Eucalyptus Obliqua Tall Forest in Cool, Temperate Tasmania Becomes a Carbon Source during a Protracted Warm Spell in November 2017

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Abstract

Tasmania, which has a cool temperate climate, experienced a protracted warm spell in November 2017. In absolute terms, temperatures during the warm spell were lower than those usually characterising heatwaves. Nonetheless the November 2017 warm spell represented an extreme anomaly based on the local historical climate. Eddy covariance measurements of fluxes made in a *Eucalyptus obliqua* tall forest at Warra, southern Tasmania, recorded a 39% reduction in gross primary productivity (GPP) during the warm spell. A coincident increase in ecosystem respiration during the warm spell resulted in the forest switching from a carbon sink to a source. Net radiation was significantly higher during the warm spell than in the same period in the preceding two years. This additional radiation drove an increase in latent heat but not sensible heat. Stomatal regulation to limit water loss was unlikely based on soil moisture and vapour pressure deficits. Temperatures during the warm spell were supra-optimal for GPP at that site for 75% of the daylight hours. The decline in GPP during the warm spell was therefore most likely due to temperatures exceeding the site optimum for GPP. These forests will be weaker carbon sinks if, as predicted, heatwave events become more common.

Introduction

The capacity for many forests to take-up carbon is diminished during heatwaves¹⁻³. In most reported cases, this diminution in carbon uptake is the consequence of the need to regulate stomatal conductance to reduce water loss under drought conditions or high evaporative demand²⁻⁴. However, there are differences among forest ecosystems in their response to heatwaves⁵. During one heatwave event in Australia for example, van Gorsel, et al.² found the pattern of responses in carbon and energy fluxes in eucalypt dry sclerophyll forests and woodlands across southern Australia differed from that of a tall eucalypt forest in south-eastern Australia. In the dry sclerophyll forests and woodlands, carbon uptake declined, and latent heat fluxes were very low relative to sensible heat fluxes during the heatwave. The reverse occurred in a tall eucalypt forest during the heatwave - carbon uptake increased and latent heat flux increased relative to sensible heat flux. van Gorsel, et al.² concluded that those heatwave responses reflected water limitation and energy limitation, respectively.

Patterns of carbon and energy fluxes during the heatwave event reported by van Gorsel, et al.² were consistent with photosynthesis and transpiration being coupled. However, measurements by Drake, et al.⁶ on young *Eucalyptus paramattensis* trees housed within whole-tree growth-chambers, suggested photosynthesis and transpiration could become decoupled during extreme heatwave conditions (maximum air temperatures of 43-44°C over four days). De Kauwe, et al.⁷ were unable to show conclusively that carbon and energy fluxes decoupled in forest ecosystems experiencing extreme heatwaves (consecutive days with maximum temperatures > 35°C). One of the reasons the authors proposed for this was the possibility that atmospheric demand associated with high vapour pressure deficits (VPD) during extreme heatwaves could cause the measured increased transpiration even with decreased stomatal conductance.

The study of De Kauwe, et al. ⁷ excluded temperate forest sites in south-eastern Australia because they rarely met or exceeded the threshold temperatures used as their heatwave definition. Perkins and Alexander ⁸ argue against simply describing extreme heatwave events in terms of consecutive days above a threshold temperature because they do not properly account for the regional differences in historical climates. Instead, they advocate regionally adjusted metrics such as consecutive days that exceed the 90th percentile value for the calendar day. Such regionally adjusted metrics should also better account for any local adaptation by the forest to the regional climate.

Optimum temperature for the gross primary productivity (GPP) of a forest has been shown to vary according to the historical climate of the forest site ⁹⁻¹¹. When the thermal optimum for GPP is exceeded, the net carbon balance of the forest rapidly declines because GPP decreases in concert with increasing ecosystem respiration ¹². In Australia, the most productive forest ecosystems occur in high rainfall areas at either end of a temperature gradient ¹³. On mesic sites in the cool, temperate regions of south-eastern Australia, high forest productivity coincides with low temperature optimum for GPP ¹¹. While van Gorsel, et al. ² detected no decline in GPP during a heatwave event in 2012-13 in one temperate eucalypt forest on a mesic site, it was the only such forest included in that study. There is a need for more observations of the GPP response to heatwaves of eucalypt forests growing on mesic sites.

The entire state of Tasmania experienced record-breaking heatwave in November 2017 ¹⁴. The Warra Supersite ^{13,15}, part of Australia's Terrestrial Ecosystem Research Network, and situated near the southern extent of the tall eucalypt forests in Australia, became operational in March 2013. Meteorological and micro-meteorological instruments installed on an 80-m tower above a *E. obliqua* tall forest at the Warra Supersite, monitored carbon, water and energy fluxes during that heatwave. Here I compare the response of a *E. obliqua* tall forest in southern Tasmania to the 2017 heatwave with previously reported responses to heatwaves in other temperate tall eucalypt forests.

Results

Analysis of historical heatwaves in southern Tasmania

Over nearly a century of measurements, 99 in-growing-season (Austral spring-summer) heatwave events have been recorded at Cape Bruny Lighthouse (59 km southeast of Warra Supersite). Two of those events occurred in November 2017: 17th -19th and 21st -23rd. Those two events were embedded within a protracted warm period extending from 10th -30th November during which all but one day exceeded the average daily maximum temperature and ten days had maximum temperatures that matched or exceeded the 90th percentile values (Fig. 1) for their calendar days. The departure from average temperatures during the 21-day warm spell in November 2017 was the largest on record (z-score = 3.86, equating approximately to a 1 in 1000 year event). Despite this, there were no days where maximum temperature exceeded 30°C: more than half of the 99 heatwave events recorded at Cape Bruny

Lighthouse were hotter than the two November 2017 events. Hereafter, the November 2017 warm spell with embedded heatwaves is referred to simply as the 2017 warm spell.

The average daily maximum temperatures during the 10–30 November period in the two years prior (2015 and 2016) to the 2017 warm spell were 16.7 and 16.6°C, respectively. While slightly above the long-term average (1923–2020) of 15.9°C for this period at the Cape Bruny Lighthouse, the maximum temperatures in 2015 and 2016 were not significantly different from that long-term average (z-scores = 0.61 and 0.55 for 2015 and 2016, respectively).

Weather conditions at Warra Supersite during the 2017 warm spell

The forest received significantly more incoming shortwave radiation (F_{sd}) during the 2017 warm spell ($F_{2,60}=4.76$; $MSE = 14.2$; $P = 0.012$), equating to a 30–32% increase in F_{sd} compared with the previous two years (Fig. 2a). Unsurprisingly, it was significantly warmer during the 2017 warm spell ($F_{2,60}=34.05$; $MSE = 5.79$; $P < 0.001$). More than 75% of the 30-minute daytime temperature records during the 2017 warm spell exceeded 15°C, whereas only about a quarter exceeded 15°C in the two previous years (Fig. 2b). Despite the general warming in November 2017, only six 30-minute periods had air temperature of 30°C or more. In parallel with temperature, vapour pressure deficit (VPD) was significantly higher during the 2017 warm spell than the same period in the two previous years ($F_{2,60}=4.48$; $MSE = 0.22$; $P = 0.015$). Despite being higher during 2017 warm spell than the previous two years, VPDs were still relatively low – only sixteen 30-minute periods during the warm spell had a VPD of 3 kPa or more (Fig. 2c). The soils at Warra were significantly drier during the 2017 warm spell (Kruskal-Wallis statistic = 41.5; $P < 0.001$) than the previous year (2016) but was comparable with 2015 (Fig. 2d) and did not drop below 20% VWC.

In the month following the 2017 warm spell (1–31 December), weather conditions moderated. F_{sd} , T_a and VPD all dropped to levels that were not significantly different from those of the December period in the preceding two years – 2015 and 2016. Soil moisture in the month after the heatwave, changed little in 2017 nor the two preceding years.

Turbulent fluxes at Warra Supersite during the November 2017 warm spell

In comparison with the 10–30 November period in 2015 and 2016, the 2017 warm spell had: significantly lower average daily gross primary productivity, GPP, ($F_{2,60}=14.4$; $MSE = 13923$; $P < 0.001$); significantly higher average daily ecosystem respiration, ER, ($F_{2,60}=21.6$; $MSE = 1739$; $P < 0.001$); and, significantly lower average daily net primary productivity, NPP, ($F_{2,60}=25.2$; $MSE = 16289$; $P < 0.001$) (Fig. 3). Over the duration of the 2017 warm spell, the cumulative GPP was 120 g C/m² – 39% less than the average GPP for the same period in the two previous years (Fig. 4a). The cumulative ER over the 21 days of the 2017 warm spell was 159.7 g C/m², an increase of 26% compared with the average cumulative ER for the same period in 2015 and 2016 (Fig. 4b). The combined effect of the lower GPP and the higher ER during

the 2017 warm spell was to switch the forest at Warra from a carbon sink with an uptake of 77 and 63 g C/m² over the 21 days from 10th -30th November in 2015 and 2016, respectively, to a carbon source of 39.5 g C/m² (Fig. 4c). This equates to a change in NEE of some 110 g C/m². In the month following the 2017 warm spell, the forest returned to being a net carbon sink - NEE returned to levels that were not significantly different from those recorded in 2015 and 2016 (Kruskal-Wallis test statistic = 4.72; P = 0.094).

The forest at Warra had significantly higher net radiation (Fn) during the November 2017 warm spell compared with the same period in the previous two years ($F_{2,60}=4.41$; MSE = 7.26; P = 0.014; Fig. 5). Latent heat flux (Fe) – the energy associated with evapotranspiration - followed the same pattern and was significantly higher during the 2017 warm spell compared with the same period in the previous two years ($F_{2,60}=14.8$; MSE = 2.12; P < 0.001; Fig. 5). In contrast, sensible heat flux - the energy associated with the air temperature - during the 2017 warm spell was not significantly different from the same period in the previous two years ($F_{2,60}=1.53$; MSE = 2.74; P = 0.22; Fig. 5). The higher net radiation during the November 2017 warm spell thus preferentially dissipated as latent heat rather than sensible heat. Cumulative evapotranspiration for the 10–30 November period was 104 and 62% (average 83%) higher in 2017 than in 2015 and 2016, respectively (Fig. 6).

Discussion

Compared with same period in the preceding two years, the November 2017 warm spell at Warra resulted in: a reduction in GPP of 39%; an increase in ER of 26%; the forest switching from a sink to a source; and an increase in evapotranspiration of 83%. This combination of responses during such mild heatwave conditions have not been reported previously. Temperatures during the November 2017 warm spell and embedded heatwaves in southern Tasmania were mild relative to those recently documented for other heatwaves affecting forest ecosystems in the southern Australian mainland^{2,7,16}. This reflected the method used to determine heatwaves in this study – three consecutive days with temperatures above the 90th percentile value for that calendar period – as proposed by Perkins and Alexander⁸, rather than continuous days above an absolute temperature threshold. In this context, the November 2017 warm spell in Tasmania was of exceptional severity, locally, and eclipsed previous records for the state by a large margin¹⁴. So, even using a less stringent definition of a heat-wave, the changes in carbon fluxes were large.

Eucalypt-dominated ecosystems can change from a carbon sink to carbon source during heatwaves as the result of increased ER alone, or the combination of increased ER and reduced GPP. Increased ER was the sole driver of the forest ecosystem switching from a carbon sink to a source during a heatwave in the case of *Eucalyptus* spp. at Wombat Forest during the January 2014 heatwave¹⁶ and *E. delegatensis* at Tumbarumba during the 2012-13 heatwave². The combined effect of increased ER and decreased GPP in causing a switch from a carbon sink to a source during heatwaves has been reported in eucalypt dry sclerophyll forests and Mediterranean woodlands in during the 2012-13 heatwave across southern

Australia²; in young *E. parramattensis* during an induced heatwave¹⁷; *E. moluccana* / *E. fibrosa* at Cumberland Plains during summer months¹⁸.

Declines in GPP during heatwave events in Australian eucalypt forests are believed to involve regulation of stomatal conductance to limit water loss when soils are dry^{2,16} and/ or when VPDs are very high^{2,7,17}. The decline in GPP during the 2017 warm spell at Warra was different. Soil moisture was not limiting at Warra during the 2017 warm spell and VPDs did not reach high values. GPP declines in eucalypt ecosystems that coincide with reduced latent heat flux and attributed to low soil moisture typically report soil water contents of less than 10%^{2,16}. Soil water content (swc) at Warra did not drop below 20%. This was comparable with, or higher than, swc reported for heatwave events at Tumbarumba in 2012-13² and Wombat Forest in 2014¹⁶. High latent heat fluxes were sustained during those heatwaves at Tumbarumba and Wombat Forest as they were at Warra, but in contrast with Warra showed no declines in GPP. Declines in GPP during heatwaves in eucalypt ecosystems that are attributed to VPD-mediated reductions in stomatal conductance report VPD values that approach, or exceed, 6 kPa, typically when temperatures exceed 40°C^{2,17}. In contrast to these extreme heatwaves, conditions were much less severe during the 2017 warm spell in Tasmania – VPD rarely exceeded 3kPa and the maximum VPD was only 3.3 kPa. This was also well below the average VPD (4.5 kPa) reported by Griebel, et al.¹⁶ during the driest days of summer months between 2013-15 at Wombat Forest where both sapflow and latent heat flux increased relative to baseline.

Temperatures that are supra-optimal for GPP provide a simple explanation for the reduction in GPP measured at Warra during the 2017 warm spell. Bennett, et al.¹¹ recently documented the GPP versus temperature relationship for 17 eucalypt-dominated forest ecosystems in Australia. For each ecosystem, the GPP versus temperature relationship was a convex parabola with the vertex corresponding to the optimum temperature for GPP (T_{opt}). The T_{opt} of each ecosystem was linearly related to the historical daytime mean temperature of the ecosystem. This matched the finding of Tan, et al.¹⁰ for tropical rainforests. Bennett, et al.¹¹ found the temperature optimum for GPP at Warra was 16°C - one of the lowest for the sites they examined. This reflected the relatively cool climate in southern Tasmania. Nearly 75% of the 30-minute average temperature records during daylight hours of the November 2017 warm spell were in the supra-optimal range. Bennett, et al.¹¹ also found that Warra, together with tropical rainforest sites, GPP showed a high temperature sensitivity (rate of decline in GPP as temperature departs from the optimum) compared with other eucalypt forests in Australia.

On the basis of the evidence presented, the *E. obliqua* tall forest at Warra switched from a strong carbon sink to a source during the 2017 warm spell because daytime temperatures exceeded the site optimum temperature for GPP for most of the three-week period. The reduction in GPP and the increase in ER during the 2017 warm spell indicate their decoupling as described by Duffy, et al.¹². The forest was resilient to the 2017 warm spell and quickly recovered to being a carbon sink once temperatures moderated. Such resilience to transient heatwave events has been seen in other forests¹⁹. However,

decoupling events will become more regular as temperatures increase, which may lead to ecosystems transitioning to carbon sources ¹².

Based on the historical climate of southern Tasmania the 2017 warm spell was an exceedingly rare event. Such events, however, will become more common as temperatures continue to increase and may result in Tasmania's tall eucalypt forests transitioning to become carbon sources in the future. The tall eucalypt forests in Tasmania are among the most productive natural forest ecosystems globally and can store large amounts of carbon ²⁰⁻²³. There would be many adverse consequences if these forests were to transition to carbon sources with warming temperatures. While adaptation options to reduce the risks of adverse effects of climate change have been evaluated for tall eucalypt forests ²⁴, the direct effect of higher temperatures were not considered. Our understanding of the direct effect of warmer temperatures on the productive and ecological processes in tall eucalypt forests is currently rudimentary. This will need to change, and quickly.

Methods

Site description

Warra Supersite, (Lat: 43°5'42" S; Long: 146°39'16" E) is located on a floodplain of the Huon River within the Warra Long Term Ecological Research site (<https://warra.com/>) 60 km southwest of Hobart, Tasmania. The forest at the Supersite is an *Eucalyptus obliqua* tall forest with a canopy height of 50-55m, overtopping a 15-40m tall secondary layer of rainforest and wet sclerophyll tree species. Ferns dominate the ground layer. The forest is very productive with an aboveground biomass of 790 tonnes/ha ¹⁵ and a leaf area index of 5.7 m²/m² ²⁵.

The Supersite is within the Tasmanian Wilderness World Heritage Area (TWWHA). That part of the TWWHA experiences infrequent, but sometimes intense, wildfire. Except for a small proportion of mature (>250 years-old) *E. obliqua* trees, the current forest resulted from seedling regeneration following the last major wildfire in that part of the landscape in 1898. No timber harvesting has ever been done in the forest at the Supersite.

The climate at Warra is classified as temperate, with no dry season and a mild summer ²⁶. Mean annual rainfall measured at the nearby Warra Climate Station (Bureau of Meteorology Station 097024) is 1736 mm and the mean daily temperature is 14°C and 5.6°C in January and July, respectively. The soil at the site is a Kurosolic Redoxic Hydrosol ¹⁵.

Analysis of historical heatwaves in southern Tasmania

Daily maximum temperature records from the Bureau of Meteorology station at Cape Bruny Lighthouse (station number 94010) were extracted from the Bureau of Meteorology's online climate data portal

(<http://www.bom.gov.au/climate/data>). Cape Bruny Lighthouse is one of the 112 stations in the ACORN-SAT network of Australia's reference sites for monitoring climate change²⁷. The station provides a record of daily maximum temperature measurements commencing in 1923 and spanning almost a century. It is the southern-most station in the ACORN-SAT network; is 59 km south-east of the Warra Flux Site; and bounds the south-eastern extent of *E. obliqua* tall forest in Tasmania.

Missing temperature measurements represented less than 0.6% of the 35795 records collected at Cape Bruny Lighthouse between January 1st 1923 and December 31st 2020. The missing measurements were gap-filled using predicted values calculated from linear regression models constructed from measurements made at nearby Bureau of Meteorology stations (listed in order of proximity to Cape Bruny Lighthouse and priority for gap-filling) – Cape Bruny Automatic Weather Station (1997-present), Hastings Chalet (1947-1987) and Hobart-Ellerslie Road (1892-present).

Average, standard deviation and 90th percentiles of daily maximum temperature were calculated for each calendar day of the year. Further analysis of heatwaves was restricted to the period between the beginning of August and the end of February. This period bounds the growing season of the forest at the Warra Supersite when there is normally a net carbon gain by the forest (Wardlaw unpublished data). Heatwaves were identified as three or more consecutive days with maximum temperatures that met or exceeded the 90th percentile value *sensu* Perkins and Alexander⁸. For each heatwave event that was identified, the following three statistics were calculated: (i) average daily maximum temperature during the heatwave; (ii) summed departures (as standard deviations) from average daily maximum temperature during the heatwave; (iii) summed departures (as standard deviations) from average daily maximum temperature of the 21 day period centred on the middle day of the heatwave. The November 2017 heatwave as described by these three statistics was ranked against all the other heatwave events identified between 1923-2020 at Cape Bruny Lighthouse. In addition, the z-score was calculated to measure the magnitude of the departure of the average daily maximum temperatures during the November 2017 heatwave from the long-term average of this 21-day period. These statistics were also calculated for the month immediately after the November 2017 heatwave (1-31 December) and the same period in 2015-16 to examine to what extent temperature conditions returned towards average conditions.

Weather conditions at Warra Supersite during the 2017 warm spell

Four attributes of weather were used to describe the November 2017 warm spell – air temperature, vapor pressure deficit (calculated from temperature and relative humidity), incoming shortwave radiation and soil moisture. Air temperature and relative humidity were measured using an HMP155A probe (Vaisala, Finland) and incoming shortwave radiation was measured using a CNR4 radiometer (Kipp and Zonen, The Netherlands). Both instruments were mounted 80-metres above ground level at the top of the Warra

Flux tower. Data was processed to 30-minute averages and logged onto a CR3000 datalogger (Campbell Scientific, Logan, USA).

Soil moisture was measured by time-domain reflectometry using two CS616 soil moisture probes (Campbell Scientific, Logan, USA) each installed at a depth of 20cm. These probes were installed in two pits approximately 40m west of the tower. Soil moisture data were processed to 30-minute averages and logged onto a CR1000 datalogger (Campbell Scientific, Logan USA).

Turbulent fluxes at Warra Supersite during the November 2017 warm spell

Measurement of turbulent fluxes (carbon, water and energy) were done by eddy covariance (EC) using a closed-path infra-red gas analyser (Model EC155, Campbell Scientific Inc., Logan, USA) to measure CO₂ and H₂O concentrations and a 3-D sonic anemometer (Model CSAT3A, Campbell Scientific Inc, Logan, USA) to measure turbulent wind vectors and virtual air temperature. High frequency (10 Hz) measurements of turbulent fluxes were processed to 30-minute averages in a datalogger (Model CR3000, Campbell Scientific, Logan USA).

Soil heat flux (SHF) was measured to enable calculation of energy balance that was needed to partition energy fluxes into latent and sensible heat. SHF was measured using five SHF plates (Model HFP01SC, Hukseflux, Delft, The Netherlands) inserted in the soil at depth 8cm adjacent to the two pits in which the soil moisture probes were installed. Each of the five SHF plates were allocated to one of the two soil pits in a 2-3 split. Changes in soil temperature was measured by an averaging thermocouple (Model TCAV, Campbell Scientific Inc, Logan, USA) inserted into the soil above each SHF plate at depths of 2 and 6 cm. Soil moisture measurements at 20cm depth were as described previously. Heat flux, soil temperature and soil moisture data were processed to 30-minute averages on a datalogger (Model CR1000, Campbell Scientific Inc, Logan, USA)

Raw 30-minute flux and climate data were processed using the standard OzFlux QA/QC processing stream ²⁸ using the PyFluxPro Version 0.1.1 software. At the final stage of data processing gap-filled net ecosystem exchange (NEE) data were partitioned into gross primary productivity (GPP) and ecosystem respiration (ER) using the u*-filtered night-time CO₂ flux records to calculate ER with the SOLO artificial neural network algorithm as described in ²⁸. The standard conventions of the global flux network were adopted in partitioning NEE as described in ²⁹. Latent heat fluxes were converted to evapotranspiration by dividing the measured latent heat flux by the latent heat of vaporisation of water.

The full period between 10-30th November 2017 was defined as the November 2017 warm spell. The climate and fluxes measured during this period were compared with measurements of those made during the same calendar days of the preceding two years 2015 and 2016.

Data analysis

For each day of the 10-30 November period, daily sums were calculated for measurements of fluxes (carbon, water and energy) and incoming shortwave radiation (Fsd), while daily averages were calculated for air temperature, VPD and soil moisture. The significance of differences in measurements during the 10-30 November period among the three years of each variable were tested by analysis of variance. Tests were first done to confirm the data for each variable were normally distributed and between-group variances were homoscedastic. Latent heat flux was significantly skewed and non-normal due to one significant outlier (3.8 standard deviations from mean). This outlier corresponded to a day of unusually high latent heat flux and probably was due to evaporation from a wet canopy as 25 mm rainfall fell during the preceding 24 hours. Removal of this outlier corrected the non-normality. Log-transformation was used to correct skewness in the VPD data. Soil moisture data were strongly skewed, and transformation was unable to correct. For this variable, the Kruskal-Wallis method was used to test the significance of differences in medians among the three years. These analyses were repeated for the month immediately after (1st – 31st December) the heatwave period to examine the persistence of any changes in carbon fluxes once the heatwave had ended.

Declarations

Acknowledgements

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Author contributions

T.W. conceived the study, did the data analysis and wrote the paper.

Competing interests

The author declares no competing interests.

Data availability

Climate data were accessed from the online repository of the Bureau of Meteorology (<http://www.bom.gov.au/climate/data/?ref=ftr>) for the stations referenced: Cape Bruny Lighthouse (094010), Cape Bruny Automatic Weather Station (094198), Hastings Chalet (094027), Hobart – Elderslie

Road (094029). Weather data, turbulent fluxes and partition carbon fluxes for Warra Supersite for the 10-30 November period in 2015, 2016 and 2017 are available on the OzFlux Data Portal (<http://data.ozflux.org.au/portal/home.jspx>).

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Figures

Figure 1

Daily maximum temperatures recorded at Bruny Island Lighthouse during the 2017 warm spell. Average daily maximum temperature during the period 10-30th November 2017 are plotted together with the average and 90th percentile values for those days calculated from long-term (1923-2020) records.

Figure 2

Climate conditions at Warra Supersite during the 2017 warm spell and the same period in the preceding two years. Plots of daily averages or sums for the period (10-30 November), are shown for: (a) average total daily incoming shortwave radiation (with 95% least significant difference error bars); quantile plots of 30-minute averages of (b) air temperature and (c) vapour pressure deficit; and (d) box and whisker plot of average daily soil water content.

Figure 3

Average of daily carbon fluxes at Warra Supersite during the 2017 warm spell and the same period in the previous two years. The carbon fluxes have been partitioned into gross primary productivity (GPP), ecosystem respiration (ER) and net ecosystem exchange (NEE). 95% least significant difference of means for each of the three component fluxes are shown.

Figure 4

Cumulative fluxes of carbon measured at the Warra Supersite during 10-30 November in 2015, 2016 and 2017. The carbon fluxes have been partitioned into (a) gross primary production (GPP), (b) ecosystem respiration (ER), and (c) net ecosystem exchange (NEE).

Figure 5

Average daily energy fluxes at Warra Supersite during the November 2017 warm spell and the same period in the previous two years. The energy fluxes have been partitioned into net radiation (Fn), latent heat flux (Fe) and sensible heat flux (Fh). 95% least significant difference of means for each of the three component fluxes are shown.

Figure 6

Cumulative evapotranspiration measured at the Warra Supersite during the 10-30th November period in 2015, 2016 and 2017.