporation, Massachusetts). Tree basal area was used to scale from collected volume to stemflow depth (mm) for each site. The volume of water collected from sample trees was expressed as an equivalent per unit basal area (m^2) and then this volume was multiplied by the basal area of that tree type on the plot. The palm tree stemflow system was used to scale for palms, whereas the pine tree stemflow system was scaled using the basal area of pines and other tree species on the plot. McJannet, Wallace, and Reddell (2007a) tested the same stemflow scaling approach in two groups of trees in a tropical rainforest in north Queensland, Australia and found excellent agreement between the derived stemflow measurements despite the two groups having different bark and size characteristics.

2.3.4 | Wet canopy evaporation and cloud water interception

The technique used to determine cloud water interception was similar to that used by Harr (1982), Hutley et al. (1997) and McJannet, Wallace, and Reddell (2007a) which relies on comparison of the canopy water balance under conditions with and without contributions from cloud water interception. On days without cloud water interception, P_g was plotted against $(T_f + S_f)$ to produce a linear regression equation. On days with cloud water interception, the input from cloud, P_c, would be expected to evaporate from the canopy at the same rate as P_g, therefore a plot of $(T_f + S_f)$ against $(P_g + P_c)$ would be expected to fall on the same regression line. This means that when cloud water interception occurs, P_c can be estimated as the difference between that predicted by the regression equation and measured P_g for the same event. This will be demonstrated using actual data in the Results section below. One key difference between the canopy water balance approach used elsewhere and the approach utilized in this study is that there were only 15 events where rainfall occurred in the absence of cloud and the biggest of these events was just 6 mm. As an adjustment to the previously used approach, this study utilized rain events where cloud water interception was at minimal levels. These events were identified from the available dataset as those at the upper limit of the plots of $(T_f + S_f)$ against $(P_g + P_c)$ which will be discussed below. In the derivation of the relationship between $(T_f + S_f)$ against $(P_g + P_c)$, only events greater than 4 mm were used as smaller events may be insufficient to saturate the canopy and would therefore produce a different and less stable relationship (Wallace et al., 2013; Wallace & McJannet, 2008). Across the entire dataset, events were defined by the onset of rainfall, throughfall, or stemflow at a site and continued until all of these pathways had ceased for a period of 4 h or more.

To quantify wet canopy evaporation and cloud water interception across the entire study period it was necessary to develop infilling procedures for events when instrumentation failed. Failures typically occurred due to blockages from leaf debris but also occasionally occurred during periods of high-intensity rainfall. For both sites T_f was successfully measured during 80% to 86% of events while S_f was successfully measured during 86 to 98% of events. Missing T_f and S_f data were filled with linear regression equation fitted to event data on complete measurement days. During five events, both the T_f and S_f systems were overwhelmed by intense rainfall and data were filled using a two-step process. Firstly, P_c was estimated based on a derived relationship between the number of hours of cloud immersion (as defined by leaf wetness sensors) and P_c from complete data days (results below). Secondly, missing $(T_f + S_f)$ was calculated using an inversion of the regression equations developed at each site between P_g and $(T_f + S_f)$ for complete data days with very low/no P_c.

The canopy storage capacity and trunk storage capacity represent the minimum depth of water required to saturate the canopy, trunks and stems of a forest stand and these values are an important determinant of wet canopy evaporation loss. The canopy and trunk storage capacity for the forest sites was derived by determining the linear regression equation for the relationship between $(T_f + S_f)$ and P_g on days with low to no cloud water interception input. The negative intercept of these regression lines is equal to the canopy capacity according to the 'mean method' described by Klaassen et al. (1998)

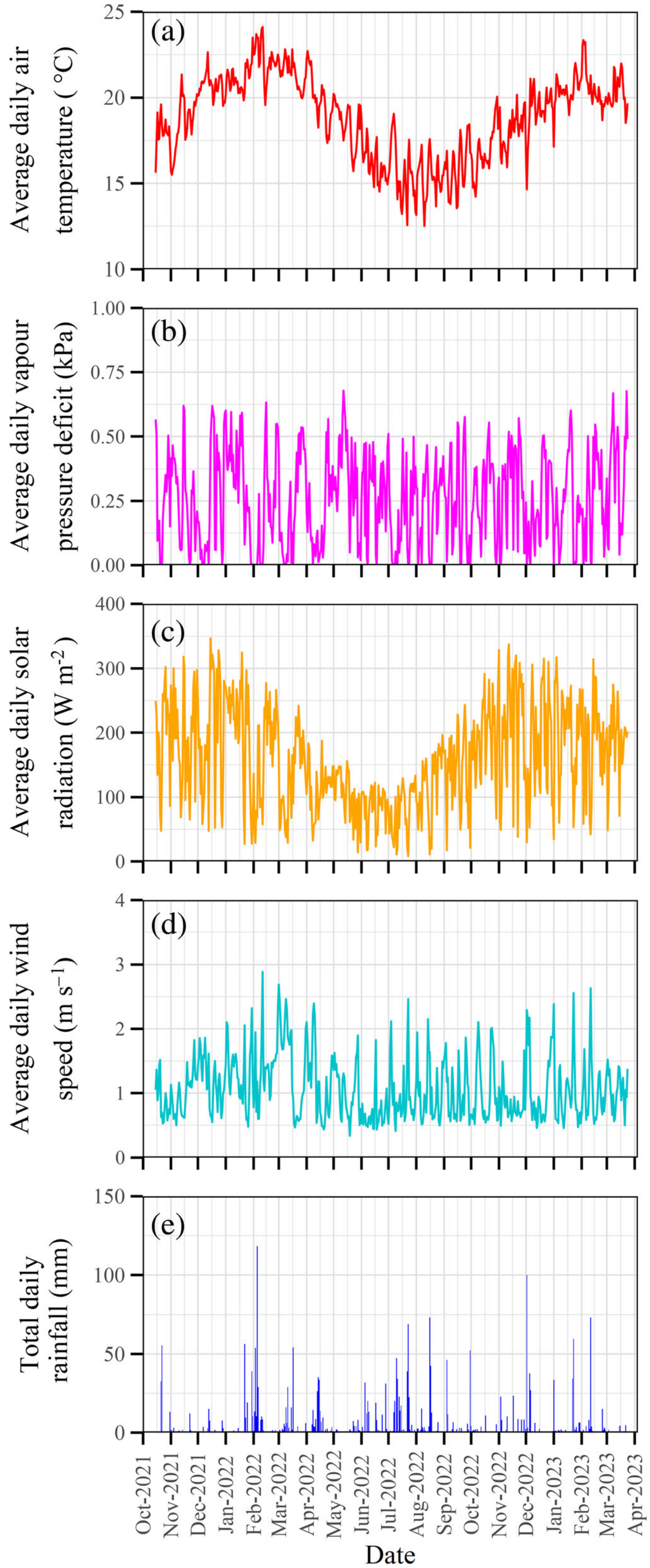

FIGURE 3 Average daily air temperature (a), vapour pressure deficit (b), solar radiation (c) and wind speed (d) and total daily rainfall (e) across the study period at the Landslip weather station on Mt Pitt.

and Wallace and McJannet (2006). Canopy and trunk storage terms are not separated for reasons discussed below.

2.4 | Software packages

Analysis was undertaken using R (R Core Team, 2022) and figures were produced using the following R packages; ggplot2 (Wickham, 2016), ggmap (Kahle & Wickham, 2013), patchwork (Pedersen, 2020), ggrepel (Slowikowski, 2018), dplyr (Wickham et al., 2015) and openair (Carslaw & Ropkins, 2012).

3 | RESULTS

3.1 | Weather observations

Norfolk Island has a subtropical climate which is moderated by the surrounding ocean. During the 524-day study period (15 October 2021 to 23 March 2023) diurnal and seasonal temperature variations were small. On average, diurnal temperatures ranged by just 5.1°C. Average daily temperatures recorded during the study varied from a low of 12.5°C to a high of 24.1°C (Figure 3a). The highest temperature recorded was 27.6°C and the lowest was 10.6°C. Average vapour pressure deficit (VPD) showed no seasonality and was generally very low with an average value of just 0.26 kPa (Figure 2b). This low value reflects a very high average relative humidity (88%). The highest VPD was just 0.68 kPa. Average daily solar radiation exhibited typical season trends with peaks of nearly 350 W m^{-2} in the summer and 125 W m^{-2} in the winter (Figure 3c). High day-to-day variation reflects the regular occurrence of cloud cover. Average daily wind speed at 2 m height was also relatively stable throughout the year at 1.1 m s^{-1}, although peak wind speeds of more than 11.4 m s^{-1} were observed (Figure 3d). Rainfall showed no distinct seasonal trend (Figure 3e). The wind rose for the Landslip site shows that winds were predominantly from E and ENE directions with wind from other directions occurring only occasionally and at much lower speeds (Figure 4).

Total rain gauge rainfall (P_g) at the Landslip site over the 524-day study period was 2330 mm and the highest daily rainfall was 118.4 mm which occurred on 5 February 2022. For this same period, total rainfall at the Norfolk Island Aerodrome (Station 200288, 112 m ASL) was 2624 mm, which is 294 mm or 12% greater than that measured at the Landslip site. Much of this difference, 163 mm, is accounted for on just 7 days. Presumably, these days represent events where spatially restricted rainfall events moved across the island.

Using rainfall measured at Norfolk Island Aerodrome (Station 200288) for the study period and comparing it to long-term average for the same station (1939–2023), the study period was shown to be 47% wetter than average (Figure 5). Only 3 of the 16 complete months of observations had below-average rainfall reflecting the La Niña conditions that existed throughout the study period.

In this current study, immersion of the forest in cloud was identified using a leaf wetness sensor which was sheltered from direct rainfall by a cover. Long-term observations using a leaf wetness sensor are not available, however, the height of the cloud base has been measured by the Bureau of Meteorology at Norfolk Island Aerodrome using a ceilometer since 2002. The detection of cloud below 300 m elevation was used as an indication of the forests being immersed in cloud. To investigate how reliably the ceilometer could represent forest immersion in cloud, we compared the percentage of each day that

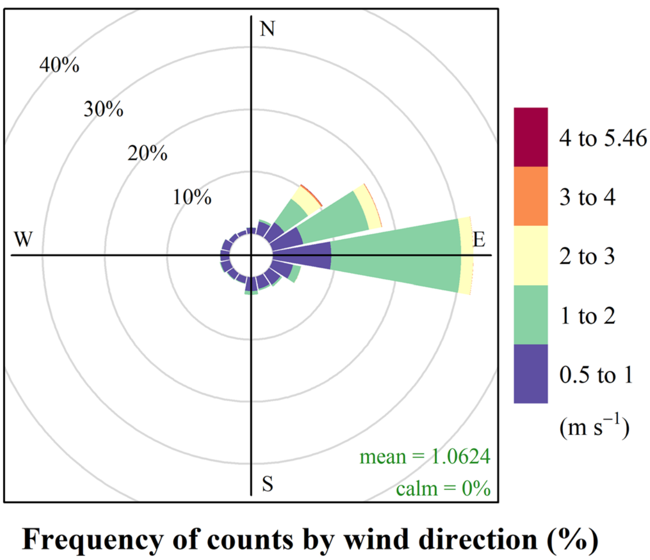

FIGURE 4 Wind rose for the Landslip weather station over the entire study period.

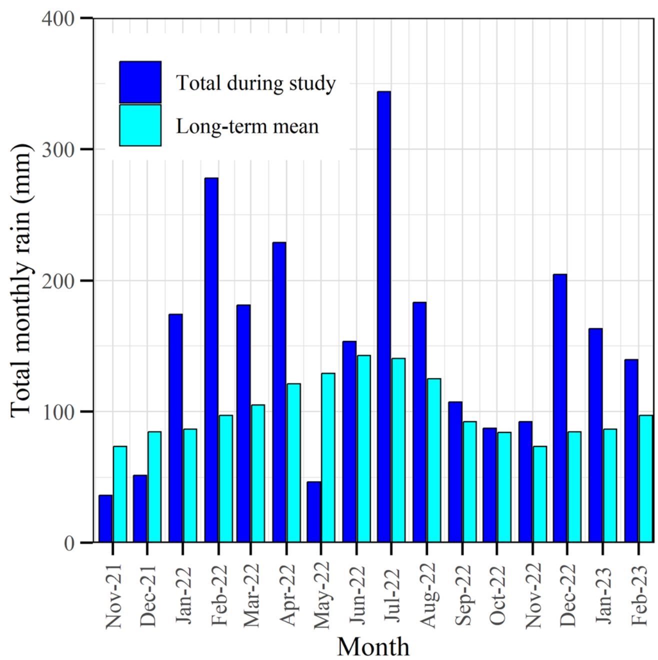

FIGURE 5 Monthly rainfall from the study period compared to long-term mean monthly rainfall (1939 to 2023). All data taken from Bureau of Meteorology station 200288 (Norfolk Island Aero). Only months with complete water balance datasets are shown.

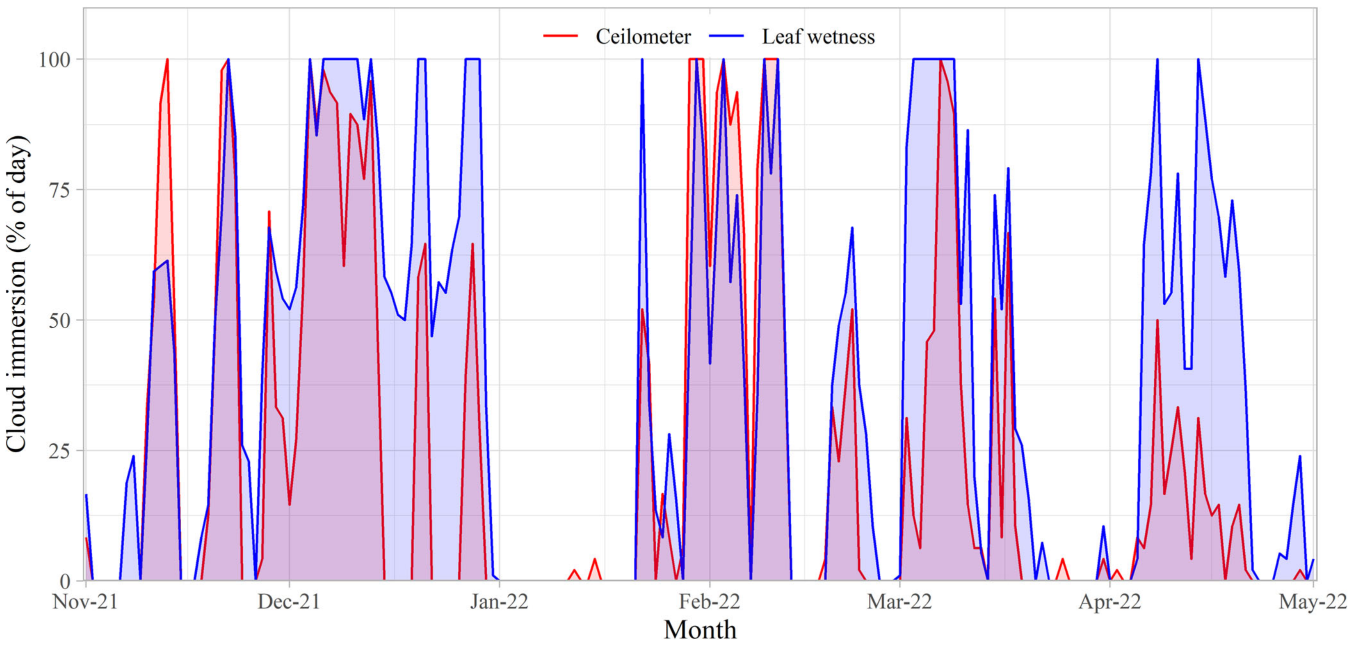

FIGURE 6 Percentage of each day where the forest was immersed in cloud as determined by ceilometer at Norfolk Island Aerodrome (cloud base <300 m ASL) and leaf wetness sensor at the Landslip site.

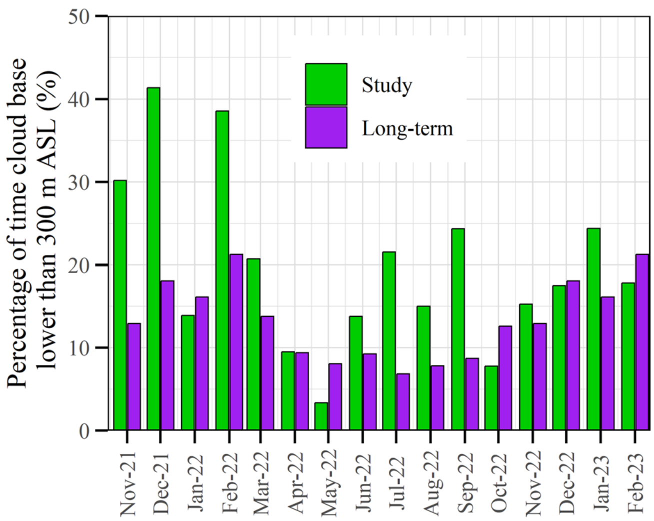

FIGURE 7 Percentage of time during each month where the cloud base was less than 300 m as determined by the ceilometer at Norfolk Island Aerodrome (cloud base <300 m ASL) and comparison of this value to the long-term average for each month.

cloud immersion occurred as determined independently using the leaf wetness sensor and ceilometer. Comparison of the two datasets (Figure 6) shows that for most of the time the ceilometer gives a reliable estimate of forest cloud immersion. There are periods where the ceilometer underpredicts the duration of cloud immersion and this is most probably due to the formation of clouds around the higher peaks due to orographic uplift. This is particularly evident in April 2022. Such uplift is not typically observed over the aerodrome. Acknowledging this shortcoming, the ceilometer data does provide an opportunity to investigate how cloud immersion in this current study compares to those predicted over the last 20 years.

Figure 7 shows the percentage of each month that the cloud base was below 300 m elevation as compared to the average for the same months from the complete data set. This figure shows that the study period typically experienced more low-level cloud that the 20-year average. Only 2 of the 16 complete months (May 2022 and October 2022) had levels of cloud immersion considerably less than the long-term average. Like the comparison of study and long-term rainfall (Figure 5), the comparison of low-level cloud observations suggests that cloud water interception inputs were likely to be higher during the study than in most years.

The ceilometer data can also be used to consider the regularity of cloud immersion at given elevations. Over the duration of the study a cloud base level of less than 300 m ASL was experienced for 20% of the time and this dropped only slightly to 18% of the time for a cloud base level of 250 m ASL. Cloud immersion time then reduced more rapidly to 13% for a cloud base level of level less than 200 m ASL and 7% for a cloud base level of less than 150 m ASL. These results suggest that forested areas above 200 m AHD are most likely to experience cloud immersion. Below this level, cloud water interception is likely to be a smaller hydrologic input.

3.2 | Canopy water balance

The relationship between rainfall and stemflow (S_f) measured separately for palms and trees at both forest sites is shown in Figure 8a,c. These data points represent events with complete measurements for all systems. At the Summit site the trees accounted

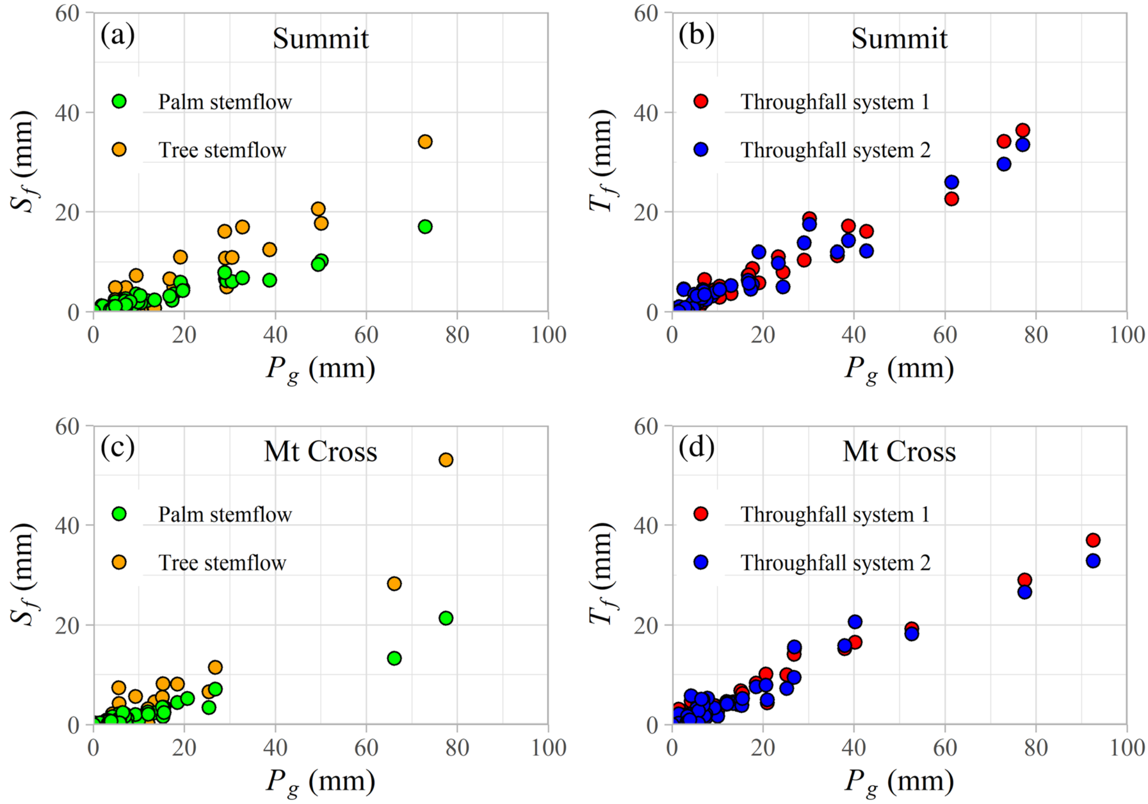

FIGURE 8 Stemflow (a and c) and throughfall (b and d) versus rainfall at the Summit and Mt Cross sites. Data points represent events with complete measurement data sets only. Stemflow is presented for palm and tree measurement sets and throughfall is presented for throughfall system replicates.

for 60% of total stemflow and the palms accounted for 40%, while at Mt Cross the tree system account for 61% of total stemflow and the palms accounted for 39%. The contribution from palms is particularly high given that they represent just 10% and 11% of the total stand basal area at the Summit and Mt Cross sites, respectively (Table 2). While there is a clear positive relationship between rainfall and stemflow, there is some scatter in the relationship at both sites which reflects the fact that rainfall is not the only precipitation input to these forests. Regression of the palm and tree datasets showed them to be highly correlated (Summit, $R^2 = 0.93$ and Mt Cross, $R^2 = 0.95$) providing a reliable means by which to fill data gaps in either measurement.

The relationship between total rainfall (P_g) for each event and throughfall (T_f) from the replicates of throughfall troughs is shown in Figure 8b,d. At both sites the replicates showed very similar responses to rainfall with neither system showing a greater response that the other. At the Summit site, total throughfall from System 1 was just 3% greater than from System 2, and at Mt Cross total throughfall from System 1 was just 1% greater than from throughfall System 2. The similarity between responses of the throughfall trough replicates suggest that the length of trough utilized for these systems was able to adequately account for the variability in throughfall that might be expected beneath the canopy at these two forest sites. The throughfall trough replicates were very highly correlated with each other at both sites (Summit, $R^2 = 0.96$ and Mt Cross, $R^2 = 0.95$) which facilitated gap filling for events where one of the replicates was missing. As with stemflow, some variation in the relationship between rainfall and throughfall is expected because not all precipitation inputs to the forest have been accounted for.

Figure 9a shows the progression of cumulative rainfall, throughfall and stemflow during a heavy cloud event at the Summit site in July 2022. The most striking feature of this figure is the commencement of throughfall and stemflow from palms 20 h before the first rainfall is recorded. This is the first clear evidence of cloud water interception as a contributing process. Interestingly, stemflow from the pines did not commence until after rain commenced but once it did start it then increased at a more rapid rate to exceed the contribution from palms. The stemflow and throughfall contributions followed a trend of a more continuous input compared with the input for rainfall which on a cumulative water input plot displays as a series of stepped increases over time (Figure 9). Again, this suggests a continuing input of cloud water which is continually adding to the forest water input. During this event, the input of water to the forest floor exceeded that recorded as rainfall in the open by 3.2 mm. The final observation is the magnitude of stemflow which combined contributes more than 50% of the water input to the forest floor.

Figure 9b shows cumulative rainfall, throughfall and stemflow during a low cloud event in June 2022. In this event, rainfall precedes

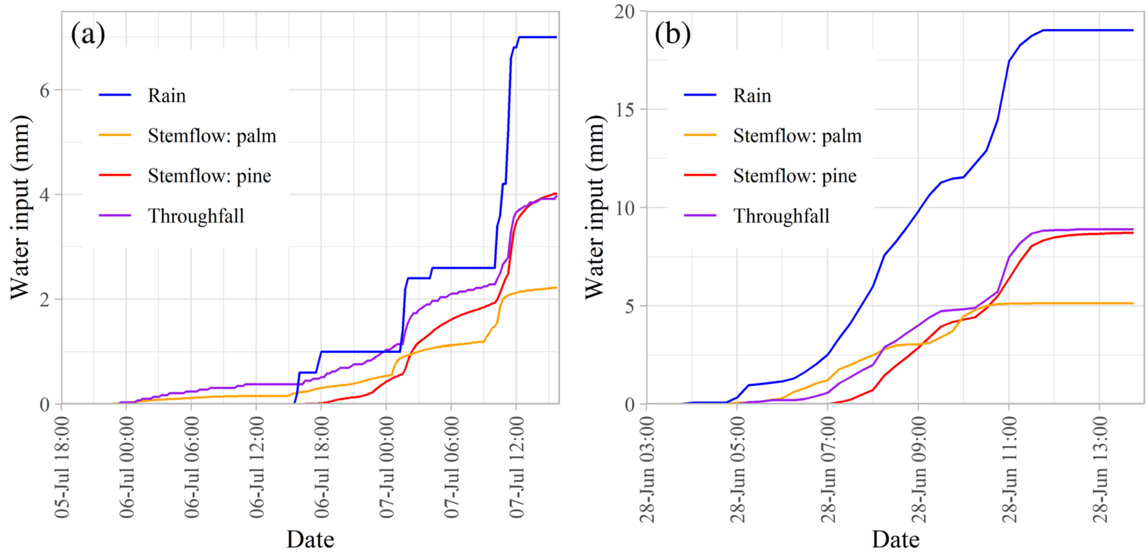

FIGURE 9 Stemflow, throughfall and rainfall for a demonstration event at the Summit site during a cloudy event (a) and at the Mt Cross site during a low cloud event (b).

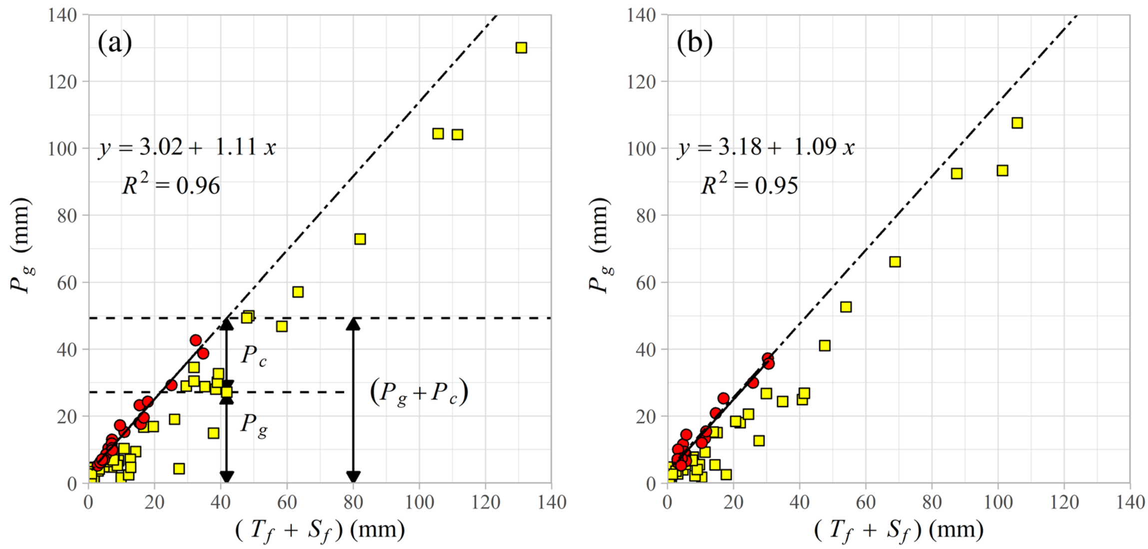

FIGURE 10 Total rainfall (P_g) versus ($T_f + S_f$) at Mt Cross (a) and Summit (b) sites for days with cloud water interception (squares) and with low or no cloud water interception (circles). A linear regression equation was fit to the data for low or no cloud water interception days. Arrows and text are used to illustrate how P_c is calculated using an example data point.

the commencement of observations of other hydrologic pathways. As with the July 2022 event (Figure 9a), stemflow from palms and throughfall start simultaneously, however, pine stemflow does not commence until 2 h later. This suggests that the stemflow on the pines does not commence until canopy saturation has been achieved. Over the entire event, stemflow and throughfall combined were approximately equal to measured rainfall which suggests there was still some contribution from cloud water interception as wet canopy evaporation loss and replenishment of canopy storage would also have occurred during the event.

The relationship between the combined total of throughfall and stemflow ($T_f + S_f$) and rainfall for each event at both the Summit and Mt Cross sites is shown in Figure 10. In total there were 144 individual events with the longest lasting more than 6 days. A linear relationship has been fitted to the low, or no cloud events for each of the two data sets giving the following equations for the Mt Cross (Equation 2) and Summit (Equation 3) sites, respectively:

$$P_g = 1.11(T_f + S_f) + 3.02, \tag{2}$$

$$P_g = 1.09(T_f + S_f) + 3.18. \tag{3}$$

Using these regression lines, it is then possible to estimate cloud water interception (P_c) inputs for remaining events as any precipitation input would be expected to be intercepted and evaporated in the same way as P_g. The way in which this is achieved is illustrated graphically using a single datapoint in Figure 10a. On days where cloud water interception was active (square points), total event P_c was calculated using the following equations for Mt Cross (Equation 4) and the Summit site (Equation 5), respectively.

$$P_c = [1.11(T_f + S_f) + 3.02] - P_g, \quad (4)$$

$$P_c = [1.09(T_f + S_f) + 3.18] - P_g. \quad (5)$$

The canopy and trunk storage capacity for the forest sites was derived by swapping the x and y axes in Figure 10 and determining the linear regression equation for the relationship between $(T_f + S_f)$ and P_g. The negative intercept of these regression lines is the canopy and trunk storage capacity which was 2.4 mm at Mt Cross and 2.5 mm at the Summit site. Calculating canopy and trunk storage capacity values separately is often achieved using separate plots of throughfall and stemflow versus rainfall, however, the analysis is more complicated at the Norfolk Island sites as much of the throughfall from the canopy is intercepted by the palm understorey and diverted to stemflow. Palms are likely to have only a very low storage capacity due to their hard and smooth fronds and trunks which shed water very quickly, hence, a large component of palm stemflow is just rediverted throughfall. Separating stemflow measurements and comparing these to rainfall would result in an unreasonably high trunk storage capacity. To avoid introducing any bias in trunk or canopy storage terms they are represented as a single combined value for each site.

During 5 events, the throughfall and stemflow systems at both sites were overwhelmed by intense rainfall. For these events P_c was estimated based on a relationship between the number of hours of

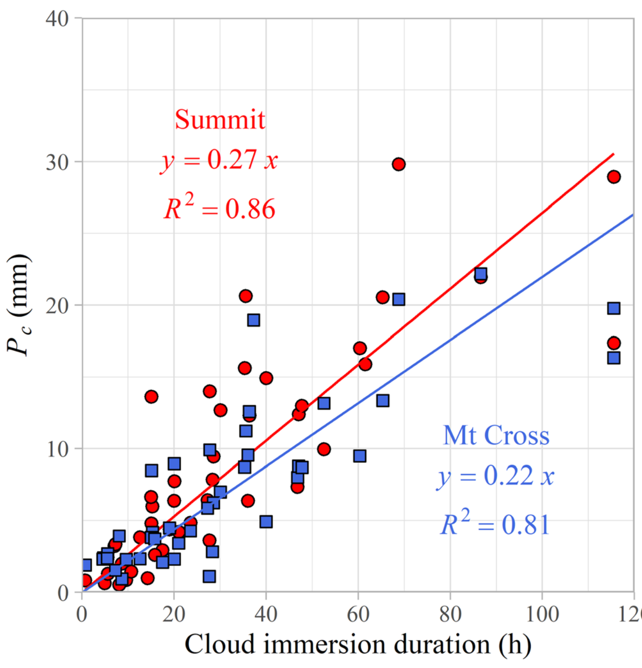

FIGURE 11 Relationship between the duration of forest cloud immersion (as defined by leaf wetness sensors) and event P_c for both the Mt Cross (squares) and Summit (circles) sites.

cloud immersion (as defined by the leaf wetness sensor installed on a 45° angle) and P_c for complete data days. These relationships are shown in Figure 11. The $(T_f + S_f)$ for these same events was then calculated by rearranging Equations 2 or 3. We note here that the leaf wetness sensors installed at 90° (i.e., vertically) and at 45° angle produced almost identical cloud immersion results, whereas the sensor installed at 0° angle indicated that the cloud immersion continued slightly longer. This longer duration is likely due to water droplets remaining on the sensor after cloud immersion rather than being shed as is the case with the other angles.

All events were summed by month to enable construction of a monthly water balance for each site (Figure 12). Only complete months are used for this analysis. Water input to the two forest sites (Figure 12a,c) and water pathways from the forest canopy at each location (Figure 12b,d) show very similar trends. The greatest precipitation input occurred during July 2022 at both sites and the least occurred in May 2022. The percentage contribution of cloud water interception to total precipitation input was typically around 20% to 25% at both sites, however very high contributions (>50%) were observed during the first 2 months of the study when rainfall inputs were low, yet conditions remained cloudy. Cloud water interception contributions varied strongly from a minimum of 6 mm during May 2022 at Mt Cross to a maximum of 72 mm during December 2022 at the Summit site.

The pathways of water from the forest canopy at both sites was dominated by stemflow with throughfall then accounting for the next greatest component of the water balance (Figure 12b,d). Wet canopy evaporation (E_w) varied throughout the study and tended to reflect the rainfall conditions during each month. The percentage of interception loss was much higher during low rainfall months, and this typically reflected smaller rainfall events with a greater proportion of the precipitation input being utilized to replenish canopy storage.

An over-all water budget for the canopy of each forest site for the duration of the study (15 October 2021–23 March 2023; $n = 524$ days) is given in Figure 13. At Mt Cross the total precipitation input to the canopy was 2357 mm of which 460 mm (or 20%) of the input came from cloud water interception. Represented as annualized values to facilitate comparison with other studies, total precipitation input, rainfall and cloud water interception were 1641, 1321 and 320 mm y^{-1}, respectively. At the Summit site the total input was 2772 mm with 577 mm (or 21%) delivered as cloud water interception. Total rainfall at Mt Cross was 1897 mm which is 299 mm, or 14%, less than that at the Summit site. Annualized totals for total precipitation input, rainfall and cloud water interception at the Summit site were 1932, 1530 and 402 mm y^{-1}, respectively. Cloud water interception added 24% to the rainfall measured at the clearing site for Mt Cross and 26% to the clearing site for the summit site. Total cloud water interception at Mt Cross was 116 mm or 20% less than at the Summit site. The lower inputs from rain and cloud at Mt Cross may reflect the reduced exposure of this site to the prevailing E to ENE winds (Figure 4). With its SE aspect, the Summit site is better aligned with the dominant winds, however, it is also slightly sheltered and given the importance of exposure to rain and cloud water inputs (Bruijnzeel & Scatena, 2010; McJannet, Wallace, & Reddell, 2007b) it is not unreasonable to expect that forests with an E aspect could have higher

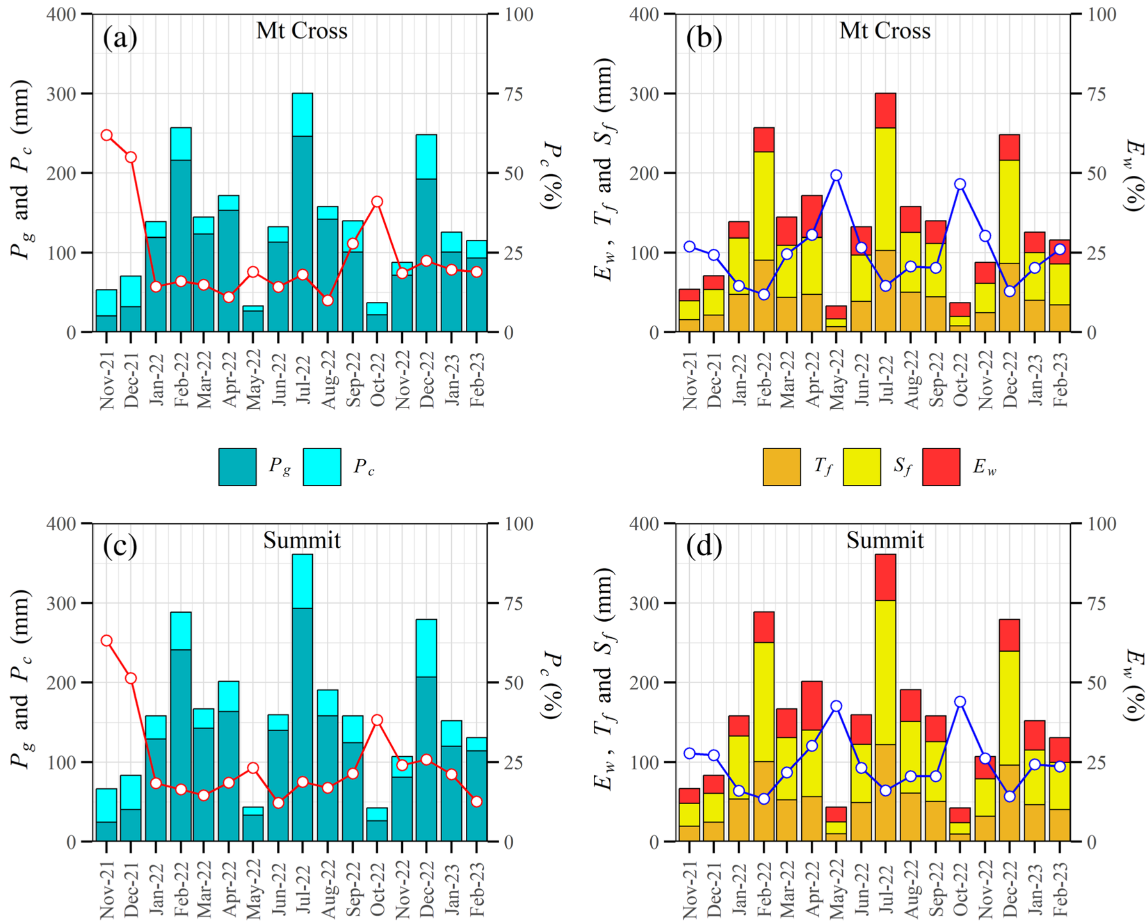

FIGURE 12 Seasonal variation in monthly rainfall and cloud water interception for Mt Cross (a) and Summit (c) sites and seasonal variation in monthly stemflow throughfall and wet canopy evaporation for Mt Cross (b) and Summit (d) sites. Also shown is the percentage of total water input occurring as cloud water interception (red line and secondary y-axis in a and c) and wet canopy evaporation (blue line and secondary axis in b and d). Events that span months are assigned to the month where most of the event occurred. Only complete months are shown.

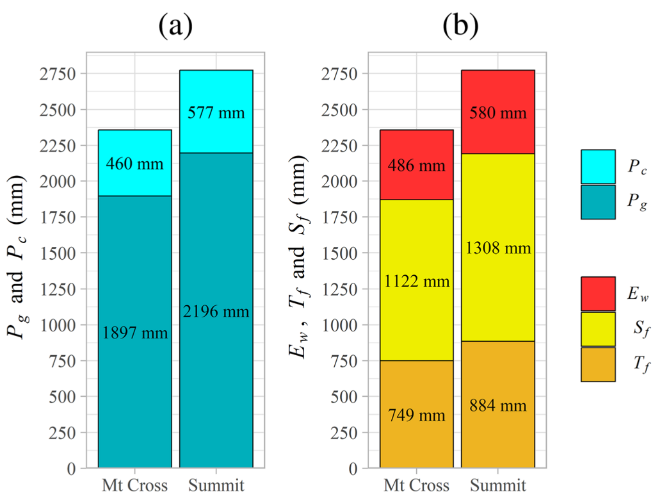

FIGURE 13 Forest canopy precipitation inputs (a) and canopy hydrologic pathways (b) for the Mt Cross and Summit sites over the duration of the entire study.

inputs than those reported in this study. Another factor that could contribute to the lower measured inputs of rain for the Mt Cross site is the 100 m difference in elevation from the rainfall measurement site at Palm Glen. This would be expected to produce some uncertainty if there was a strong gradient between rainfall and elevation, but earlier research has shown that this is not the case for Norfolk Island (see Discussion for more details). The lack of elevation-driven rainfall gradients and short distance between the two sites (400 m), gives confidence in the rainfall observations. Over the duration of the study, the total rainfall measured at the Landslip site using the throughfall troughs was 2196 mm, which was 4% less than that measured using the standard rain gauge at this site. This close agreement gives confidence in measurements made using the trough systems.

Interestingly, total interception loss was approximately equal to cloud water interception addition at the two sites with 486 mm (or 21%) at Mt Cross and 580 mm or (21%) at the Summit site. The predominant pathway for water to reach the forest floor was via stemflow. Total stemflow was 1122 mm, or 48% of total precipitation input at Mt Cross and 1308 mm, or 47% of total precipitation input at the Summit site. Total throughfall was 749 mm and 884 mm at Mt Cross and the Summit site, respectively which is or 32% of total precipitation input. At Mt Cross, wet canopy evaporation, stemflow and throughfall expressed as annualized values were 339, 782 and 522 mm y^{-1}, respectively. At the Summit site the equivalent annualized values were 404, 911 and 616 mm y^{-1}.

4 | DISCUSSION

Total rainfall reported for the different measurement sites did not suggest that there are any distinct elevational effects, however, there was some limited evidence for variation due to site aspect. Total rain for the entire period was greatest at Norfolk Island aerodrome (2624 mm) which is the lowest elevation monitoring location at 112 m ASL. The next highest rainfall was 2330 mm at the Landslip site (270 m ASL) using a rain gauge and 2195 mm using throughfall troughs. Finally, the lowest rain total of 1897 mm was recorded using throughfall troughs at the Palm Glen site (210 m ASL). Using a network of 15 rain gauges positioned around Norfolk Island, Stow and Dirks (1998) undertook an in-depth analysis of spatial variation in rainfall and concluded that rainfall distribution was highly variable and that this was partially driven by rain passing over the island in swaths. In their study, Stow and Dirks (1998) observed the highest cumulative rainfall in gauges located on the lower elevation areas to the south of the island, which included the aerodrome. These areas are relatively flat and exposed to winds from most directions. Rainfall on Mt Pitt was the second lowest observed which concurs with the lower rain observed in this current study at the Landslip site (just below the peak of Mt Pitt). Without a distinct pattern in rainfall distribution, it is difficult to assess the representativeness of the forest sites monitored of forests in other locations, however the limited spatial extent of forests above 200 m ASL (145 ha) would help to minimize any variability.

Throughfall and stemflow make up the two hydrological pathways that transfer precipitation to the forest floor. Combined, these two pathways typically account for 70 to 90% of incident precipitation in forest environments (see reviews of Levia et al., 2011 and Crockford & Richardson, 2000). The Mt Cross and Summit sites fall right in the middle of this range with stemflow and throughfall combined accounting for about 79% of total precipitation. What is unusual about the Norfolk Island forests though, is the relative contributions of stemflow and throughfall.

Throughfall typically dominates the delivery of water to the forest floor with most studies reporting throughfall contributions of around 70 to 85% of precipitation (Levia et al., 2011). In comparison throughfall for both forest sites from Norfolk Island was much lower at 32% of precipitation. Stemflow contributions are typically reported to be less than 10% of precipitation (Levia & Frost, 2003; Levia & Germer, 2015), however, contributions on Norfolk Island are much greater at ~48% at both sites. These are some of the highest values reported in the literature. Other studies in cloud affected ecosystems have reported high stemflow rates but none as high as those observed in this study. Examples include studies in Jamaica (Hafkenscheid et al. (2002), 12%–18% stemflow in low-stature upper montane rain forest), Puerto Rico (Holwerda et al. (2006), 26% stemflow in cloud affected montane palm forest), Australia (McJannet, Wallace, Fitch, et al. (2007), 11% stemflow in upper montane cloud forest), Peninsular Malaysia (Kumaran, 2008, 30.5% in stunted upper montane rain forest), and Japan (Xu et al., 2006, 31% in subtropical evergreen broadleaved forest). Higher than average stemflow rates have been attributed to high stem density, smooth bark and canopy morphology (Crockford & Richardson, 2000; Garcia-Estringana et al., 2010; Levia et al., 2015). Very low stemflow rates of <1% were reported for individual *Araucaria columnaris* trees (21.3–24 m tall, DBH 0.64–0.78 m) subjected to intense fog on Lana'i Island, Hawaii (Juvik et al., 2011). The authors cite the canopy architecture of *Araucaria columnaris* as the cause because isolated trees develop drooping branches at lower levels, and this can channel water away from the trunk. Similar drooping of lower branches can be observed for isolated Norfolk Island pines whereas trees in a forest environment have no lower branches and are typically angled upwards.

Of particular relevance to Norfolk Island is the importance of palms to the generation of stemflow. In a study of stemflow in Brazilian rainforest, Germer et al. (2010) showed that palms contributed 57% of the total stemflow and attributed this high contribution to the palm fronds which are effective in diverting rainfall toward the straight and smooth trunk. Similar observations of the importance of palms were also made in Costa Rican rainforest (Raich, 1983). Palms make up just 10% of the basal area at the Summit site and 12% at the Mt Cross site (Table 2) yet they contribute 37% of stemflow and 36% at these sites, respectively.

If it had been assumed that all basal area scaled equally to Norfolk Pines for stemflow calculations, a ~ 25% underestimation of stemflow would have occurred. The Norfolk Island palms are particularly well suited to stemflow generation due to their smooth stems and upwardly angled fronds (Dowe, 2010) which efficiently channel water to the forest floor. The high stemflow value reflects the ability of the palms to intercept throughfall from the canopy above and divert it to stemflow. In a forest setting, the branches of Norfolk Island pines are typically upward angled, and this also helps to divert water toward the straight vertical trunk (Silba, 1986) resulting in a high stemflow contribution from the pines. With Norfolk Island pines and palms collectively contributing 94% and 82% of the site basal area the forest, vegetation characteristics are ideal for stemflow generation. As noted by De Soyza et al. (1997), the morphology of the dominant vegetation is very important to stemflow production and this is clearly demonstrated for these Norfolk Island sites.

The canopy and trunk storage capacity at Mt Cross was 2.5 mm and at the Summit site it was 2.4 mm. This is reasonably high by international standards (see reviews in Link et al., 2004 and Pypker et al., 2005) and this reflects the large canopy depth and densely arranged scale-like leaves of the Norfolk Island pine trees (Silba, 1986) in combination with the colonies of mosses, orchids, and other epiphytes which grow in the canopy (Director of National Parks, 2010). Despite these relatively high values, other studies in cloud-affected forests, particularly those with high loadings of moss and epiphytes, have reported higher canopy storage capacities. Examples of these studies are; Holwerda et al. (2010) who report a canopy storage capacity of 3.9 mm for mature lower montane cloud forest with in Mexico, Wallace and McJannet (2008) who report canopy storage capacity of 3.6 mm for lower montane cloud forest in Australia, and Köhler et al. (2007) who report a canopy storage capacity of 4.4 mm for old growth cloud forest in Costa Rica.

In this study cloud water interception was found to contribute approximately 20% of total precipitation input to the higher-elevation forests of Norfolk Island. This rate of contribution falls well within the range of contributions reported for other cloud-affected forests around the world (e.g., tropical montane rainforest: 2% to 60%; Bruijnzeel et al., 2005; Cavelier et al., 1996; McJannet, Wallace, & Reddell, 2007b), Californian redwood forest: up to 34% (Dawson, 1998), Norway Spruce forest up to 29% (Köhler et al., 2015). Long-term analysis of rainfall (Figure 5) and cloud frequency below 300 m ASL (Figure 7) suggested that the study period was wetter and cloudier than average. Given this observation, it is likely that that the cloud water interception rate measured at Mt Cross (310 mm y^{-1}) and the Summit site (402 mm y^{-1}) was higher than might be expected in an average year. Month-to-month variations in cloud water interception contribution (Figure 12) showed reasonably stable contributions to total precipitation (except in the direst months), hence, the percentage contribution to total precipitation is likely to remain at ~20% across years unless there are extended period of consecutive dry months.

Cloud water interception at Mt Cross was 82 mm y^{-1} less than that at the Summit site. Pryet et al. (2012) also observed differences in cloud water interception at forest sites on Santa Cruz Island and concluded that the cause was an elevational gradient in cloud water density (Pryet et al., 2012). Cloud water density is unlikely to be the cause of observed differences in this current study as the two forest sites were at a similar elevation (Mt Cross ~20 m higher). As with rainfall, the more sheltered aspect of the Mt Cross site is a more likely explanation for the observed differences in cloud water interception. Exposure is a key factor in cloud water interception, and this has been noted in numerous previous studies (Bruijnzeel & Scatena, 2010; Juvik et al., 2011; McJannet, Wallace, & Reddell, 2007b; Prada et al., 2009). In addition, while elevational effects in cloud water density may be present on Norfolk Island, they are likely to be small as the difference in height between the frequently observed cloud base (250 m ASL) and the highest point on the island (319 m ASL) is less than 70 m.

The impact of climate change on cloud formation and frequency and cloud base elevation is one of the least certain aspects of climate projections as there are many feedback processes involved (Voigt et al., 2021). As a result, the potential impact of climate change on cloud water interception processes on Norfolk Island are hard to quantify but any reduction in cloud frequency or increase in cloud base could have negative effects on the hydrology and ecosystems of Norfolk Islands peaks. The cloud base elevation is dependent on the level at which water vapour in a rising air parcel becomes saturated (Narsey et al., 2020). The rate of cooling with altitude is known as the temperature lapse rate and varies with location. A rise in temperature typically implies an increase in cloud base level, however, the magnitude of this would depend on concurrent changes in atmospheric humidity (Still et al., 1999). Air and sea surface temperatures in the ocean surrounding Norfolk Island have shown an increasing trend over recent decades (Garcia-Soto et al., 2021; Hughes et al., 2022) so an increase in cloud base is certainly not inconceivable. In the context of Norfolk Island, an increase

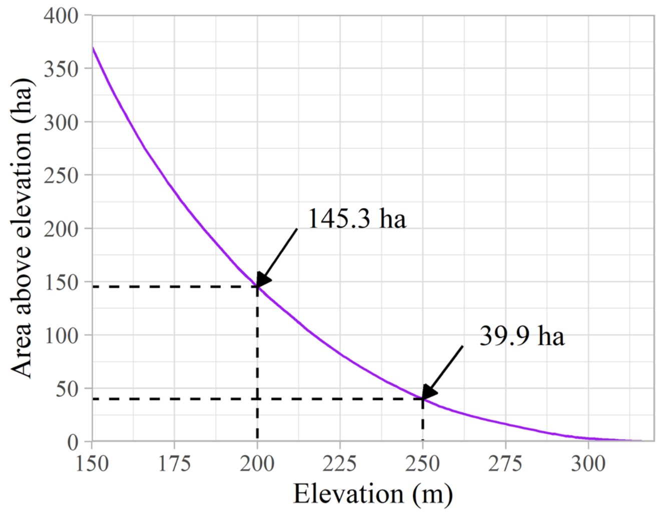

FIGURE 14 Decrease in mountain top land surface area with increasing elevation on Norfolk Island. Values indicate the change in surface area with a rise in cloud base from 200 to 250 m elevation.

in cloud base would result in major impacts on the area of forest regularly immersed in cloud (see Figure 14). Assuming a hypothetical cloud base of 200 m ASL (based on ceilometer observations, Section 2.2), the three-dimensional land surface area (i.e., not planar) above this elevation is 145.3 ha. However, an increase in cloud base height of just 50 to 250 m ASL would decrease the land surface area regularly immersed in cloud to 39.9 ha, a reduction of 72%. This vulnerability of mountain peak ecosystems and cloud forests to warmer temperatures is becoming being recognized in studies from around the world (e.g., Auld & Leishman, 2015; Bruijnzeel et al., 2011; Loope & Giambelluca, 1998; Wallace & McJannet, 2013; Williams et al., 2003) with issues becoming exacerbated by the reduction of water input and concurrent increase in evaporative demand under drier conditions. Like other locations, the unique plant, animal and insect species of Norfolk Island, which have more prevalence in the moister environments of the peaks, may also be vulnerable to decreasing habitat and drier conditions in the future.

Finally, while the additional water from cloud water interception is considerable at a local scale, it is worth considering it hydrological importance at an island scale. Hughes et al. (2022) undertook a water balance analysis for Norfolk Island for the period between 2010 and 2019 and estimated that average annual rainfall volume for the island was 39 000 ML y^{-1}. If we adjust this number to include a 25% increase in water input as a result of cloud water interception (i.e., 20% of total precipitation input) for Norfolk Island pine forests above a lower cloud base layer of 200 m ASL, that is, 145.3 ha surface area and average annual rain of 1184 mm (rainfall value from Hughes et al., 2022), then the total water input for the island increases by 430 ML y^{-1}. This is just a 1% increase in total water input which indicates that the contributions of cloud water interception are minimal from an island-wide hydrological perspective. Despite this, it cannot be ignored that this extra source of water is still likely to be very important to localized hydrology around the mountain peaks and to the survival of endemic species which thrive in the moister conditions of the higher elevation mountain sites.

5 | CONCLUSIONS

The field instrumentation installed as part of this study has provided the first set of observations by which to measure the canopy water balance and quantify the contribution of cloud water interception to the precipitation inputs of upland mountain forests on Norfolk Island. Instrumentation of two forest locations revealed similar hydrologic behaviour despite different landscape settings. The use of large-volume automated tipping buckets removed the need for frequent site visits, however, laboratory testing showed that dynamic calibrations are required for such devices to account for the variation in tip volume with flow rate.

Detailed observations of stemflow from Norfolk Islands pines and palms revealed stemflow contributions of ~48% at both sites which is far greater than any values reported in the literature. Both pines and palms have upwardly angled branches/fronds which favour funnelling of water to the stem of individual trees. The high contribution of stemflow from palms suggest that this understorey layer is collecting throughfall from the over storey pines and directing it down the smooth palm stems. Throughfall values at both sites were 32% which is low by international standards.

A canopy water balance method, where differences in water delivered to the forest floor as compared to rainfall delivered in the open, was utilized to quantify cloud water interception for individual events. Results showed that cloud water interception was ~20% of the total water input to both forest stands; this represents a 25% increase on precipitation based on rainfall measurements alone. There were no distinct patterns in the seasonality of cloud water interception, but monthly inputs varied depending on prevailing weather conditions. On a monthly basis, percentage contributions of cloud water interception to total precipitation typically ranged between 20% and 25%. Setting the study findings in the long-term context suggests that the period of observation was wetter and experienced more cloud than average. However, results suggest that cloud water interception, expressed as a proportion of precipitation input, is likely to be a reasonable estimate of forest inputs because rain rarely falls in the absence of cloud immersion.

A simple island-wide water budget revealed that the contribution of extra water from cloud water interception from the upland forests is unlikely to significantly increase available water or recharge, however, the extra water and moist conditions are likely to be very important for the survival of endemic and endangered plant, animal and insect species that favour these wetter and cooler environments. Given this importance, the potential impacts of climate change on these vulnerable environments need to be better understood. The impacts of a warmer future climate are hard to quantify, but any reduction in cloud frequency or increase in cloud base could have negative effects on the hydrology and ecosystems of Norfolk Islands' peaks.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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