***Authors' response* to reviewer comments on "Net ecosystem carbon exchange of a dry temperate eucalypt forest" *by Hinko-Najera et al.* (bg-2016-192)**

We would like to thank both reviewers for their time spent reading the manuscript, their constructive comments and valuable suggestions on changes and/or additions particularly regarding methodology and data analysis that, we think, will strongly improve our manuscript. We have addressed all comments and issues raised by the reviewers, propose changes to the manuscript accordingly and provide following detailed responses to reviewer comments below. For facilitation we have copied the comments of both reviewers (black text) and our responses are outlined in blue.

Relevance of the study and major issues raised by both reviewers:

Some of the major concerns of both reviewers were similar and thus are outlined in summary points as follows:

- **Relevance of the study:**

R1: By sampling a drier temperate eucalyptus forest than has been studied in the past, this study brings unique observations of ecosystem scale carbon fluxes that provide a valuable expansion of the Australian and (semi-)global ecosystem flux measurement networks. The paper's major contribution and strength is to present estimates of daily, seasonal and annual NEE, GPP, and ER from multiple years of observation.

R2: The paper brings forward some very important numbers in terms of carbon budgets for this dry temperate eucalypt forest that were missing from global flux measurements, and reveals among the largest CO2 sequestration for any ecosystem studied thus far. Such numbers, as well as how the fluxes vary over time (diurnal, seasonal, inter-annual), are highly needed to better understand how different ecosystems vary in their growth dynamics and ecophysiology.

Response: Both reviewers highlight the importance of the study and agree that it is addressing an important knowledge and data gap that is relevant on a global scale to improve our process understanding.

- **Measurement or tree height (comments R1.1a, R2.1):**

R1.1a: Measurement of turbulent fluxes at only 3 meters above a 30 meter canopy puts these observations barely into the roughness sublayer where the near-field effects of scalar sources and sinks can have a major influence. In other words, it is unclear that these measurements can provide a reliable sample of well-mixed turbulent fluxes.

R2.1: On line 105, the forest height is said to be 21-27 m, while in Table 1 it is 25-27 m. Which one is it? How uniform is the distribution of tree heights in the forest? The reason why this matters is that the eddy covariance (EC) system is at a height of 30 m, thus only 3 m above the tallest trees. How turbulent are the winds at 30 m? Did you assess whether the EC system is high enough to provide reliable fluxes or if it is located too close to the sources/sinks of fluxes and thus not well-mixed? For e.g., the wet eucalypt forest in the paper from van Gorsel et al. 2013 has a tree height of 40 m and the EC system is at a height of 70 m. Why are the measurements made so close to the canopy at this site? Please show that the EC measurements are reliable at this site.

Response: Both reviewers have expressed concern that the eddy covariance (EC) measurements are not reliable given the stated range of tree heights and the height of the EC measurements. We acknowledge the concern of the reviewers and have addressed these by 1) an updated canopy height in the revised manuscript with a more accurate value that has been measured using ground-based Lidar, 2) clarifying the existing description of the EC measurements, and 3) adding text that directly addresses the issues surrounding EC measurements within the roughness sub-layer (RSL).

In addressing this issue, we also make the following 3 points:

1) The stated tree height of the forest in both the text and in Table 1 was based on an initial approximation and has since been replaced with more accurately measured figures. We have corrected the text and Table 1 accordingly in the revised manuscript. The actual canopy height is 22 m and based on terrestrial Lidar measurements as presented in a recent publication about the site (Griebel et al., 2015). The revised canopy height increases the height of the EC instruments above the canopy to 8 m (emergent trees will reduce this but their contribution to the total LAI is estimated to be less than 5%). This is still within the RSL using the definition of RSL depth as between 2 and 5 times the canopy height (Katul et al., 1999). We discuss the implications of this on the measurements in the next paragraph.

2) Katul et al. (1999) give a detailed report of an experiment performed over the Duke Forest, Durham, North Carolina, USA. The objective of the experiment was to explore the effect of taking EC measurements within the RSL by comparing data from 6 EC systems mounted at 15.5 m over a 14 m canopy (managed loblolly pine). This is 1.5 m above the canopy compared to the 8 m height difference at our study site (based on a more accurate measurement of canopy height, see above). Given the greater height difference between the EC instruments and the canopy at our study site, we can reasonably expect the results in Katul et al. (1999) to represent a worst case for our study site. In the context of the measurements taken at our study site, the important conclusion Katul et al. (1999) state is that the observed site-to-site differences in CO_2 (and H_2O) fluxes of 20% may be a result of taking measurements within the RSL and may not be attributable to site-to-site differences in phenology or function. Translating this result to a single site implies that we may expect ±10% uncertainty (based on the 20% range quoted in Katul et al. 1999) about a mean value (half the observed range from highest to lowest) due to uncertainty associated with the measurements being taken within the RSL. Again, we stress that the EC instruments at our study site are more than 5 times higher above the canopy than those used in Katul et al. (1999). These results suggest that errors due to the location of EC instruments in the RSL are of the order of 10% at our study site.
3) Barr et al. (2013) used data from 38 sites from Canada and the USA in their investigation of the use of the change point detection (CPD) method for determining the u* threshold. 10 of these sites have canopy heights of 20 m or greater. Of these 10, 7 have their EC instruments located 10 m (half canopy height) or less above the canopy. Thus, location of EC instruments in the RSL over tall canopies is not uncommon. We do not suggest by this that it is not an issue, the effect of taking EC measurements in the RSL certainly needs more study, but that it is an issue that is very common at many sites.

- **The use of 30 min averaged data (comments R1.1h, R2.5):**

R1.1h: Data post-processing is inadequate. It is customary and important to perform post processing on the high frequency (here 10Hz) data rather than to rely on automated online software to calculate half-hour averaged fluxes. Unfortunately this was not done for the present work. There does not appear to be any check for non-stationarity and detrending over the 30-minute interval. There does not appear to be any despiking of raw 1/10th of a second data, certainly not the recommended method of despiking based on a moving assessment of instantaneous data relative to the standard deviation in a time-local window of data. There

cannot possibly be a co-spectral correction for issues of instrument separation or frequency attenuation of measurements, for specific conditions of stability, wind direction, turbulence intensity. There was only a simple 2D coordinate rotation rather than a full planar coordinate rotation such as with the Wilczak method. All of these elements are missing and are standard requirements for the production of reliable eddy covariance flux estimates.

R2.5: On lines 123-125, the writing suggests that only the 30 min fluxes were stored, is that correct? If not please add more details. If it is correct, this seems like it would bias your fluxes because you cannot quality filter the raw data before flux calculations so any spikes in the raw fluxes is reflected in the 30 min fluxes. Although this cannot be changed now, it would be needed in the future to store the raw fluxes as well.

Response: Both reviewers have expressed concerns about the method used to process data presented in this manuscript. The EC data was processed using "OzFluxQC" and gap-filled using DINGO. "OzFluxQC" is described in detail by Isaac et al. (2016), an already accepted paper in this Special Issue. DINGO is described in detail by Beringer et al. (2016b) and also accepted with minor revisions in this Special Issue. However, the reviewers are correct to question the data processing where there is uncertainty over the method used.

Our response to these concerns from the reviewers has 2 parts. First, we address some of the related points raised by the reviewers. Second, we describe the extra work done to address the reviewers' primary concern (fluxes not calculated from the 10 Hz data in post-processing).

To the related points raised by the reviewers:

1) R1: *"... to rely on automated online software to calculate half-hour averaged fluxes."*: The fluxes presented in the manuscript were not calculated by automated online software but are calculated by "OzFluxQC" during post-processing from the 30 minute average covariances output by the data logger after applying quality control checks and coordinate rotation to the covariances. This is mathematically equivalent to processing the 10 Hz data using EddyPro (or similar) with the exception of de-spiking and rejection of non-stationary time periods which we address below.
2) R1: *"There does not appear to be any despiking ..."*: The reviewer is correct that calculating the fluxes from the 30 minute covariances does not allow despiking in the traditional sense employed in EddyPro and other similar packages. However, the data logging methods used by OzFlux allow the sonic anemometer and IRGA diagnostic

information to be recorded at the sampling frequency (10 Hz). The data logger program uses this diagnostic information to accept or reject each individual 10 Hz sample prior to the calculation of the covariances at the end of each 30 minute averaging period. To the extent that spikes in the sonic or IRGA outputs are detected by the instruments and flagged by the instrument's diagnostic information, this process will result in the removal of data spikes from the covariance calculation.

3) R1: *"There does not appear to be any check for non-stationarity and detrending ..."*: The data processing adopted by OzFlux does not apply any detrending. This is the approach recommended in Kaimal and Finnigan (1994). The reviewer is correct that the non-stationarity checks used by EddyPro and similar programs cannot be done on the 30 minute data. However, we believe that the quality control checks described in Isaac et al. (2016) act to reduce the effect of this on the final data set. In particular, we have found during processing at another site (Cumberland Plains, Alexis Renchon, personal communication) that non-stationary conditions are often associated with low u* conditions and are rejected when a u* filter is applied to the data. However, we have addressed this point by calculating fluxes directly from the 10 Hz data using EddyPro with the appropriate stationarity checks applied.
4) R1: *"There cannot possibly be a co-spectral correction ..."*: Correction of half-hourly fluxes for path averaging, instrument separation and frequency response is done in OzFluxQC using the method of Massman (2000). However, we agree with the reviewer that this method lacks some of the features of other correction algorithms. We have addressed this point by calculating fluxes directly from the 10 Hz data using EddyPro with the appropriate frequency corrections applied.
5) R1: *"There was only a simple 2D coordinate rotation ..."*: We have addressed this point by calculating fluxes directly from the 10 Hz data using EddyPro with the planar fit option chosen.
6) R2: We believe that in addressing the concerns of reviewer 1 as outlined above we have also addressed the concerns about data processing raised by reviewer 2.

We have processed the available 10 Hz data from our study site using EddyPro and included this data in the revised manuscript. As part of this process, we have compared results obtained from EddyPro using the 2D rotation method (used when "OzFluxQC" calculates the fluxes from the covariances) and using the planar fit method to establish if the different methods yield significantly different results at this site.

We have done five different runs of QA/QC on 10 Hz data with EddyPro v6.3 (see Table R1 below) with Run 1 as the "OzFluxQC" comparison run, i.e. with settings according to "OzFluxQC", Run 2 as Run 1 including low-pass frequency correction according to Massman (2001; 2000), Run 3 as Run 2 including high-pass frequency correction according to Moncrieff et al. (2005) and Run 4 as Run 3 with default statistical tests. Same settings for EddyPro as for OzFluxQC resulted in excellent agreement (see Run 1 Table R2). EddyPro data were about 4% larger than OzFluxQC data due to the frequency correction (Run 2 and Run 3, Table 2). Introducing default statistical analysis versus check for absolute limits only did not change results (Run 4, Table R2) and thus, did not cause differences. For Run 5 we used OzFluxQC data including frequency correction to compare with EddyPro data that had the same settings as in Run 4 but applying the planar fit method according to Wilczak et al. (2001) instead of the 2D coordinate rotation.

Table R1: overview of QA/QC settings for various EddyPro runs on 10 Hz data

		Run 1	Run 2	Run 3	Run 4	Run 5
WPL correction		x	x	x	x	x
coordinate rotation	2D	x	x	x	x	
	planar					x
frequency correction	low-pass		x	x	x	x
	high-pass			x	x	x
statistical analysis	absolute limits	x	x	x		
	default*				x	x

*(spike, amplitude, drop-outs, absolute limits, skewness/kurtosis)

In agreement with previous experience and work presented in Isaac et al (2016) differences between the EddyPro results and OzFlux QC were small, EddyPro data were about 7% greater than OzFluxQC data and much less compared to uncertainties due to gap filling and partitioning (Table R2). Around 4% of these 7% difference were attributed to the frequency correction which has been implemented in the "OzFluxQC" procedure now. The remaining 3% difference were attributed to the planar fit correction which is not implemented in the "OzFluxQC" procedure, hence data derived from "OzFluxQC" has been accounted for this difference and resulted in an very good agreement between both data sets (slope = 1.01, intercept = 0.06, R^2 = 0.90).

Table R2: comparison of quality controlled data from various runs with EddyPro and "OzFluxQC"

	slope	intercept	R^2
Run 1	1.00	-0.01	0.95
Run 2	0.96	-0.02	0.95
Run 3	0.96	-0.02	0.95
Run 4	0.96	-0.01	0.95
Run 5	0.97	-0.01	0.95

We have also modified section 2.3. in the revised manuscript to clarify the data processing methods and included, where appropriate, references to Isaac et al. (2016) and Beringer et al. (2016b) from this Special Issue.

- **Possibility of advection (comments R1.1b, R2.2):**

R1.1b: Measurement atop a ridge with sloping terrain in prevailing wind directions could significantly bias flux estimates and one cannot help but wonder what role advection fluxes may play in the very strong carbon sink that is reported for the site.

R2.2: The flux tower is located on a ridge surrounded by some gently sloping gullies. Does the ridge affect the wind directions? Did you investigate if it leads to some advection or decoupling within the forest canopy? This is especially important for your dry eucalypt forest, as the numbers you report are extremely large for NEE while ER is low. This suggests a potential for advection within the canopy, which needs to be addressed for these numbers to be considered reliable. It is puzzling that a forest with such a low LAI sequesters so much carbon. Please consider the possible influence of advection on your fluxes. Also, please put more emphasis on the reasons why ER is so low because for the reader at the moment this is not well explained and raise scepticism on advection. How much organic matter/litter is on the soil surface? Do the eucalypt leaves ever fall? Do the trees themselves respire less than other type of trees?

Response: Both reviewers highlighted and made important comments regarding the issue of advection. The reviewers are correct that we cannot exclude the influence of advection fluxes in our forest study site and we have acknowledged this fact in the discussion and emphasise the possibility/probability of advection in conjunction with annual estimates in a revised version of the manuscript.

We have observed low night time fluxes of NEE, hence ER, which indicated a decoupling within the forest canopy and thus advection fluxes during night time. We tried to account for

this by including the storage term (from single point calculations in 2010 and 2011 and from profile measurements in 2012), by using a yearly u* thresholds determined via change point detection (Barr et al., 2013) and by using only flux data from the first 3 hours after sunset (Beringer et al., 2016b; van Gorsel et al., 2007) to estimate/ calculate ER. As outlined in the revised manuscript and further below, this data selection yielded the highest estimates of ER. Leaf litter fall generally is highest during summer months concurrent to shoot growth and in agreement with highest GPP and ER estimates within a year.

We like to emphasize that we present as a first results of ecosystem carbon fluxes and their seasonality in a dry temperate eucalypt forest. The seasonal behaviour is unlikely to change or be affected by an overestimation of NEE which rather is a systematic error than a random error. However, we have highlighted the need to further investigate/ account for advection in the future in the discussion. Moreover, results from a recent study to validate more recent annual NEE estimates with a biomass inventory (biomass increment and carbon content) indicated that the NEE estimates from the EC measurements were systematically 30% greater than the NPP of the tree biomass from inventory methods (Bennett, 2016). It is a reasonable assumption that tree NPP contributes the bulk of NEE and as such the inventory data would be a confirmation that the flux tower is underestimating ER, resulting in a greater NEE. However, the underestimation was systematic and very similar in each of the measurement years. Nonetheless, even the inventory approach confirmed the high uptake rate of this dry temperate eucalypt forest when compared to other ecosystems. We have included this in the discussion.

- **Storage term/ profile data (comments R1.1c, R2.5):**

R1.1c: It is well known that above canopy turbulent exchange cannot be assumed to represent net ecosystem exchange over tall canopies because of the build-up of CO_2 during conditions of low turbulence, the subsequent ventilation of CO_2 when more turbulent conditions resume, as well as depletion of within-canopy CO_2 by uptake in the canopy but that may not be detected as prompt above-canopy flux. Therefore, estimates of NEE over tall canopies requires measurements of the vertical profile of CO_2 to estimate the storage flux in addition to turbulent above canopy flux. Unfortunately, these measurements do not appear to have been included in the present deployment. There is no mention of data post-processing techniques that are used to mitigate this problem and the effects can be quite significant. It is a problem not only for NEE but also the gross fluxes inferred from NEE separation. This, too,

calls into question the validity of the data record and the findings regarding large and persistent carbon dioxide uptake at the site.

R2.5: In addition, did you estimate the CO_2 storage in the canopy?

Response: The reviewers made valuable suggestions regarding profile measurements and we agree with the reviewers and have included our available profile measurements in the revised manuscript. A profile system similar to that described in McHugh et al. (2016) in the same Special Issue was installed at our study site in early February 2012. Hence, within the scope of this manuscript, we have 8 months (March to October 2012) worth of profile data as we experienced technical problems with the IRGA at the start of measurements in February and again in November 2012 which lasted until the end of 2012. We have analysed/calculated the storage term following McHugh et al. (2016) and Finnigan (2006). However, the contribution of storage is nearly balanced out over the diurnal course of the day (McHugh et al., 2016) (Fig. R2) and therefore the addition of the storage term only marginally changed the magnitude of NEE in 2012 with differences ranging from 3 to -4% (mean of 2%) depending which partitioning method has been applied (Fig. R1, Fig. R2, Fig. S1 in supplementary materials). Nonetheless, we have included the profile data, i.e. change in storage term, for available months in 2012 and have re-done the analysis in the revised manuscript. Furthermore, we have included single point storage terms, calculated within the "OzFlux QC" data processing (Isaac et al., 2016), for data when profile storage measurements were not available. Again, similar to the addition of the profile storage term in 2012, addition of the single point storage term marginally changed the magnitude of NEE fluxes in 2010 and 2011 (Fig. R2 below, Fig. S1 in supplementary materials).

Apart from the small effect the measured profile storage term addition had on overall NEE fluxes, profile measurements clearly improved storage term estimation compared to single point storage term calculations. We have tried to get a better estimate of the storage term for time periods when no profile system was in place; however we have been unsuccessful to establish a reasonable relationship between single point storage term calculation and measured profile storage term.

Following paragraph has been added to section 2.2: *"In February 2012 a custom-built profile system including an IRGA (Li-840, LI-COR, Lincoln, USA) and with six vertical layers (1, 2, 4, 8, 15 and 30 m) was installed to measure CO_2 concentrations of each layer in 2 min intervals. A detailed description of the profile system can be found in (McHugh et al., 2016). Due to technical problems with the IRGA profile data were available from March to October*

2012. Changes in the storage term between forest floor and EC-measurement point were calculated following McHugh et al. (2016) and Finnigan (2006). For periods of time when profile storage measurements were not available, ecosystem CO2 fluxes were accounted for storage terms derived from single point calculations within the "OzFlux QC" data processing (Isaac et al., 2016)."

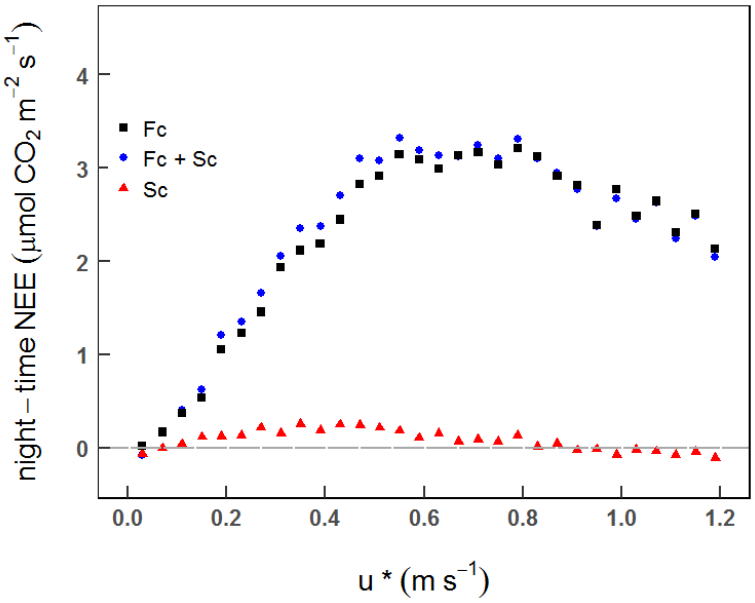

Figure R1: Dependence of night time NEE flux (Fc, black squares) on friction velocity (u*) and changes in night time NEE flux when storage term (Sc, from single point calculation and profile measurements, red triangles) is included (Fc+Sc, blue circles)

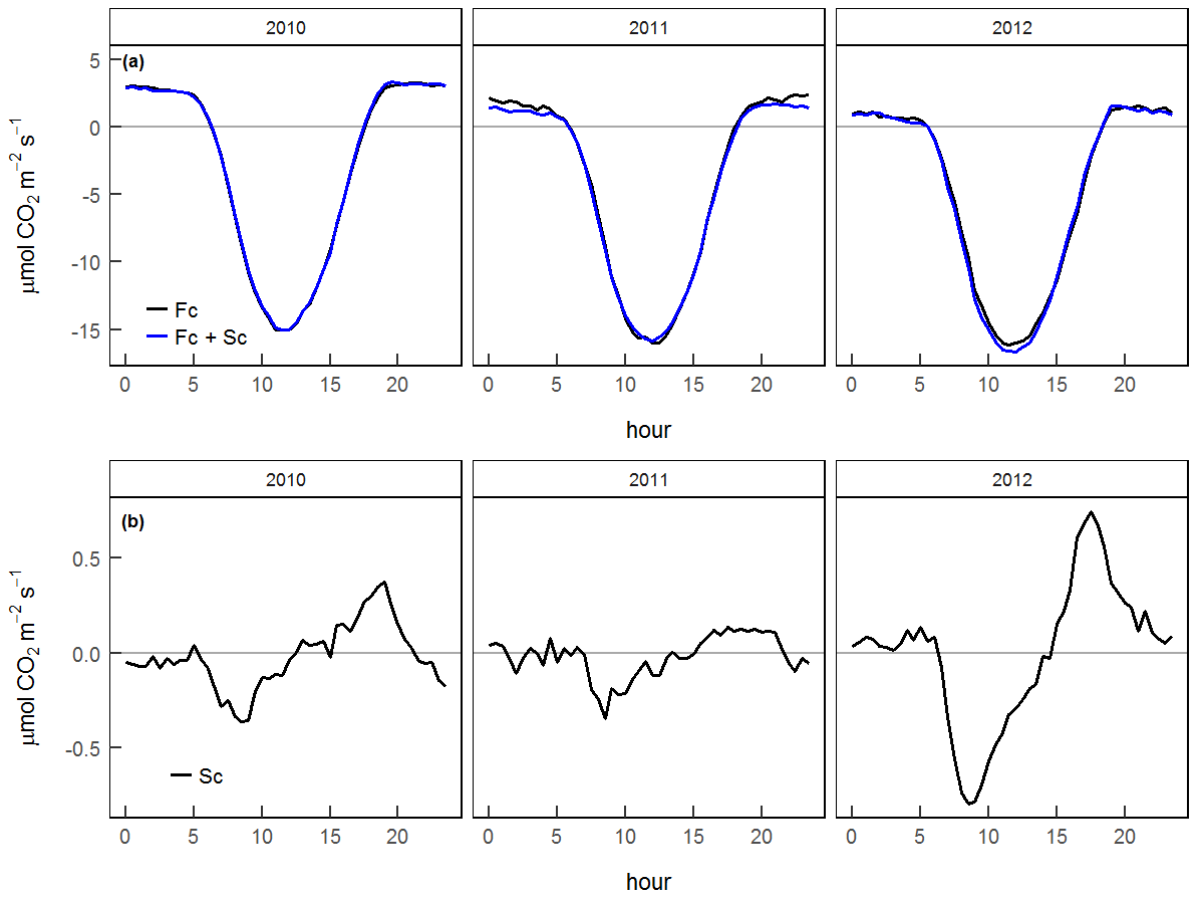

Figure R2: diurnal annual means of (a) NEE and (b) the storage term (Sc); upper panels: NEE excluding Sc (Fc, black line), NEE including Sc (Fc+Sc, blue line)

- **Analysis of environmental drivers (R1.2a-e, R2.6)**

R1.2: The Study's Methods of Data Analysis are Significantly Flawed.

R1.2a: Did analysis of the drivers of temporal variability rely on gap-filled data or only on trusted direct observations? If gap-filled data were used then all of these analyses are circular.

R1.2b: It is logically unsound to ask if ER relates to temperature when ER is determined based on a relationship between Fc and temperature. It is circular to use temperature to model ER over time and then to assess the importance of temperature for determining temporal variability in ER.

R1.2c: The analysis that alleges to diagnose the relative importance of different environmental variables in driving seasonal variability is significantly flawed. The authors examine which environmental variable best explains variability in 30-minute 'daytime' data for each month of the year and for each flux separately. This analyzes sources of diel variation, or hourly variation, not seasonal variation. Day-time appears to be defined here as half-hours when shortwave radiation was greater than 10 W m-2. Not surprisingly, sunlight

turns out to be an important variable for GPP for all months of the year. This does NOT indicate that solar radiation is the dominant factor governing seasonal variability in carbon fluxes at the site. To assess that you would need to do something like use daily data, or mean daylight values for each day, and then study the full year to explore relationships to environmental variables. You would need to consider LAI dynamics as well. Of course there will likely be collinearity in these daily values, but it at least has the right time scale to answer your question of attributing seasonal variability to drivers. It is also not surprising the temperature turns out to be important for ER variability at the within-month time scale because temperature is one of the predictor variables used to model ER. Again, this is circular.

R1.2d: The analysis that intends to identify the relative importance of different drivers of interannual variability is also severely flawed. What the authors examine, really, is if the relative importance of drivers that determine 30-minute fluxes over the whole year differs between years. Not only does this alias diel variation into the analysis as noted above (2c) but it also conflates all seasonal variability as well. What should be done instead would be to examine daily (or monthly) anomalies relative to the acrossyear mean for that day (or mean monthly values). Or, you could study if the functional response of fluxes to PAR, air temperature, VPD, or soil moisture differed across years, stratifying to control for the effects of the other variables. Simultaneously you would want to study if the environmental conditions varied meaningfully across years, partly examined earlier in the paper but not linked to implications for fluxes. What might be best would be a real attribution exercise in which you use the 2010 functional response to environmental conditions to estimate what the 2011 and 2012 fluxes would have been with that functional response surface and then compare that synthetic result to the real measured case. You could do the same for the other years. Similarly, you could use the environmental conditions of 2010 combined with the functional response of 2011 (and then 2012) to estimate the effects of any drift in the functional responses alone by, again, comparing to the real case. This would allow you to truly assess the drivers of IAV in fluxes as being due to variation in environmental conditions, variation in flux responses to environmental conditions, or both. Unfortunately what has been done is simply not testing anything meaningful about IAV in fluxes.

R1.2e: For the above reasons, much of the discussion section on environmental drivers of CO2 fluxes includes misinterpretations.

R2.6: The authors use the random forest algorithm to determine the environmental drivers for NEE, GPP and ER. This analysis shows some serious circular argumentation. GPP is

partitioned using solar radiation, thus it is beyond expected that there will be a strong relationship there. Same for ER and air temperature. Instead, I think what would help is to look at functional relationships between GPP and solar radiation, and between ER and air/soil temperature. This would provide the reader with a better understanding of how the dry eucalypt forest behaves compare to other ecosystems, as the numbers from photosynthetic capacities and such could be directly compared to those of other ecosystems. This would also add to the discussion when compared with other ecosystems to help us understand what is so different about this forest so that it sequesters so much CO2. At the moment the paper does not deliver clearly what makes this ecosystem so different. Improving this analysis as well as providing functional relationships figures would help to address objective 2.

Response:

1) Much of the concerns raised by reviewer 1 referred to the use of half-hourly data to assess seasonal and inter-annual variability in environmental drivers. We would like to clarify that we used daily averages of gap-filled ecosystem carbon fluxes binned per month or year for the random forest approach to assess seasonal and inter-annual variability in environmental drivers. However, we acknowledge that using daily averages was not clearly enough stated throughout the manuscript and in figure captions and have done so in the revised version of the manuscript.
2) We agree that using gap-filled data for the random forest approach is circular and thus potentially erroneous. We initially thought using valid observations with gaps could introduce a greater bias to such an analysis as gaps might occur predominantly for a particular time of day or year. However, we re-analyse the data with valid observations only in a revised version of the manuscript. Therefore we will use mean midday (11:00-13:00) values of measured NEE representing carbon uptake and the mean of the first evening hours of u* filtered night time NEE representing respiration. Consequently, we have amended the discussion according to the results of this analysis, although the outcome has not changed considerably.
3) We agree with reviewers that the current presentation of linear relationships between non gap-filled half-hourly day time or night time data and environmental drivers is inconclusive and have removed this section.

Other concerns and issues:

Anonymous Referee #1

Received and published: 18 May 2016

Main Concerns:

R1.1d: It would seem that CO2 emissions from the diesel generator could appear as an erroneous CO2 source from the ecosystem. The text simply states that the generator is 'remote' but how remote can it be given concerns of power loss over long cables. How this concern is mitigated should be clarified.

Response: The remote area power system with the diesel generator is primarily there to power an automated soil GHG chamber system and directly located next to the tower (< 10 m) within the fenced component. Moreover, the generator is set to run only at night time for a couple of hours to recharge the battery bank. Given that we have observed only small night time fluxes we are confident that CO_2 emissions from the generator are not influencing our EC-tower measurements.

R1.1e: The explanation of footprint modeling and associated screening as well as screening based on wind direction so that "fluxes were constrained to the same forest type and dominant tree species" is inadequately described. Citing the Griebel et al. 2016 study is incomplete. The method should be explained more fully here.

Response: The footprint modelling was done by Griebel et al. (2016) in a separate study. For details on the method and further explanation the reader is directed to the Griebel et al. (2016) paper and we do not think it appropriate to be reproduced in this manuscript. However, we rephrased the text in section 2.2 in the revised manuscript to*:"A footprint analysis by Griebel et al. (2016) using the parameterisation of flux footprint predictions of Kljun et al. (2004) showed that the distribution of fluxes were relatively homogeneous and that the whole footprint consisted of the same forest type and dominant tree species, and roughly uniform basal area. For further details see Griebel et al. (2016)."*

R1.1f: Measurement of soil moisture at 5 cm depth is unlikely to represent the soil water status relevant to 25 m tall trees. Measurement at a single point is also unlikely to be adequately representative given the typically large spatial variability of soil water content.

Response: We would like to clarify that the correct soil depth for soil moisture measurements was actually 10 cm soil depth and that soil moisture has been measured at and averaged over two micro-sites from 2011 onwards. We have amended the text in the instrumentation section

(section 2.2) accordingly. Soil moisture was also measured at 50 cm soil depth at one of the micro-sites. Although we tested the soil moisture variable from 50cm soil depth in our data analysis, there was no difference or improvement compared to using the soil moisture variable at 10cm.

R1.1g: Measurement of rainfall with a rain gage placed 1 m above the ground where trees are 25 m tall is sure to undersample the real rainfall rate above the canopy.

Response: At the time of installation of the rainfall gauge the surrounding area was relatively clear, i.e. no obstruction from trees, but we acknowledge that rainfall might be under sampled as rain falls seldom down straight. However, we currently have not used rainfall data from our study site for anything other than presenting annual rainfall amounts which are, as well as monthly rainfall data, in good agreement with data from the nearest Bureau of Meteorology rainfall station in Daylesford (11km N).

R1.1i: NEE separation was done four ways but then the results of only a single method were selected without adequate justification. It would seem more appropriate to present results from all four methods as a source of methodological uncertainty.

Response: We agree with the reviewer and have provided a table with annual sums of ecosystem carbon fluxes derived from different partitioning methods for comparison as supplementary materials (Table S1), time series figures comparing the relative contribution of soil respiration data to the different outputs of ER (Fig. S1 to S3) as well as the variation around the different partitioning methods (Fig. S4 and Table S2).

R1.1j: A description of the method of NEE separation is needed. For example, what was the temporal window over which data were used to assess the relationship between ER (from selected Fc measurements) and environmental variables (principally temperature but also some others)?

Response: We have included a better description of the chosen partitioning method in section 2.3.3 and will also refer to the two methods papers in the same Special Issue: Beringer et al. (2016b) for DINGO and Isaac et al. (2016) for "OzFluxQC". In both papers detailed descriptions of various options of NEE partitioning methods can be found.

R1.3a: L 296: Comparison to these other forest types is valuable but the narrative is overly confident here. You cannot state that leaf longevity explains the differences in GPP rates

between these various forests. The findings presented in this paper do not substantiate that supposition or conjecture.

Response: We have removed this statement.

R1.3b: L304: Delayed spring increase in ER relative to that for GPP may be partly due to soil respiration but it could still be partly linked to temperature control on plant respiration, no? Soil respiration is not shown in the present study and so this remains supposition.

Response: We have modified the sentence and added more information on the observed soil respiration fluxes from separate but concurrent studies (Hinko-Najera, 2016, unpublished; 2015) to justify the likely explanation for the delayed increase in ER. Moreover a time series of soil respiration is now shown in Figures S1 to S3 in supplementary material. We think it is unlikely that temperature control on plant respiration might explain the delayed increase of ER in spring. Hinko-Najera (2016, unpublished) has estimated the relative contribution of soil respiration to ecosystem respiration estimates which were low during spring time indicating an already higher contribution of aboveground respiration to ER. In addition, partitioning of soil respiration into its component fluxes heterotrophic (microbial) and belowground autotrophic (plant) respiration showed that springtime soil respiration was dominated by belowground autotrophic respiration whereas heterotrophic respiration peaked and dominated soil respiration during (late) summer months (Hinko-Najera et al., 2015)

R1.3c: L335: This site's very large carbon sink (NEE of around -1,000 g C m-2 y-1) is surprising and noteworthy. Could it be related to secondary recovery and the site's 25 year old stand age? What is the disturbance legacy for this site?

Response: The statement that the forest is a secondary regrowth forest refers to the heavy logging during the gold rush around 1850. General forest history includes harvesting and patchy occurrences of bushfires. Selective harvesting occurred until early 1970 when replaced by a more intensive shelterwood (two-stage clear-felling) system (Poynter, 2005). Since 2003 the Wombat State Forest has been under community forest management (Poynter, 2005) and harvesting has been strongly reduced. Forest management practices also include periodic low-intensity prescribed fires, and firewood collection in designated areas. Specific information on disturbances, i.e. harvests, wild fires or prescribed fires, for the study site are very limited. The study area was selectively harvested last in the early 1970s with the last bushfire on the outskirts of the study site recorded in 1982 and no recorded history of prescribed fires (DSE, 2012). We would like to clarify that the correct age of the forest within

the study area could not clearly be determined and is rather of mixed age. The statement of ~25 years age rather referred to the last recorded disturbances. We have corrected this information and added more information of the site history in section 2.1 in the revised manuscript.

R1.3d: L383: It is not much of a finding to discover that seasonality is different in a dry, warm (winter free) temperate eucalypt site compared to temperate coniferous and deciduous forest sites with a strong seasonality in climate with sustained winter freezing. Furthermore, this study did not really show the difference in seasonality explicitly. Also, it is stated that this alleged difference in seasonality is due to the opportunistic response of eucalypt forests. This is not supported by any analysis and it is not even clear what is meant by "opportunistic response". A simpler explanation is that they in a different climate setting.

Response: We partly agree with the reviewer and have clarified the statement in the conclusion. However, we believe that it is still important to point out that temperate forests in the southern hemisphere are very different from those in the northern hemisphere. This is partly due to the evergreen nature of the trees and therefore their ability to respond quickly to favourable conditions by increasing photosynthesis and growth. And it is partly due to the mild climatic conditions, i.e. the absence of a strong winter and (in our case) also of drought conditions during the summer months. Hence, unlike their northern hemisphere counterparts the southern temperate forests are able to sustain a year-long carbon uptake and present a near-continuous carbon sink. The forest still consistently showed a distinct seasonality that was characterised by greater NEE in summer and lower NEE in winter. It will be important to differentiate this growth response from other, well characterised ecosystems and that is why comparisons with northern hemisphere ecosystems are made.

The "opportunistic" nature of eucalypts refers to their broadleaf evergreen nature, which has been described in a number of papers before. More specifically it refers to their ability to respond to ideal growth conditions quickly, which is one of the main reasons for the absence of distinct growth rings in most eucalypts. We have already outlined the "opportunistic" behaviour of eucalypts in the introduction: *"The behaviour of temperate deciduous or coniferous forests in the Northern Hemisphere cannot be presumed to be an analogue for temperate eucalypt forests. Apart from being broadleaf evergreen, with mostly sclerophyllous leaves, a key trait of eucalypt forests in Australia is the ability to rapidly and opportunistically respond to changing, either favourable or stressful, environmental*

conditions (Jacobs, 1955; Keith, 1997)." We have clarified this in more detail in the discussion in the revised manuscript and added more references.

R1.3e: L 385: This study did demonstrate "that seasonal and inter-annual variability in carbon uptake were not limited by temperature but predominantly driven by radiation". The study also did not demonstrate that "carbon loss from the forest was dominated and overall ecosystem carbon exchange dynamics were not water limited due to the high rainfall" and this sentence has a hanging statement (its first part about carbon loss).
Response: We have rephrased and finished the highlighted text sections accordingly.

R1.3f: L 387: Nothing presented in the paper quantitatively supports the statement that "temperate eucalypt forests represent a unique forest type and should be considered separately in future classifications of ecoystems...". To demonstrate this you would need to show that these forests have a different functional response to environmental conditions than other forest types. This has not been shown and would require a synthesis analysis, not simply data from a single site. It is entirely possible that if you were to control for site and time specific conditions of LAI, PAR, VPD, Tair, and soil moisture you might find that these forests behave similarly to others. This has not been tested in the present study.
Response: We agree with the reviewer and have deleted this section.

R1.3g: L 389: Could drop the last sentence. It doesn't seem to add much of substance and I'd argue it does not really need to be said. It sounds a bit like a proposal statement or a sales pitch.
Response: We have deleted this sentence.

R1.4a: Figure 2: it would be better to use a line chart for panel a rather than a bar chart.
Response: We are unclear what the reviewer is referring to. Fig 2 is a line chart for all continuous measurements and has a bar chart for the 7-day sums of precipitation data.

R1.4b: Figure 2: it would be helpful to show midday VPD either in addition to or instead of mean daily VPD.
Response: We have updated Figure 2 to show mean midday VPD as 7-day running means in the revised manuscript. Although the magnitude in VPD increased (e.g. maximum midday VPD of 3.41 kPa versus maximum daily VPD of 2.87 kPa; and maximum 7-day run mean of

midday VPD is 1.96 kPa versus maximum 7-day run mean of daily VPD of 1.52 kPa,), there is no change in the seasonal variation of VPD.

Anonymous Referee #2

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Main concerns:

R2.3: The u* threshold is unusually high at 0.56 to 0.69 m s-1. This is above most u*-thresholds reported in the literature (see for e.g. Papale et al. 2006 Biogeoscience Fig.1) Why is it so high? Greater details need to be given on how this threshold was determined. Is there really an inflection point around those values? In my experience, when the common methods determine such a high threshold, it is when they do not apply i.e. there is no inflection point because it is a site with advection or with some other abnormality making the u*-threshold determination not applicable.

Response: The u* threshold of the revised data set range now from 0.52 to 0.66 m.s^{-1}. The u* thresholds for our site are high, yes, but not unreasonably high when compared to other u* thresholds in the literature, e.g. Fig. 10 in Barr et al. (2013). We refer to Figure R1 in this response to reviewers showing the relationship between u* and night time NEE clearly showing the inflection point, i.e. u* threshold. We have extended our current reference in section 2.3.1. on details on how this threshold was determined, i.e. Barr et al. (2013), to both data processing papers for OzFlux in this Special Issue (Beringer et al., 2016b; Isaac et al., 2016) that also briefly outline the adopted change point detection method by Barr et al. (2013).

R2.4: As a result of the very high u*-threshold, only a low number of actually measured data is kept for the three years (37%, 47%, 47%). This means that the outputted annual budgets depend mostly on the gap filling and thus, represent more modelled numbers rather than measurements. Sometimes, depending on the data quality, it can be better to use less ideal, measured data than modelled data. How different would the cumulative numbers be if for e.g. 60-70% of the measured data is kept?

Response: 1) We would like to clarify that the low percentage of available measured data is not only the result from the application of a u* threshold but also from the QA/QC process in which for example bad data due to rainfall has been discarded. On average 31% of data was rejected due to QA/QC whereas u* filtering removed on average 14% of data over the three

year study period. Table R3 below provides an overview of yearly and total data availability in percentages due missing measurements, after QA/QC process and u* filter application.

2) To increase the percentage of measured data would require to lower the u* threshold which would result in a bias of low NEE values. However, we also have added an uncertainty analysis as described in McHugh et al. (2016) in this Special Issue which includes an uncertainty estimation of combined random and model error (Hollinger and Richardson, 2005; Keith et al., 2009) (Table R4 below) and the effect of uncertainties in u* thresholds on annual NEE estimates by using the lower (5%) and upper (95%) confidence interval of the probability distribution of the mean u* threshold (Barr et al., 2013) (Table R5 below).

The uncertainty introduced due to random (measurement) and model error was small for 2010 and 2012 (4% and 6% of annual NEE estimate) and slightly higher for 2011 (10% of annual NEE estimate) (Table R4). Estimation of the uncertainties in u* thresholds on annual NEE were small for the lower u* uncertainty bound (5% CI) ranging from -19 g C m^{-2} yr^{-1} in 2012 to 26 g C m^{-2} yr^{-1} in 2011 (1-2% of annual NEE estimate). We could not estimate an upper u* uncertainty bound (95% CI) as data availability was insufficient (Table R5).

3) We also would like to point out it is not unusual to have a high fraction of night time data removed through u* filtering and refer to Barr et al. (2013) who tested that even 90% of fractional night time data exclusion had a smaller impact on gap-filled NEE than the alternate option of underestimating the u* threshold.

Table R3: Data availability (%) per year and in total from measurement through data processing

	2010	**2011**	**2012**	**Total**
prior to QC	78	98	94	90
after QC (with storage)	48	64	66	59
u* filter (NT)	37	48	50	45

Table R4: Random, model and combined error uncertainties in g C m^{-2}yr-1 for NEE excluding and including storage term (Sc) per calendar year

		Random error			**Model error**			**All errors combined**
	Year	**DT**	**NT**	**Total**	**DT**	**NT**	**Total**	
NEE	2010	7.3	5.8	9.3	20.2	20	28.8	29.8
	2011	8.1	7.6	11.4	35.2	103.1	109.5	110.6
	2012	8.6	7.9	11.8	30.8	63.4	70.9	71.7
NEE+Sc	2010	7.8	6.9	10.3	24.5	31.9	39.7	41.4
	2011	8.2	7.7	11.3	41.5	113	120.9	121.9
	2012	8.9	8.5	12.3	33.7	72.1	79.3	80.6

Table R5: Effect of uncertainties in u* thresholds (u^*_{th}) on annual NEE estimates by using the lower (5%) and upper (95%) confidence interval of the probability distribution of the mean u* threshold (Barr et al., 2013)

Year		u*	Data excl. (%)	Data excl. u* filter (%)	NEE (gC m^{-2} yr^{-1})
2010	5% CI of u^*_{th}	0.25	56	4	-1099
	u^*_{th}	0.53	63	11	-1080
	95% CI of u^*_{th}	0.81	69	17	-
2011	5% CI of u^*_{th}	0.37	44	8	-1275
	u^*_{th}	0.67	52	16	-1248
	95% CI of u^*_{th}	0.96	60	24	-
2012	5% CI of u^*_{th}	0.32	39	5	-1463
	u^*_{th}	0.66	50	16	-1482
	95% CI of u^*_{th}	1.00	59	25	-

Minor comments:

Lines 51 to 57: there are four "while" in those 7 lines, including two in one sentence.

Please reduce the number of "while".

Response: We agree with the reviewer and We have modified the sentences as follows (section 1): *"While some studies primarily attributed inter-annual variability in NEP to changes in respiration (Cox et al., 2000; Valentini et al., 2000), others pointed to a primary dependence on the variability in ecosystem GPP (Ahlström et al., 2015; Jung et al., 2011; Sitch et al., 2015).*

Across various ecosystems the main environmental factors controlling GPP have been identified being solar radiation, water vapour pressure deficit (VPD) and leaf area index (LAI), whereas temperature and soil moisture are the main environmental drivers of ER (Baldocchi, 2008; Beringer et al., 2016a; Yi et al., 2010). ... For instance, the overall effect of drought conditions has been shown to decrease NEP but it often varies on which component, GPP or ER, drought conditions have the greatest impact".

Line 66: comma wrongly placed

Response: We have corrected accordingly.

Line 77: comma missing between abundant and there

Response: We have corrected accordingly.

Line 105: describe tree height better (how uniform and such) and add LAI in text.

Response: We have amended the text accordingly and please see our extensive response regarding tree height from page 3 (above) and our response regarding LAI to Line 169 below.

Line 114: Is it really a mean of 114 years??

Response: Yes, it is the 114 year mean (1901 – 2014) of rainfall records from the nearest Bureau of Meteorology station to the study site.

Lines 130-131: Having one soil temperature, one soil moisture and one soil heat flux plate measurement is not sufficient to characterise soil due to its spatial variability. You need replicates horizontally and vertical profiles within the soil. On line 131, SWC is at 5 cm depth then on line 149 you talk about 10 cm depth. Please clarify the soil measurement depths.

Response: Soil temperature, soil moisture and soil heat flux have been measured at two micro sites and averaged over these two sites. The correct soil depth for SWC measurements is 10 cm soil depth. We have corrected and clarified the text in the instrumentation section accordingly.

section 2.2: *"... soil heat flux, averaged over two sites, at 8 cm depth (HFT3 plate, Campbell Scientific Inc., Logan, USA and HFP01 plate, Hukseflux, Delft, NLD), soil temperature (Ts), averaged over two sites, at 10 cm depth (TCAV Thermocouple probes, Campbell Scientific Inc., Logan, USA) and volumetric soil water content (SWC) at 10 cm (averaged over two sites) and 50 cm depth ..."*

Line 144: There is an additional space before Contiuum.

Response: We have corrected accordingly.

Lines 145-146: Greater details need to be given on the quality filtering. This is not clear. What range checks? What thresholds for spikes? What thresholds for outliers? etc. . .

Response: We have amended the text to clarify the process steps during the Ozflux QA/QC procedure and included a reference to the Isaac et al. (2016) paper in this Special Issue where the standard QA/QC filtering procedure is described in detail. This includes the standard application of range checks in plausible limits, spike detection, dependency checks and manual rejection of date ranges of all measured variables (covariances and meteorological variables) per month and year. When necessary, i.e. depending on site characteristics, these settings have been modified based on visual revision of the data during the QA/QC procedure.

Line 169: Is that how LAI was derived? Are there any ground measurements of LAI to validate the MODIS data?

Response: No, the LAI value (1.8) for this study site was obtained from another study (Moore, 2011) at the same study site (see Table 1) based on ground measurements (hemispherical images). The mean LAI of 1.8 has also been confirmed in a later study (Griebel et al., 2016) and was based on ground measurements (hemispherical images). We have included this information in section 2.1 (site description) and citations in the discussion (section 4.3).

section 2.1: *"The study site is a secondary regrowth forest (DSE, 2012), of mixed age, with an average canopy height of 22 m (Griebel et al., 2015), a basal area of 37 m^2 ha^{-1} (Moore, 2011) and a LAI of 1.8 (Griebel et al., 2016; Moore, 2011)."*

section 4.3: *"A possible explanation for the greater net carbon uptake estimates in our dry temperate eucalypt forest might be the higher leaf area index (~ 1.8) (Griebel et al., 2016; Moore, 2011) than in the wet temperate eucalypt forest (~ 1.4) near Tumbarumba,... "*

Section 2.3.3: it is confusing which method you used in the end for partitioning. Please give the equations used for partitioning and show a figure comparing the different approaches if you mention you compared different methods in text. Also, show a comparison with the soil respiration measurements that you mention on line 185.

Response: We agree with the reviewer and have made extensive changes to section 2.3.3 to clarify what partitioning method was used to estimate gross ecosystem carbon fluxes. We have provided as supplementary material additional time series figures derived from different partitioning methods comparing the relative contribution of soil respiration data to the different outputs of ER. Furthermore we have presented a table with annual sums of ecosystem carbon fluxes from different partitioning methods for comparison, variation of different annual estimates (see Table S1, S2, Figures S1 to S4 in supplementary materials).

Line 301: temperate evergreen coniferous forests (add evergreen). It is not because they are coniferous but rather because they are evergreen.

Response: We have corrected accordingly.

Figure 2(a) is it NEE or –NEE (why is there a minus in the caption?) Same for Figure 3 and 4. Also, please describe what you display better, for e.g. in figure 3, what are the shaded lines

at the back, the actual daily totals? Typically NEE is what is measured by EC, and sometimes people convert it to NEP=-NEE. In your case, you do not need the minus there because you display NEE.

Response: The reviewer is correct and we have clarified the presentation of NEE in Figure 2a, 3 and 4. The minus sign before NEE has been removed in all figure captions and throughout the text. We have also clarified and added additional description of Figures 2, 3 and 4, i.e. the shaded lines in Figure 3 are daily totals (g C m^{-2} d^{-1}) of ecosystem carbon fluxes, while bold lines represent 7-day running means of daily totals for better illustration.

Figure caption for Figure 2 has been changed to*:"Time series of (a) 7-day running means of daily total net ecosystem exchange (NEE), 7-day running means of daily averages of (b) incoming solar radiation (Fsd), (c) air (Ta) and soil (Ts) temperature, and (d) 7-day running means of mean midday (11:00-13:00) vapour pressure deficit (VPD), (e) daily averages of volumetric soil water content (SWC) and (f) 7-day sums of rainfall (P) from 2010 to 2012".*

Figure caption for Figure 3 has been changed to:*"Ecosystem carbon fluxes of the Wombat State forest OzFlux site from 2010 to 2012: ecosystem respiration (ER, red lines), gross primary productivity (GPP, blue lines) and net ecosystem carbon exchange (NEE, black lines), displayed is the output of DINGO partitioning method (2a) using the night time data approach with NN and early evening hours selection with daily totals (g C m^{-2} d^{-1}) of ecosystem carbon fluxes (shaded lines) and 7-day running means of daily totals (bold lines) for better illustration."*

Figure caption for Figure 4 has been changed to:*"Box- and whisker plots of daily totals of a) NEE, b) ER and c) GPP for years and seasons; inter-annual differences are displayed for each seasons with p-values (significance level p <0.05), letters indicate year to year differences"*

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Net ecosystem carbon exchange of a dry temperate eucalypt forest

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Abstract. Forest ecosystems play a crucial role in the global carbon cycle by sequestering a considerable fraction of anthropogenic CO_2 thereby contributing to climate change mitigation. However, there is a gap in our understanding about the carbon dynamics of eucalypt (broadleaf evergreen) forests in temperate climates, which might differ from temperate coniferous or deciduous forests given their fundamental differences in physiology, phenology and growth dynamics. To address this gap we undertook a three year study (2010 – 2012) ~~using~~ of eddy covariance measurements in a dry temperate eucalypt forest in south-eastern Australia. We determined the annual net ~~ecosystem carbon exchange (NEE)~~carbon balance

and investigated the temporal (seasonal and inter-annual) variability and environmental controls of net ecosystem carbon exchange (NEE), gross primary productivity (GPP) and ecosystem respiration (ER). The forest was a large and constant carbon sink throughout the study period, even in winter, with an overall mean NEE of -1234~~1062~~ ± 109 (SE)~~53~~ g C m^{-2} yr^{-1}. ~~Gross CO_2 ecosystem fluxes~~ Estimated annual ER was similar for 2010 and 2011 but decreased in 2012 ranging from 1603 to 1346 g C m^{-2} yr^{-1} whereas GPP annual showed no significant inter-annual variability ~~and~~ with an mean annual estimate of ~~GPP was 2521~~ 2728 ± ~~35~~ 39 ~~g C m^{-2} yr^{-1} and ER was 1458 ± 31~~ g C m^{-2} yr^{-1}. All ecosystem carbon fluxes had a pronounced seasonality ~~GPP and ER had a pronounced seasonality~~ with GPP being greatest during spring and summer and ER during summer whereas peaks of NEE occurred in early spring and again in summer. High NEE in spring was likely caused by a delayed increase in ER due to low temperatures. A random forest analysis showed that variability in ~~GPP~~ day time NEE was mostly explained by incoming solar radiation whilst air temperature was the main environmental driver of ~~ER~~ night time NEE on seasonal and inter-annual time scales. The forest experienced unusual above average annual rainfall during the first two years of this three year period so that soil moisture content remained relatively high and the forest was not water limited. Our results show the potential of temperate eucalypt forests to sequester large amounts of carbon when not water limited. However, further studies using bottom-up approaches are needed to validate measurements from EC flux tower and to account for a possible underestimation in ER due to advection fluxes. ~~Our observations can provide data on an underrepresented biome to test and parameterise ecosystem models. However, longer monitoring is needed to assess the inter-annual variability of the carbon sink strength particularly during years with drought conditions.~~

Keywords. net ecosystem productivity, south-eastern Australia, 2011 La Niña, OzFlux, Wombat State Forest, dry sclerophyll forest, random forest approach

1 Introduction

Terrestrial ecosystems, together with the ocean, take up more than half of the yearly anthropogenic CO_2 emissions and their combined sink strength has increased over the past five decades in step with increased emissions (Ballantyne et al., 2012; Le Quere et al., 2013; 2015, unpublished). The terrestrial sink has been mostly attributed to the world's forest ecosystems over the last two decades (Le Quere et al., 2013; Pan et al., 2011) and only recently the importance of semi-arid ecosystems in the global carbon sink has been identified (Ahlström et al., 2015; Poulter et al., 2014). Even so, forests play a crucial role in the global carbon cycle and climate change mitigation (IPCC, 2013; Pan et al., 2011).

Nonetheless, uncertainty remains regarding the future trend and strength of this terrestrial carbon sink (Ciais et al., 2013; Mystakidis et al., 2016; Reichstein et al., 2013; Sitch et al., 2015). This is mainly related to the high inter-annual variability in the carbon uptake of ecosystems because of regional and even global variations in climate year-to-year (Ahlström et al., 2015; Reichstein et al., 2013). The balance between gross primary productivity (GPP) and ecosystem respiration (ER) is commonly termed net ecosystem productivity (NEP - that mostly approximates net ecosystem exchange (~~-~~-1*NEE)) and can be positive (a carbon sink) or negative (a carbon source), although other carbon exchanges such as dissolved organic transport and/or ~~fire~~ disturbance provide a true net ecosystem carbon balance (NECB) (Chapin et al., 2006). Hence, variability in NEP is dependent on variations of the component fluxes GPP and ER and their responses to climate and resource availability (Ahlström et al., 2015; Ciais et al., 2013; Reichstein et al., 2013). While some studies primarily attribute inter-annual variability in NEP to changes in respiration (Cox et al., 2000; Valentini et al., 2000), ~~while~~ others point to a primary dependence on the variability in ecosystem GPP (Ahlström et al., 2015; Jung et al., 2011; Sitch et al., 2015).

Across various ecosystems the main environmental factors controlling GPP have been identified being solar radiation, water vapour pressure deficit (VPD) and leaf area index (LAI), ~~while~~ whereas temperature and soil moisture are the main environmental drivers of ER (Baldocchi, 2008; Beringer et al., 2016a; Yi et al., 2010). Variability in NEP has also been demonstrated to be strongly influenced by variation in water availability (i.e. changes in rainfall). For instance, ~~while~~ the overall effect of drought conditions has been shown to decrease NEP~~,~~ but it often varies which component, GPP or ER, drought conditions have the greatest impact (Ciais et al., 2005; Reichstein et al., 2007; Schlesinger et al., 2015; Zhao and Running, 2010). It is therefore critical to assess the carbon balance of ecosystems to improve our knowledge of processes

controlling NEP (or —NEE) and their response to variability of environmental drivers and climate change. Another factor contributing to the uncertainty of future terrestrial carbon sinks is the still limited empirical data available on forest carbon dynamics to better constrain uncertainties of global and continental process-based carbon models and/or to improve data-driven model frameworks (Haverd et al., 2013a; Jung et al., 2011; Keenan et al., 2012; Roxburgh et al., 2004).

Forests in Australia occupy around 19% of the continent and account for about 3% to forested area worldwide (ABARES, 2013) and~~,~~ until recently their potential contribution to the global carbon cycle has not been considered~~ignored~~. The role of Australian ecosystems generally in the global carbon cycle has had recent attention in the light of the 2011 strong La Niña event and global record terrestrial carbon sink, where Australian ecosystems, particularly semi-arid ecosystems, played a major role in the continental and global carbon uptake anomaly (Haverd et al., 2013b; 2016; Poulter et al., 2014). Although semi-arid ecosystems have been suggested as dominant drivers in inter-annual variability and trends of the global net carbon sink (Ahlström et al., 2015), little is known about how Australian temperate eucalypt (broadleaved evergreen) forests may contribute to the global sink and inter-annual variability. Two thirds of native forests in Australia are eucalypt forests (92 M ha) and dry temperate eucalypt forests account for the largest proportion (37% or 8.3 M ha) of forest ecosystems in south-eastern and south-western Australia and are of high socio-economic value (ABARES, 2013). Growth and regeneration of temperate forests in the Northern Hemisphere are considered to account for the increasing global terrestrial carbon sink (Pan et al., 2011), although a recent study showed a decline in this trend (Sitch et al., 2015). While studies of the carbon balance in the Northern Hemisphere temperate forests are abundant, there are only a handful of studies that have been undertaken in temperate eucalypt forests in Australia and none of these in dry temperate eucalypt forests (Beringer et al., 2016a; Keith et al., 2009a; 2012; Kilinc et al., 2012; 2013; Leuning et al., 2005; van Gorsel et al., 2013). The behaviour of temperate deciduous or coniferous forests in the Northern Hemisphere cannot be presumed to be an analogue for temperate eucalypt forests. Apart from being broadleaf evergreen, with mostly sclerophyllous leaves, a key trait of eucalypt forests in Australia is the ability to rapidly and opportunistically respond to changing, either favourable or stressful, environmental conditions (Jacobs, 1955; Keith, 1997). This is an adaptation to disturbances such as fire or drought that are a major component of ecosystems on the Australian continent (ABARES, 2013; Beringer et al., 2015; Whitehead and Beadle, 2004). Moreover, Australian forests are generally water and nutrient limited and soils are highly weathered (Attiwill and Adams, 1993;

Whitehead and Beadle, 2004). Keith et al. (2009a) showed that a wet temperate eucalypt forest had a high-carbon uptake capacity compared with other forests globally when not limited by water availability. No studies have been published on ecosystem carbon exchange in dry temperate eucalypt forests, where rainfall is considerably lower and soil moisture likely to be a greater limiting factor.

The aim of the study was to assess the carbon uptake potential of a dry temperate eucalypt forest and to gain an understanding of its temporal carbon exchange dynamics and controls thereof by using the eddy covariance (EC) technique (Baldocchi, 2008; 2003; Hutley et al., 2005) as part of the regional OzFlux network (Beringer et al., 2016a).

Therefore the objectives of our study were to 1) investigate seasonal and inter-annual variability in net ecosystem carbon exchange (NEE), gross primary productivity (GPP) and ecosystem respiration (ER), 2) identify the environmental controls of these CO_2 ecosystem fluxes, and 3) quantify annual estimates of NEE and its component fluxes in a dry temperate eucalypt forest.

2 Materials and methods

2.1 Site description

The Wombat State Forest OzFlux tower site (Fluxnet ID: AUS-Wom) is located in the Wombat State Forest, Victoria, about 120 km west of Melbourne, Australia (37° 25' 20.5" S, 144° 05' 39.1" E). ~~The flux tower is located on a ridge at a mean altitude of 706 m a.s.l. and the terrain within the footprint is relatively level to the east of the tower and with gently sloping gullies (<8°) towards the southwest and northwest (Griebel et al., 2016).~~ The Wombat State Forest is classified as dry sclerophyll eucalypt forest or Open (crown cover >50-80%) forest (ABARES, 2013) is dominated by three broadleaved evergreen tree species: *Eucalyptus obliqua* (L'Hérit.), *Eucalyptus rubida* (Deane & Maiden) and *Eucalyptus radiata* (Sieber ex DC). General forest history includes harvesting and patchy occurrences of bushfires. Selective harvesting occurred until early 1970 when replaced by a more intensive shelterwood (two-stage clear-felling) system (Poynter, 2005). Since 2003 the Wombat State Forest has been under community forest management, a cooperative between state government and local community (Poynter, 2005) and harvesting has been strongly reduced. Forest management practices also include periodic low fire intensity prescribed fires and firewood collection in designated areas.

The study site is a ~~~25 years old~~ secondary regrowth forest (DSE, 2012), of mixed age, with an average canopy height of 22 m (Griebel et al., 2015),~~approximate canopy height of 21-27 m and~~ a basal area of 37 m^2 ha^{-1} (Moore, 2011) and a LAI of 1.8 (Griebel et al., 2016; Moore, 2011).~~.~~ The area was selectively harvested last in the early 1970s with the last bushfire on the outskirts of the study site recorded in 1982 and no recorded history of prescribed fires. The flux tower is located on a ridge at a mean altitude of 706 m a.s.l. and the terrain within the footprint is relatively level to the east of the tower and with gently sloping gullies (<8◦) towards the southwest and northwest (Griebel et al., 2016). The understorey is sparse and dominated by Austral bracken (*Pteridium esculentum* (G. Forst.) Cockayne), Forest wire-grass (*Tetrarrhena juncea* R. Br.), Tussock Grass (*Poa sieberiana* Sprengel), herbs (e.g. *Gonocarpus tetragynus* Labill., *Viola hederacea* Labill.) and rushes (*Lomandra* spp.) (Tolhurst, 2003). ~~Forest management generally includes rotational low fire intensity prescribed burns of understorey vegetation which has been exempted at the studied area.~~ The climate is cool temperate to Mediterranean with wet, cold winters and dry, warm/hot summers. Long-term (2001-2013) mean annual air temperature was 12.1 ± 0.1 °C with mean monthly maximum air temperatures of 26.3 ± 0.5 °C in January and mean minimum air temperatures of 3.2 ± 0.1 °C in July (nearest Bureau of Meteorology (BOM) station Ballarat, 28km SW, Fig. 1a). The silty clay soil overlying clay derived from Ordovician marine sediments and are classified as Acidic-mottled, Dystrophic, Yellow Dermosol (Robinson et al., 2003), ~~that are~~ moderate to highly weathered and exhibit low fertility. The long-term (~~114 year~~1901-2014) mean annual rainfall at the nearest rainfall BOM station (Daylesford, 11km N, Fig. 1b) is 879 ± 18 mm with the highest rainfall occurring during winter and spring. ~~Prior to 2010 and our study period, south-eastern Australia experienced a 13-year drought with a mean annual rainfall of 760 ± 32 mm at the closest BOM station Daylesford.~~ For overview and more detailed site characteristics see Table 1.

2.2 Instrumentation and data aquisition

The guyed Eddy – Covariance (EC) flux tower was established in January 2010 within a fenced compound. The micro-meteorological measurement system was installed at 30 m height and consisted of an open-path infrared gas analyser (IRGA, Li-7500, LI-COR, Lincoln, USA) that measures CO_2 and water vapour concentrations and atmospheric pressure, and a 3D – sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, USA) that measures turbulent wind vectors and virtual air

temperature. Instantaneous measurements were carried out at 10 Hz ~~–~~and stored on a CF-card. Furthermore calculated covariances ~~and covariance's were calculated~~ with a ~~block averaging of~~ 30 min averaging period~~and~~ were stored on a data logger (CR-3000, Campbell Scientific Inc., Logan, USA). Prior to the calculation of covariances at the end of a 30 min averaging period, 10 Hz data were filtered by the data logger depending on diagnostic information from both the sonic anemometer and IRGA in which data spikes got removed (Isaac et al., 2016). Concurrent measurements of environmental variables included~~:~~; air temperature (Ta) and absolute and relative humidity (HMP-45C probe, Vaisala, FIN) at 2 m and 30 m height, incoming and reflected shortwave radiation and atmospheric and surface emitted longwave radiation with a CNR1 net radiometer (Kipp and Zonen, Delft, NLD) at 30 m height, rainfall with a tipping bucket rain gauge (CS702, Hydrological Services Pty Ltd., Sydney, AUS) at 1 m height, soil heat flux, averaged over two sites, at 8 cm depth (HFT3 plate, Campbell Scientific Inc., Logan, USA and HFP01 plate, Hukseflux, Delft, NLD), soil temperature (Ts), averaged over two sites, at 10 cm depth (TCAV Thermocouple probes, Campbell Scientific Inc., Logan, USA) and volumetric soil water content (SWC) at ~~5~~ 10 cm~~-~~ (averaged over two sites) and 50 cm depth (CS616 water content reflectometer probes, Campbell Scientific Inc., Logan, USA).~~–~~All instrumentation was powered by a remote area power system consisting of a diesel generator and a 24V battery bank inverter system (Powermaker Ranger 4.5, Eniquest, QLD, AUS). An automated remote connection using a GSM modem (GPRS/ GSM Quadband Unimax Router and Ethernet modem, Maxon Australia Pty Ltd, Padstow, NSW, AUS) provided real time information on system status and ensured data acquisition on a daily basis. Additionally data were stored on an external CF (compact flash) cards which were interchanged on a monthly basis. A footprint analysis by Griebel et al. (2016) using the parameterisation of flux footprint predictions of Kljun et al. (2004) showed that the distribution of fluxes were relatively homogeneous and that the whole footprint consisted of the same forest type and dominant tree species, and roughly uniform basal area. For further details see~~The footprint of the ecosystem flux tower during turbulent conditions extended to about 250 m in south-westerly direction covering a potential source area of 25 ha and measured CO_2 fluxes were constrained to the same forest type and dominant tree species~~ Griebel et al. (2016).

In February 2012 a custom-built profile system including an IRGA (Li-840, LI-COR, Lincoln, USA) and with six vertical layers (1, 2, 4, 8, 15 and 30 m) ~~(McHugh et al., 2016)~~was installed to measure CO_2 concentrations of each layer in 2 min intervals (McHugh et al., 2016). A detailed description of the profile system can be found in McHugh et al. (2016). Due to

technical problems with the IRGA profile data were available from March to October 2012. Changes in the storage term between forest floor and EC-measurement point were calculated following McHugh et al. (2016) and Finnigan (2006). For periods of time when profile storage measurements were not available, ecosystem CO_2 fluxes were accounted for storage terms derived from single point calculations within the "OzFlux QC" data processing (Isaac et al., 2016). However, the contribution of storage term only marginally changed the magnitude of NEE (on average 2%) (Fig. S1 in supplementary materials).

2.3 Data processing

2.3.1 Quality Control

Quality assurance/ quality control (QA/QC) and eddy covariance flux corrections were performed on both available 10 Hz data and ~~the~~ 30 minute covariance data.~~s~~ 10 Hz data was processed with Eddy Pro Version 6.2 (2016) including default statistical analysis (spike removal, drop-outs, absolute limits, skewness/kurtosis), low and high frequency correction (Massman, 2000; Moncrieff et al., 2005) and planar fit coordinate rotation (Wilczak et al., 2001). The calculated covariances from the 30 min averaging period were processed following the OzFlux standard protocol and open source code OzFluxQC version 2.9.~~5~~ 6e (Isaac et al., 2016; OzFlux, 2016) using Anaconda Python version 2.7 (Continuum Analytics, Texas, USA). The procedure is described in detail in its own method paper by Isaac et al. (2016), as well as by Eamus et al. (2013) and Cleverly et al. (2013). In brief,(OzFlux, 2016) ~~using Anaconda Python version 2.7 (Continuum Analytics, Texas, USA). The procedure is described in detail by Eamus et al. (2013) and Cleverly et al. (2013) and in summary~~ the OzFluxQC procedure included quality control checks such as range checks in plausible limits, spike detection, dependency checks and manual rejection of date ranges of all measured variables (covariances and environmental variables) depending on site characteristics and based on visual revision of the data during the QA/QC procedure modified per month and year; ~~quality filtering via range checks (outlier and spike removal),~~ linear corrections for calibration anomalies and sensor drift, 2D co-ordinate rotation (Lee et al., 2005), WPL correction (Webb et al., 1980), low and high frequency correction according to Massman (2001; 2000) and Moncrieff et al. (2005), conversion of virtual heat flux to sensible heat flux and correction of ground heat flux for heat storage in the soil layer above, addition of single point calculated or profile measurement derived storage term and calculation of fluxes from the quality controlled and corrected covariances.~~.~~ ~~Due to sensor failure, SWC at 10 cm in~~

~~2010 was modelled from a linear relationship between SWC at 35 cm and a second sensor for SWC at 10 cm in 2011 and 2012.~~ Extensive comparison between 10 Hz data processed with EddyPro and 30 min covariances processed with OzFluxQC showed that the planar fit correction versus 2D-coordinate rotation resulted in a 3% difference of fluxes. When this difference was accounted for in the OzFluxQC processed data set, both data sets were in very good agreement (slope: 1.01, intercept: 0.06, R^2: 0.90). Periods of data with low turbulence conditions, predominantly during night time, were excluded based on friction velocity (u*). Night time u* was filtered with yearly determined u*- thresholds using the change point detection method after Barr et al. (2013) and is described in detail in Isaac et al. (2016), Beringer et al. (2016b) and McHugh et al. (2016), this issue. Uncertainty in the u* threshold was estimated by generating a probability distribution for u* threshold and 95% confidence interval (CI) by bootstrapping the CPD method (1000 times randomly sampling of the data per year). Annual u* thresholds ranged from 0.~~56~~ 53 to 0.~~69~~ 66 m s^{-1}. Data gaps occurred due to rainfall and occasional power failure and ~~61~~60% of data were available over the three year period. Following QA/QC and night time u* filtering this was reduced to 37%, ~~47~~49% and ~~47~~49% in 2010, 2011 and 2012. From this quality filtered data were ~~66~~64% day-time data and ~~23~~26% night-time data.

2.3.2 Gap filling

Subsequent gap filling of data was done either with the Dynamic Integrated Gap filling and partitioning for OzFlux routine (DINGO v13) (Beringer et al., 2016b) or with the OzFluxQC procedure (Isaac et al., 2016), depending on the partitioning method selected (see below). However~~-~~, both procedures have very similar data gap filling procedures and are described in detail in Beringer et al. (2016b) and Isaac et al. (2016). Small data gaps (≤ 2 hrs) of continuous 30 min flux measurements and environmental variables were filled with linear interpolation. ~~Then, firstly~~

In DINGO data gaps of environmental variables (air temperature, humidity, radiation, wind speed, atmospheric pressure and rainfall) > 2 hrs ~~environmental variables (temperature, humidity, radiation, wind speed, atmospheric pressure and rainfall)~~ were gap filled: 1) from linear regressions with AWS (Automated Weather Stations) 30 min data records from the three nearest Bureau of Meteorology Australia (BoM) weather stations ~~with 30 min records~~ which were ranked after best correlation, 2) with spatially gridded meteorological daily satellite data at 0.1° resolution from the Australian Water Availability Project (AWAP, Raupach et al. (2009)) ~~for radiation~~ and in the unlikely event that gaps were still present after

applying the above methods then a monthly diurnal means of measured climate variables were used. The frequency at which to perform the correlation analysis between flux tower data and AWS was set to use all available data. Soil ~~variables~~temperature and soil moisture variables ~~(temperature and soil water content at depths)~~ were gap filled using a simulation of the land surface using AWAP climate data and the CSIRO process-based land surface model BIOS2 at 0.05° resolution (see Haverd et al. (2013a)) adjusted to site observations.~~.~~ Following gap filling of environmental variables half-hourly NEE data were gap filled using a fast forward artificial neural network (FFNET ANN) with incoming shortwave solar radiation (Fsd), vapour pressure deficit (VPD), SWC, Ts, wind speed (Ws) and~~,~~ enhanced vegetation index (EVI) as input drivers according to Beringer et al. (2007); (2016b) and Papale and Valentini (2003). EVI was obtained from ~~8- or~~ 16- day compositing periods of enhanced vegetation index (EVI) ~~as surrogate for leaf area index~~ from MODIS (Moderate Resolution Imaging Spectroradiometer, see Huete et al. (2002)) as surrogate information of vegetation activity (i.e. leaf area index and growth) and interpolated to 30 min as proxy for production related to plant respiration. Frequency of gap filling using ANN was set to all available data.

In OzFluxQC data gaps of environmental variables > 2 hrs were gap filled: 1) with AWS as in DINGO, 2) using the regional Australian Community Climate Earth System 5 Simulator (ACCESS-R) numerical weather prediction (NWP) model at a resolution of 12.5 km run by the BoM (Isaac et al., 2016) and 3) ERA Interim (ERAI) data set from the European Centre for Medium Range Weather Forecasting (Dee et al., 2011) at 75 km resolution across Australia. Half-hourly NEE data were gap filled using the SOLO neural network (SOLO ANN) (Abramowitz, 2005; Hsu et al., 2002) with net radiation (Fn), ground heat flux (Fg), specific humidity (q), VPD, SWC, Ta and Ts as input drivers according to Isaac et al. (2016).

2.3.3 Partitioning and carbon flux definitions

The partitioning of NEE into its component fluxes GPP and ER was following the assumption of

$$-NEE = NEP = GPP - ER \quad (1)$$

where day time NEE is the difference of GPP and ER, and night time NEE is equal to ER and hence, GPP being negligible/zero. We adopt the conventions in Chapin et al. (2006) where GPP and ER fluxes are designated with a positive sign. Negative NEE fluxes denote a net carbon flux from the atmosphere to the ecosystem, thus a net carbon uptake by the forest ecosystem which equals a positive net ecosystem production (NEP).

One of the most common uncertainties in EC measurements can be an underestimation of night time NEE or ER as turbulent mixing is often lower or absent at night time which can lead to non-detectable vertical and horizontal advection of CO_2 within the canopy (Aubinet et al., 2012; Baldocchi, 2003; Goulden et al., 1996; van Gorsel et al., 2007). Although u* filtering is the most common correction for this underestimation error (Goulden et al., 1996), many studies have reported smaller estimates of ER from u* filtered and gap-filled EC-tower data compared to those from chamber measurements of soil, leaf and stem respiration (Keith et al., 2009a; Lavigne et al., 1997; Law et al., 1999; Phillips et al., 2010; Speckman et al., 2015). Although no independent up-scaled ER estimates from chamber measurements were available from our study site, we used independent daily soil respiration data from a separate study at the same study site (Hinko-Najera, 2016, unpublished)~~(Hinko-Najera, unpublished)~~ to visually compare its relative contribution to daily tower ER estimates derived from four different data selection and subsequent partitioning methods to reduce a potential underestimation of ER (see supplementary material Fig. S1, S2 and S3). We ran an ensemble of different partitioning methods (using either DINGO or OzFluxQC routines) and u* based night time filters on NEE fluxes including the storage term only to evaluate variation of ecosystem carbon fluxes depending on partitioning and filter method used. An overview of partitioning methods, estimated annual sums and their variation is given in supplementary materials in Table S1,S2 and Fig. S4, and briefly explained here: We used three different partitioning methods to estimate gross ecosystem carbon fluxes: 1) night time approach after the Lloyd and Taylor temperature response function (Lloyd and Taylor, 1994; Reichstein et al., 2005) with Ta as input driver using a window size of 15 days with an overlapping of 10 days in OzFluxQC, 2) night time approach using ANN: (2a) FFNET NN with Ts, Ta, SWC and EVI as input drivers and a window size of all available data in DINGO (Beringer et al., 2016b) or (2b) SOLO NN with Ta, Ts and SWC as input drives and a window size of one year in OzFluxQC (2b) (Isaac et al., 2016) and 3) day time approach using the light response function according to (Lasslop et al., 2010) using either (3a) DINGO or (3b) OzFluxQC with a window size of 15 days with an overlapping of 10 days. Detailed descriptions of functions and routines used within the DINGO and OzFluxQC routines are given in Beringer et al. (2016b) and Isaac et al. (2016). For the methods using the night time approach the u* filter after the u* threshold was applied to non gap filled (quality controlled observations only) night time (Fsd <1.22 MJ m^{-2} d^{-1} or 10 W m^{-2}) NEE flux data. Differences between DINGO (2a) and OzFluxQC (1, 2b) partitioning methods here is that DINGO was set to use u* filtered night time data from the first

three hours after sunset only (Fsd <1.22 MJ m^{-2} d^{-1} or 10 W m^{-2}) while with OzFluxQC three night time selections have been applied to u* filtered night time data: all u* filtered night time NEE data, first three hours after sunset of u* filtered NEE data, and a variable daily window size using all night-time data above the u* threshold from sunset onwards until u* falls below the u* threshold (Eva van Gorsel, personal communication). The selection of the first three hours after sunset is based on an extensive study in a wet temperate eucalypt forest from van Gorsel et al. (2008); (2007) who demonstrated that ER was at maximum in the early evening hours when the canopy is still coupled with the atmosphere. For the ANN methods (2a) and (2b) estimated night time ER was extrapolated to day time ER. The final NEE flux was then constructed from gap filled day time data (Fsd >= 1.22 MJ m^{-2} d^{-1} or 10 W m^{-2}) and estimated ER at night time. GPP was then subsequently estimated with Eq. (1). For the methods using the daytime approach a light response curve was fitted to day time NEE to estimate GPP and subsequently ER across day and night time. ~~Of the four methods, three were based on prediction of night time ER and subsequent extrapolation of day time ER and estimation of GPP with Eq. (1). This included (1) whole night or (2) early evening data (van Gorsel et al., 2007) selection from the observed and u* filtered 30 minute NEE data and subsequent training of ANNs to compute ER with Ts, Ta, SWC and EVI as input drivers, and (3) application of a temperature function after Lloyd and Taylor (1994) to u* filtered whole night time NEE (Reichstein et al., 2005). The last partitioning method (4) followed the procedure of Lasslop et al. (2010), where a light response curve was fitted to day time NEE to estimate GPP and subsequently ER across day and night time.~~

2.4 ~~Data management and statistical analysis~~Uncertainty analysis and analysis of environmental drivers

We performed an uncertainty analysis as described in McHugh et al. (2016) this Issue which includes an uncertainty estimation of combined random and model error (Hollinger and Richardson, 2005; Keith et al., 2009) (supplementary material Table S3) and the effect of uncertainties in u* thresholds on annual NEE estimates by using the lower (5%) and upper (95%) confidence interval of the probability distribution of the mean u* threshold (Barr et al., 2013) (supplementary material Table S4). The uncertainty introduced due to random (measurement) and model error was small for 2010 and 2012 (4% and 6% of annual NEE estimate) and slightly higher for 2011 (10% of annual NEE estimate) (Table S3). Estimation of the uncertainties in u* thresholds on annual NEE were small for the lower u* uncertainty bound (5% CI) ranging from -19 g

C m^{-2} yr^{-1} in 2012 to 26 g C m^{-2} yr^{-1} in 2011 (1-2% of annual NEE estimate). We could not estimate an upper u* uncertainty bound (95% CI) as data availability was insufficient (Table S4).

~~All data manipulation and statistical analyses on the post QA/QC - DINGO data were performed using R version 3.2.2 (R Core Team, 2016). Differences in seasonal and inter-annual variations of daily means were tested with Kruskal-Wallis rank sum test and Dunn's Test. Relationships between half-hourly data of environmental variables and carbon fluxes (not gap filled quality controlled for 30 min data) were tested with linear regressions and stepwise multiple linear regressions. Night time data were defined as Fsd <1.22 MJ m^{-2} d^{-1} (= 10 W m^{-2}).~~

The relative importance of environmental drivers on seasonal and inter-annual variability of ecosystem carbon fluxes were assessed using the Random Forest algorithm (Breiman, 2001). This method is based on multiple decision trees that groups observations as a function of independent variables. Each tree in the forest is trained on a random subset of the training dataset. A multiple linear regression is performed in each final node of each tree and the final prediction of the forest is the average of all its trees. The Random Forest has been used to extrapolate maps of biomass (Baccini et al., 2012; Exbrayat and Williams, 2015) and produce global estimates of GPP by extrapolating FLUXNET data (Jung et al., 2009; 2011). It outputs a measure of the co-variation between vectors of explanatory variable and observations. This importance is computed tree-wise as the fraction of decisions in which an explanatory variable is involved.

Therefore we used ~~T~~the Python implementation of the Random Forest algorithm (Pedregosa et al., 2011) ~~was used~~ to explain ~~four ecosystem carbon and energy fluxes (GPP, ER and NEE)~~ day time NEE fluxes of environmental drivers: Fsd, Ta, SWC and VPD and night time NEE fluxes as a function of environmental drivers: Ta and SWC. ~~of environmental conditions: Fsd, Ta, SWC and VPD~~. We performed ~~T~~two sets of analyses ~~we performed~~ using daily ~~values~~means of quality controlled half-hourly non gap filled midday NEE (11:00 – 13:00) and u* filtered night time NEE. ~~First, data~~ Data were binned per calendar month and the Random Forest was trained independently for each month to assess the seasonal evolution of environmental controls on ecosystem fluxes. ~~Second, this procedure was reproduced while binning data per calendar year to assess the inter-annual variability of these environmental controls. For ER only SWC and Ta were used as environmental drivers.~~

All subsequent data manipulation and statistical analyses were done using R version 3.3.2 (R Core Team, 2016) and for gap filled times series we chose the night time partitioning approach from the DINGO output. Differences in seasonal and inter-annual variations of daily means were tested with Kruskal-Wallis rank sum test and Dunn's Test.

3 Results

3.1 Seasonal and inter-annual variation in environmental variables

Seasonal and inter-annual pattern in rainfall varied markedly across the three year period (Fig. 1b, 2f). In the first two years unusually high rainfall was observed during the occurrence of two strong La Niña events. Annual rainfall in 2010 and 2011 was 43% and 22% above the long-term mean annual rainfall from the nearest BOM station (Daylesford) which is representative for the study site as an adjustment was less than 1% (Table 1, Table 2). Most of the anomalous rainfall occurred between August 2010 and February 2011 with a 2-fold increase in rainfall during spring 2010 (S-O-N) and a 3-fold increase in rainfall in summer 2010/11 (D-J-F, Fig. 1b). While the annual rainfall in 2012 was close to the long-term mean annual rainfall (Table 1, Table 2), monthly rainfall showed a distinct pattern with the above long-term mean rainfall in February 2012 (2-fold increase) and winter 2012 (J-J-A, +30%) but below long-term mean rainfall from spring 2012 (S-O-N, -37%) onwards (Fig 2.1b, 2.2f).

SWC at 10 cm soil depth generally varied strongly with seasons and was highest during winter with a daily maximum of 0.36 cm^3 cm^{-3} observed in August 2012 and decreased towards summer reaching a daily minimum of 0.12 cm^3 cm^{-3} in February 2012 (Fig. 2e). Seasonal variability of SWC was more pronounced in 2012 (CV = 25%) than in 2010 (CV = 18%) as high rainfall led to an absence of a dry period during summer 2010/11 (D-J-F) and SWC remained relatively stable and high throughout 2011 (CV = 13%). ~~SWC in 2011 significantly ($p < 0.001$) differed from 2010 and 2012~~.

Fsd, Ta, Ts and VPD showed a strong seasonality with maximum values during summer months and minimum values during winter months (Fig. 2b, c, d). Mean daily Fsd was 24 MJ m^{-2} d^{-1} in summer (maximum of 35.5 MJ m^{-2} d^{-1} in January 2011) and 7 MJ m^{-2} d^{-1} in winter (minimum of 0.4 MJ m^{-2} d^{-1} in May 2011, Fig 2.2b). Daily mean temperatures ranged from 2.0 ºC in winter (J-J-A) to 28.2 ºC in summer (D-J-F) for Ta and from 4.8 ºC and 23.6 ºC for Ts (Fig. 2c). Daily maximum midday

VPD of ~~2.81~~3.41 kPa was observed in January 2012 (Fig. 2d). Inter-annual variation of Fsd, Ta and Ts were marginal (Fig. 2 b,c) while mean annual VPD was significantly ($p < 0.001$) higher in 2012 (0.47 kPa) compared to 2010 and 2011 (0.36 kPa and 0.32 kPa, Table 2).

3.2 Seasonal and inter-annual variation of CO_2 ecosystem fluxes

A pronounced seasonal pattern was observed in ER (CV = 39%)~~and GPP~~, but less so in GPP (CV = 27%) and NEE (CV = 24%, Fig. 2a, 3, 4).

In general, the forest showed near-continuous net carbon uptake (negative NEE) throughout the three year period, with highest net uptake rates during summer ~~spring~~ and ~~summer~~ spring months (seasonal daily means of NEE: -~~3.55~~4.07 and -~~3.52~~3.98 g C m^{-2} d^{-1}) and lowest rates during winter ~~autumn~~ and ~~winter~~ autumn months (seasonal daily mean NEE: -~~2.26~~2.86 and -2.~~33~~ 62 g C m^{-2} d^{-1}, Fig. 2a, 3). Only in December 2010 and January 2011 NEE became distinctly positive (net carbon loss) for a short period (~~4~~ 3 to 4 consecutive days) due to a increase in ER in December 2010, ~~as~~ and a decrease in GPP in January 2011 ~~decreased greatly~~ (by ~~50~~40%) ~~due to~~in response to considerably high rainfall and limited solar input. Seasonal variability in NEE was noticeably less pronounced in 2011 (CV = ~~15~~9 %) than in 2010 ($p < 0.001$, CV = ~~35~~38 %) and 2012 ($p < 0.001$, CV = ~~25~~21 %, Fig. 4a). Inter-annual variation of NEE was ~~moderate~~ high (CV = ~~9~~15 %) ~~being~~ and significant ~~between 2010 and 2012~~ (p ~~=~~ $\leq$ 0.001~~2~~) with most evident differences during ~~autumn~~ winter and ~~winter~~ autumn (Table 2, Fig. 4a).

ER was greatest during summer (seasonal daily mean of 5.~~89~~ 77 g C m^{-2} d^{-1}), of similar magnitude in autumn and spring (4.~~03~~ 34 g C m^{-2} d^{-1} and 4.~~09~~ 23 g C m^{-2} d^{-1}, respectively) and lowest during winter (~~1.98~~2.05 g C m^{-2} d^{-1}). Similarly to NEE, GPP was greatest during summer (seasonal daily mean of 9.~~41~~ 85 g C m^{-2} d^{-1}), followed by spring (~~7.64~~8.20 g C m^{-2} d^{-1}), autumn (6.~~29~~ 96 g C m^{-2} d^{-1}), and least during winter (4.~~93~~1g C m^{-2} d^{-1}).

~~Seasonal variability was significant for both ER and GPP ($p < 0.001$) and slightly greater in ER (CV = 39%) than in GPP (CV = 30 %, Fig 2.4 b,c).~~ Overall ~~I~~inter-annual variation for ER ~~both~~ was moderate (CV = 9 %) and significant for all seasons except spring~~small (CV < 4%)~~. ~~However,~~ ER was significantly lower in summer 2012 ~~significantly~~ compared to summer months in 2010 and 2011, as was winter 2012 compared to winters 2010 and 2011 (Fig. 4b). ~~differed between summers of 2011 and 2012, and winters of 2010 and 2012 (Fig. 4b).~~ Overall, GPP estimates did not vary between years (CV

< 3 %) and only in winter 2010 GPP significantly differed from the winters of 2011 and 2012 (Fig. 4c). ~~GPP was strongly correlated with ER at monthly time scales (adj.R^2 = 0.87, p <0.001) but not at daily time scales.~~ The ER/GPP ratio was highest during autumn and summer (0.~~64~~ 62 and 0.~~63~~59) and lowest during spring and winter (0.5~~3~~2 and 0.4~~2~~7).

3.3 Environmental drivers of CO_2 ecosystem fluxes

~~Half-hourly *day time* NEE across all three years was strongest and significantly correlated with Fsd (r = −0.74, p <0.001, Table 3). Residuals from the linear regression between NEE and Fsd were significantly correlated with both Ta and VPD (adj.R^2 = 0.24 and 0.25, both p <0.001). Fsd and VPD combined could explain 69% (p <0.001) of variation in day time NEE. Similarly, Fsd and Ta combined could explain 69% of variation in NEE (p <0.001). However, a Pearson's correlation matrix of environmental variables (Fsd, SWC, Ta, Ts and VPD) showed a strong co-linearity of between Ta and VPD for day time data (r = 0.86, p <0.001, Table 3) and regressions with Ta instead of VPD had a slightly lower AIC. The influence of SWC on the variability of day time NEE was marginal, with residuals weakly but significantly correlated with SWC (adj.R^2 = 0.03, p <0.001), and multi linear regression models did not improve when SWC was included.~~

~~Half-hourly *night time* NEE that had been u* filtered showed stronger correlation with Ta (r = 0.53, p <0.001) than Ts (Table 3) across the three year study period. Ta could explain 28% of variability in night time NEE. SWC was marginally correlated with night time NEE (adj.R^2 = 0.05, p <0.001) and multi linear regression models did not improve when SWC was included.~~

Seasonal importance of environmental drivers to explain ecosystem carbon fluxes using the Random Forest method are presented for each year in Fig~~.~~ure 5 for midday NEE fluxes and in Figure 6 for u* filtered early (first 3hrs) night time NEE fluxes and averaged per month and across a year in Figure 7. Fsd was the dominant environmental driver for midday NEE fluxes across all years, particularly during autumn and winter months (Fig. 5) ~~GPP is controlled by Fsd throughout the year~~ with the relative importance ranging from 0.~~6~~ 3 during summer to 0.~~9~~ 7 in ~~winter~~autumn (Fig.7a).~~,~~ ~~while ER~~Early evening NEE ~~is~~ was ~~strongly~~ dominated by variations in Ta ~~(> 0.9) across all seasons~~with the relative importance ranging from 0.3 in spring to 0.7 in late summer and autumn (Fig 6, Fig. 7c). ~~A clear seasonal variation in the importance of environmental drivers is shown in explaining the seasonal variability in NEE. During winter NEE is predominantly explained by Fsd with a relative importance of 0.6 to 0.8, indicating that GPP limitation by Fsd is imposing a stronger influence on NEE than ER~~

~~limitation by Ta. However, during summer the relative importance of Fsd decreases to approximately 0.3 as the one of Ta is increasing to 0.6.~~

The relative importance of environmental drivers on inter-annual time scale presented in Fig. ~~6 is~~7 (b, d) was similar to those on seasonal time scale (Fig. 5,6) with ~~GPP~~ midday NEE being ~~almost exclusively~~ dominated by Fsd ~~(>~~ (~ 0.~~8~~5) -while ~~ER~~ early evening hour NEE is predominantly driven by Ta ~~alone~~. While no changes in the overall annual relative importances of environmental drivers was shown from 2010 to 2011, ~~Hence, inter-annual variability in NEE could be almost equally explained by Fsd (0.5) and Ta (0.3 to 0.4). However, there is~~ a notable increase in the relative importance of VPD for midday NEE and SWC for ~~NEE~~ early evening hours was shown in 2012~~-~~ (Fig. 7b,d).~~which was a drier year than 2010 and 2011.~~

3.4 Annual estimates of NEE, GPP and ER and associated uncertainties

From the various partitioning methods applied the DINGO output with the night time data approach using NN and u* filtered early evenings hours resulted in ER estimates most consistent with the soil respiration data – in terms of the relative contribution of soil respiration exceeding 1 was minimal (see supplementary material Fig. S2a). However, the day time approach partitioning method using the light response curve with the DINGO routine (3a) (Fig. S3a) yielded similar results followed by the night time approach using the Lloyd and Taylor temperature response function (1) when night time fluxes only were filtered after u* threshold (Fig. S1c). Overall coefficient of variation of annual estimates of ER derived from different partitioning methods ranged from 8 to 10% while variation of annual estimates of NEE and GPP were small (4-7% and 2-4%) (see supplementary materials Fig. S4, Table S2).

The forest was a considerable and continuous carbon sink during the three year study period with a mean NEE of -~~1062~~ 1234 ± ~~53~~ 109 g C m^{-2} yr^{-1}. Estimates of annual NEE increased from -~~976~~ 1046 g C m^{-2} yr^{-1} in 2010 to -~~1158~~ 1424 g C m^{-2} yr^{-1} in 2012 (Table 2). Estimates for ~~both~~ annual ~~GPP and~~ ER ~~increased between~~were similar for 2010 and 2011, whereas in 2012 annual ER decreased ~~and annual GPP was similar to that in 2011~~ (Table 2). Annual GPP estimates were slightly higher in 2010 compared to other years and similar for 2011 and 2012 (Table 2). ER was on average ~~58~~55% of GPP, but this ranged between ~~60~~61% (2010) and ~~55~~49% (2012) (Table 2).

4 Discussion

4.1 Seasonal variability of CO_2 ecosystem fluxes

Gross and net CO_2 ecosystem fluxes showed strong seasonality in this dry temperate eucalypt forest~~, and were mainly controlled by radiation and temperature~~. On a seasonal time scale, GPP exceeded ER almost continually, even in winter, thus NEE showed a net carbon uptake across all seasons. Daily minimum and maximum rates of ER, and daily minimum rates of GPP were within the reported range for temperate coniferous and temperate deciduous forests compiled by Falge et al. (2002). Although daily maximum GPP rate at our forest site (14.~~9~~ 7 g C m^{-2} d^{-1}) were comparable with those from temperate coniferous forests (16.6-26.3 g C m^{-2} d^{-1}), they were much lower than those reported for temperate deciduous forests (22.4-31.0 g C m^{-2} d^{-1}) during growing seasons (Falge et al., 2002). ~~This can be explained by differences in leaf longevity. Reich et al. (1997) showed that potential photosynthesis and leaf respiration increase in similar proportion with decreasing leaf life-span, increasing leaf nitrogen, and increasing specific leaf area. Hence, temperate deciduous forests maximize carbon uptake in their short lived foliage to compensate for having a shorter growing season compared with evergreen forest (Falge et al., 2002).~~

Both GPP and ER peaked during summer and were lowest in winter which is similarly typical for temperate evergreen *coniferous* forests (Baldocchi, 2008; Baldocchi and Valentini, 2004). However, during spring the increase in ER lagged behind that of GPP, an occurrence similarly typical for temperate *deciduous* forests (Baldocchi, 2008; Baldocchi and Valentini, 2004). Thus, NEE peaked in early spring and again in summer. ~~The~~ A likely explanation for the delayed increase in ER as compared to GPP in springtime ~~can be attributed~~could be a limitation of microbial decomposition due to lower temperatures ~~limiting microbial decomposition~~or substrate supply. Partitioning of soil respiration into its component fluxes of heterotrophic (microbial) and belowground autotrophic (plant) respiration in an earlier study (Hinko-Najera et al., 2015) showed that heterotrophic respiration was low during springtime but increased and peaked during (late) summer months corresponding to when total soil respiration fluxes were greatest (Hinko-Najera, 2016, unpublished) (Fig. S2a).~~, i.e. soil respiration (Hinko-Najera et al., 2015).~~ ~~This pattern was also in correspondence to the observed seasonal hysteresis of their respective major environmental controls temperature and radiation.~~ Similar seasonal variability in GPP and ER was observed in a wet temperate eucalypt forest, however, NEE peaked only during spring in this forest as GPP was limited by water

availability during dry summer period (Kilinc et al., 2013). These phenomena highlight that carbon exchange dynamics in this dry temperate eucalypt forest are different in their seasonal behaviour from temperate deciduous or coniferous forests in the Northern Hemisphere (Baldocchi, 2008; Baldocchi and Valentini, 2004; Falge et al., 2002), so the latter should not be used as analogues.

4.2 Environmental drivers of CO_2 ecosystem fluxes

As indicated above the overall main environmental drivers of NEE were radiation and temperature~~ and reflected the individual environmental controls of its gross fluxes GPP and ER~~. Incoming solar radiation was the ~~single~~ main environmental driver for ~~GPP~~ day time NEE at ~~half-hourly and~~ seasonal to inter-annual time scales throughout the three year study period whereas temporal variability in ~~ER~~ night time (early evening) NEE was ~~predominantly~~ mainly explained by air temperature. Interestingly, the Random Forest analyses revealed a strong seasonal variability of environmental controls on NEE.

~~During winter NEE was mostly explained by incoming solar radiation during winter due to a stronger limitation of GPP imposed by a combination of short days and cloudiness. The relative importance of radiation and air temperature were comparable in summer, indicating a stronger co-variation of NEE and ER during months when GPP was not radiation-limited.~~

Dry temperate eucalypt forests, like most of Australia's forests, are generally characterised by dry summer periods and thus are greatly influenced by changes in water availability (Haverd et al., 2013a). However, environmental drivers related to water availability such as VPD and SWC had only a ~~minor~~ small influence on ~~GPP~~ NEE fluxes during summer months and no effect at all on ER as shown by seasonal and inter-annual Random Forest Analyses. Thus, there was no apparent water limitation on carbon dynamics during our study period in this forest. This is in contrast with findings from Keith et al. (2012), van Gorsel et al. (2013) and Kilinc et al. (2013) for wet temperate eucalypt forests. In all these studies ecosystem carbon fluxes were limited by VPD and/or SWC during dry summer months with greatest effects on ~~GPP~~ day time NEE than ~~ER.~~ night time NEE. However this can be explained by the anomalously high rainfall at our forest site due to strong La Niña events from mid 2010 to early 2011 and early 2012 (BoM, 2012) during most of the study period. The lack of SWC influence on carbon fluxes until spring 2012 was also evident in concurrent studies on soil respiration dynamics at the same

study site where SWC did not decline below a certain threshold to be limiting soil respiration (Hinko-Najera et al., 2015) and Random Forest analyses revealed a notable increase of the importance of VPD and SWC on NEE in the~~ dry~~ ~~year~~ 2012, a drier year compared to preceding years.

4.3 Annual ~~C~~carbon balance and ~~inter-annual variability~~uncertainties

The dry temperate eucalypt forest was a very strong and continuous carbon sink for all three years. Our mean annual ER/GPP ratio (~0.~~58~~55) was lower than the mean ER/GPP ratio of 0.76 for Australian ecosystems (Beringer et al., 2016a), the 0.80 reported for temperate forests (Janssens et al., 2001; Luyssaert et al., 2007) and the 0.77 derived from a global data base (Baldocchi, 2008). Moreover, our annual estimates for NEE are greater than published estimates for forest ecosystems around the globe collated by Baldocchi et al. (2001) or Luyssaert et al. (2007), and at the upper end of the probability distribution for sites within the global FLUXNET network (Baldocchi, 2014). ~~Although accounted for during data processing and partitioning, the possibility of a remaining underestimation of ER cannot be excluded. (Bennett, 2016, unpublished)~~

~~Nonetheless, T~~~~t~~hat temperate eucalypt forests in Australia exhibit large carbon uptake~~ ability~~ has been shown in wet temperate eucalypt forests (>1000 mm annual rainfall) only recently.~~, such as a~~A tall old growth *E. regnans* forest had an NEE of~~(~~930 g C m^{-2} yr^{-1}~~)~~ (Beringer et al., 2016a).~~, also considered to be the world's most carbon dense forest (Keith et al., 2009b), and previously in a~~ A wet temperate ~~eucalypt~~ *E. delegatensis* forest near Tumbarumba (Keith et al., 2009a; 2012; van Gorsel et al., 2013)~~. That forest~~ was a strong sink of ~ 900 g C m^{-2} yr^{-1} during years with average annual rainfall (~ 1400 mm), but this sink was reduced (~ 750 g C m^{-2} yr^{-1}) during the above average rainfall (~ 2000-2200 mm) years of 2010 and 2011 (van Gorsel et al., 2013). Overcast conditions and thus reduced incoming solar radiation explained this reduced sink (van Gorsel et al., 2013). However, NEE estimates we report for our study site are higher than those reported from the Tumbarumba eucalypt forest during the same years of above average rainfall. A possible explanation for the greater net carbon uptake estimates in our dry temperate eucalypt forest might be the higher leaf area index (~ 1.8) (Griebel et al., 2016; Moore, 2011) than in the wet temperate eucalypt forest (~ 1.4) near Tumbarumba, conferring a higher canopy photosynthetic capacity. Our study supports the conclusion of Keith et al. (2009a) that temperate eucalypt forests have a high carbon uptake potential because they are evergreen~~, opportunistic~~ and as such photosynthetic carbon uptake can occur throughout the year

when conditions are favourable. Indeed, a detailed study of stem and canopy growth dynamics at our study site demonstrated that the trees are in fact growing all year, with canopy expansion observed mainly in summer and early autumn, and the stem growth mainly in spring and autumn, but also to a lesser degree in winter (Griebel et al., 2017).

Another possible explanation for the higher net carbon uptake estimates at our study site ~~compared to the Tumbarumba forest site~~ is the absence of summer dry periods and a stimulation of growth due to the high rainfall. Prior to the period of high rainfall in 2010-2012 forests throughout temperate Australia experienced a decade long drought that negatively affected NEE and NPP (Haverd et al., 2013b). Keith et al. (2012) and Kilinc et al. (2013) reported as well that drought conditions in the wet temperate eucalypt forest strongly reduced NEE by having a greater negative effect on GPP than ER. Therefore it is likely that the onset of high rainfall in winter/early spring 2010 ~~likely~~ led to favourable conditions for growth and high carbon uptake given the opportunistic behaviour of eucalypts to changing environmental conditions (Jacobs, 1955; Keith, 1997).

~~However,~~However, ~~-~~the possibility of a remaining underestimation of ER cannot be excluded although accounted for during data processing and partitioning and by the addition of storage term. We observed low night time fluxes of NEE, hence ER, which indicated a decoupling within the forest canopy and thus advection fluxes during night. Hence it is possible that the high NEE reported here are partly due to an underestimation of ER due to advection. However, such an error is likely to be a systematic one, meaning that an overestimation of NEE would have consistently occurred during the different measurement years and seasons. Results from a recent study to validate more recent annual NEP estimates with a biomass inventory (biomass increment and carbon content) indicated that the NEP estimates from the EC measurements were systematically 30% greater than the NPP of the tree biomass from inventory methods (Bennett, 2016, unpublished). It is a reasonable assumption that tree NPP contributed the majority to NEP and as such the inventory data would be a confirmation that the flux tower is underestimating ER, resulting in a greater NEE. However, the underestimation was indeed of a similar magnitude in each of the measurement years and confirmed the high carbon uptake rate of this dry temperate eucalypt forest when compared to other ecosystems.

Our data indicate that the main environmental controls (radiation and temperature) for GPP and ER did not vary between years~~, and as such inter-annual variability of both GPP and ER was small~~. ~~Regardless, w~~We observed moderate variations in

[NHN1]NEE amongst the three years, with an increase in NEE from 2010 through to 2012. The high rainfall in late 2010 and early 2011 most likely led to favourable forest growth conditions throughout 2011 and a stronger increase in GPP rather than ER and thus an increase in NEE from 2010 to 2011, most evident in autumn and winter. This 2011 increase in NEE is in accordance with the observed 2011 global sink anomaly (Haverd et al., 2013a; 2016; Poulter et al., 2014) which has been mainly attributed to semi-arid ecosystems in Australia (Eamus and Cleverly, 2015; Haverd et al., 2013a). Hence, our results indicate that the global sink anomaly was not only limited to semi-arid ecosystems. The further increase in ~~NEP~~ NEE from 2011 to 2012 was indicated by a reduction in ER as GPP remained steady. Rainfall was lower in 2012 as compared to the previous two years and hence, soil water content decreased towards the end of 2012 (summer) likely influencing ER but not GPP. Given that ER is often dominated by soil respiration, this pattern is in agreement with findings on soil respiration patterns from concurrent studies in the same forest (Hinko-Najera et al., 2015) where low soil water contents led to a decrease in soil respiration.

~~Nonetheless, longer monitoring will be needed to assess the net carbon sink strength of dry temperate eucalypt forests during years with average climate and under drought conditions, of which the latter is predicted to prolong and intensify (Christensen et al., 2013; CSIRO, 2012).~~

5 Conclusion

Temperate eucalypt forests are underrepresented in global assessments concerning terrestrial/ forest carbon dynamics and productivity (Baldocchi, 2008; Falge et al., 2002; Luyssaert et al., 2007) and so far no data has been available on ecosystem carbon exchange dynamics from dry temperate eucalypt forests. This study shows that not only wet temperate eucalypt forests but also dry temperate eucalypt forests have a large carbon uptake potential, particular during above average rainfall, and thus adds further evidence that temperate eucalypt forests are strong carbon sinks during favourable conditions (Keith et al., 2009a). Furthermore, carbon dynamics in this dry temperate eucalypt forest, similar to other temperate eucalypt forests, do differ in their seasonal behaviour compared to temperate coniferous and deciduous counterparts forest in the Northern Hemisphere. The evergreen nature of the trees, coupled with mild winter temperatures allow for ~~owing to the opportunistic response and~~ all year round physiological activity of eucalypts, which can lead to a continuous growth throughout the year.

When this is coupled with high rainfall in the warmer summer months it can lead to very large carbon uptake. However, long term measurements over multiple years are required to evaluate the net carbon sink strength of dry temperate eucalypt forests further particularly in years with drought conditions, a scenario predicted to increase in occurrence and intensify in south-eastern Australia (Christensen et al., 2013; CSIRO, 2012). Furthermore studies using alternative approaches, for example independent up-scaled ER estimates from component flux measurements (Keith et al., 2009a; Lavigne et al., 1997; Law et al., 1999; Phillips et al., 2010; Speckman et al., 2015) are needed to account for underestimation in ER due to advection fluxes and to validate measurements from EC flux tower.~~This study further demonstrates that seasonal and inter-annual variability in carbon uptake were not limited by temperature but predominantly driven by radiation whereas carbon loss from the forest was dominated and overall ecosystem carbon exchange dynamics were not water limited due to the high rainfall. Therefore, temperate eucalypt forests represent a unique forest type and should be considered separately in future classifications of ecosystems regarding their vegetation functional types and potential contribution to the global terrestrial sink strength. Our results provide the various global and continental carbon cycle and land surface model frameworks with necessary empirical data for parameterisation and model evaluation and hence contribute in reducing uncertainties in ecosystem feedback predictions to climate change.~~

Author contribution. N. Hinko-Najera, S.K. Arndt, S.J. Livesley and J. Beringer designed the experiment. Field work was primarily carried out by N. Hinko-Najera with help from I. McHugh and J. Beringer. Data preparation and analysis was primarily performed by N. Hinko-Najera with contribution from P. Isaac, C.Ewenz and I. McHugh (quality control), J. Beringer (DINGO), C.Ewenz and E. van Gorsel (partitioning), and J-F Exbrayat (random forest approach). N. Hinko-Najera prepared the manuscript with contributions from all co-authors.

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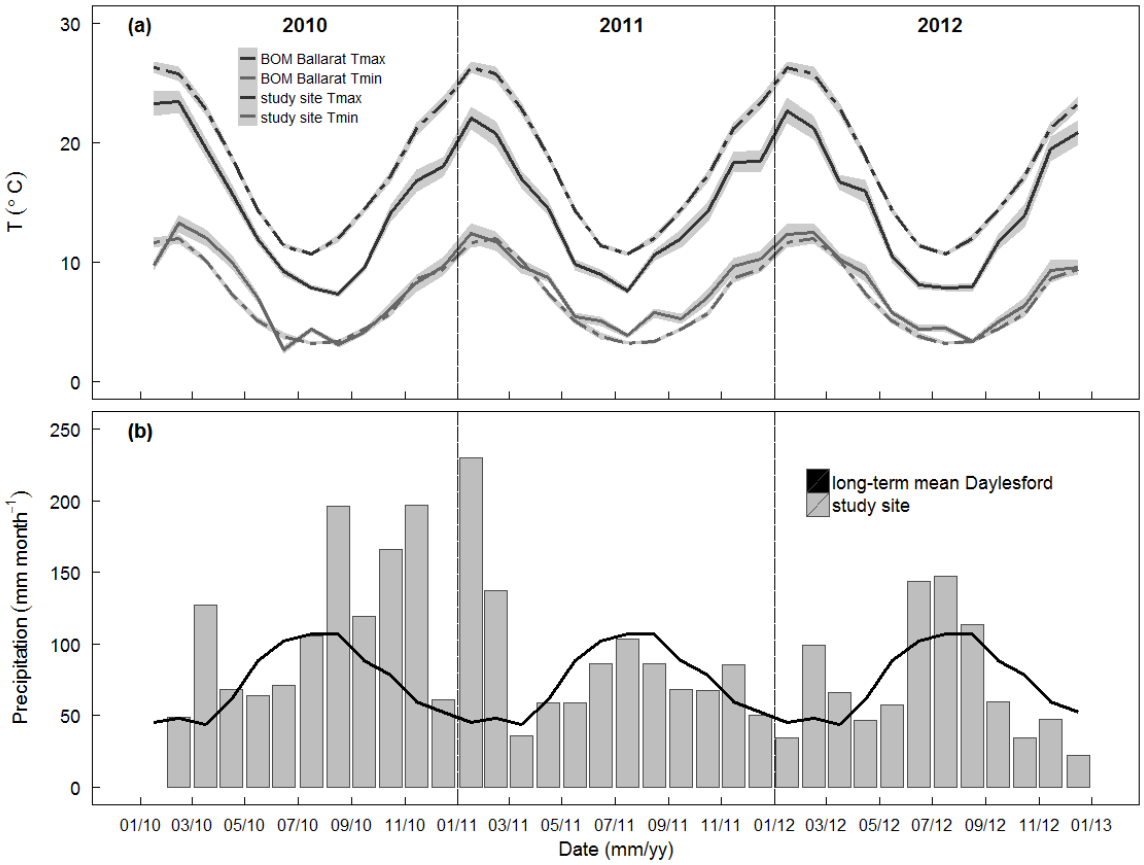

Figure 1: Climate time series of (a) monthly averages of minimum (grey lines) and maximum (black lines) air temperatures from the study site from 2010 to 2012 (solid lines) and from the BoM station Ballarat from 2001 to 2013 (dashed lines), shaded areas indicate ±1SE, and (b) monthly rainfall at Wombat State Forest OzFlux EC tower site from 2010 to 2012 (grey bars) and 114 year (1901-2014) long-term monthly mean rainfall at BoM station Daylesford (black line)

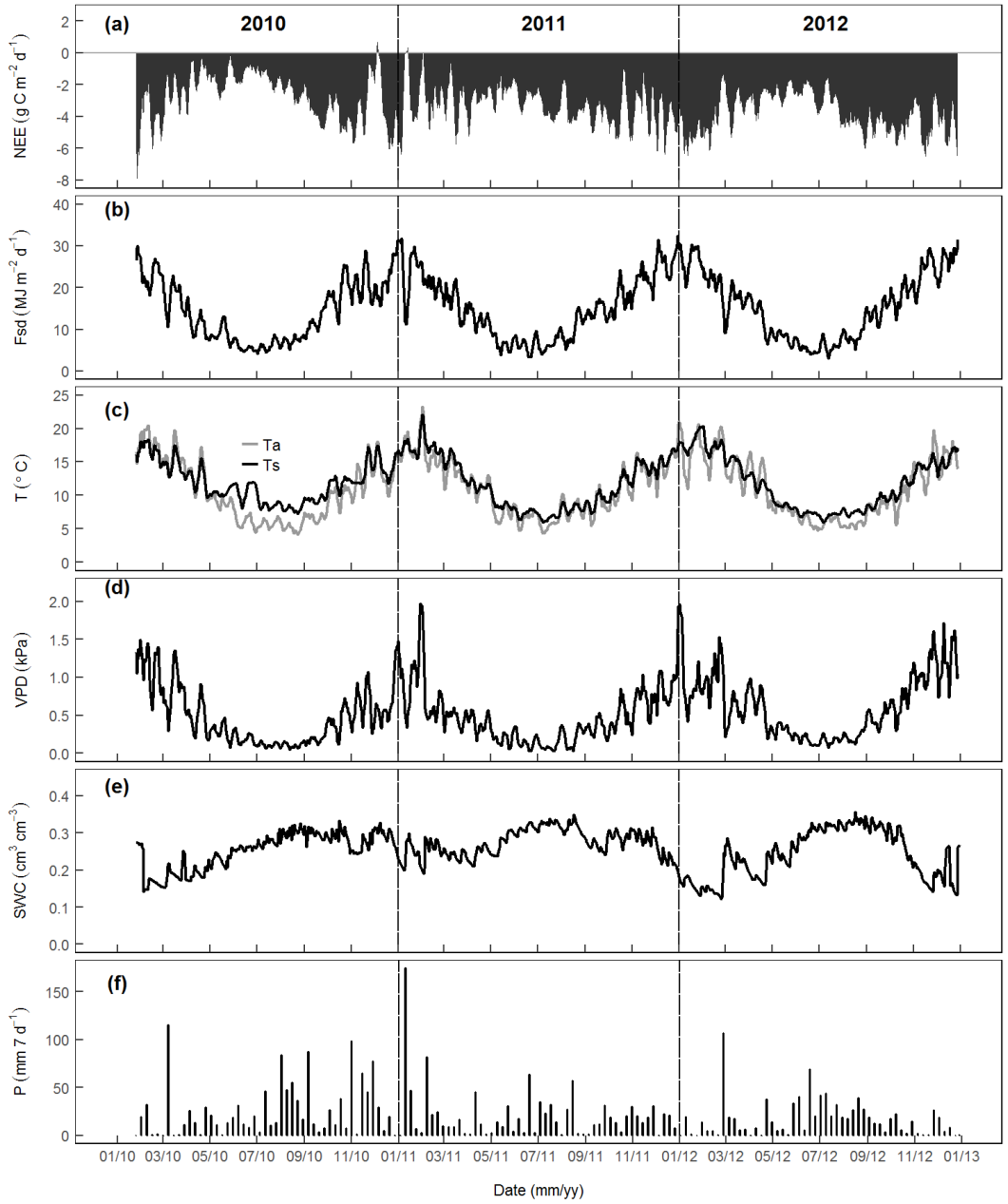

Figure 2: ~~Time series of daily (a) total net ecosystem exchange (-NEE), daily averages of (b) incoming solar radiation (Fsd), (c) air temperature (Ta) and soil temperature (Ts), (d) vapour pressure deficit (VPD), (e) volumetric soil water content (SWC) and (f) 7-day sums of rainfall (P) from 2010 to 2012; NEE, Fsd, Ta, Ts and VPD are displayed as 7-day running means for better illustration~~Time series of (a) 7-day running means of daily total net ecosystem exchange (NEE), 7-day running means of daily averages of (b) incoming solar radiation (Fsd), (c) air (Ta) and soil (Ts) temperature, and (d) 7-day running means of mean midday (11:00-13:00) vapour pressure deficit (VPD), (e) daily averages of volumetric soil water content (SWC) and (f) 7-day sums of rainfall (P) from 2010 to 2012

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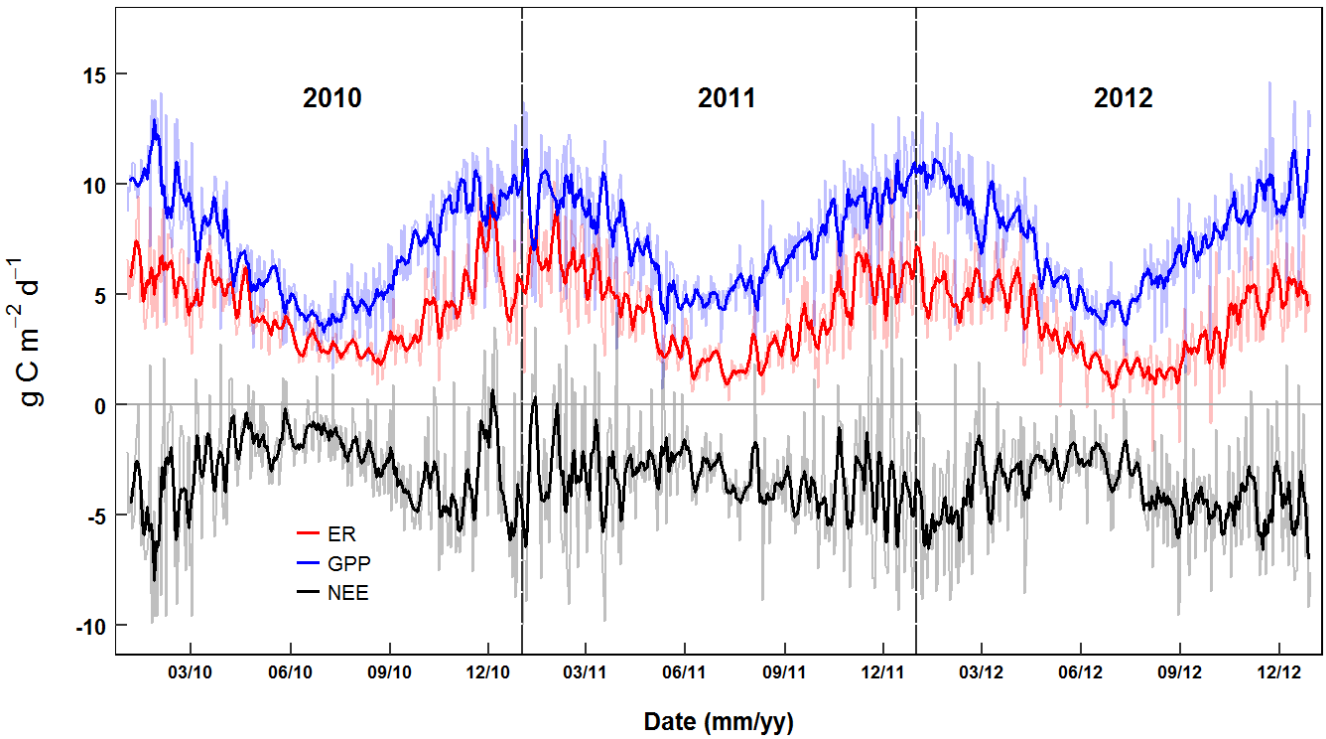

Figure 3: ~~**Daily total carbon fluxes of the Wombat State forest OzFlux site from 2010 to 2012: ecosystem respiration (ER, red lines), gross primary productivity (GPP, blue lines) and net ecosystem carbon exchange (NEE, black lines), 7-day running means (bold lines) are displayed for better illustration.**~~**Ecosystem carbon fluxes of the Wombat State forest OzFlux site from 2010 to 2012: ecosystem respiration (ER, red lines), gross primary productivity (GPP, blue lines) and net ecosystem carbon exchange (NEE, black lines), displayed is the output of DINGO partitioning method (2a) using the night time data approach with NN and early evening hours selection with daily totals (g C m^{-2} d^{-1}) of ecosystem carbon fluxes (shaded lines) and 7-day running means of daily totals (bold lines) for better illustration.**

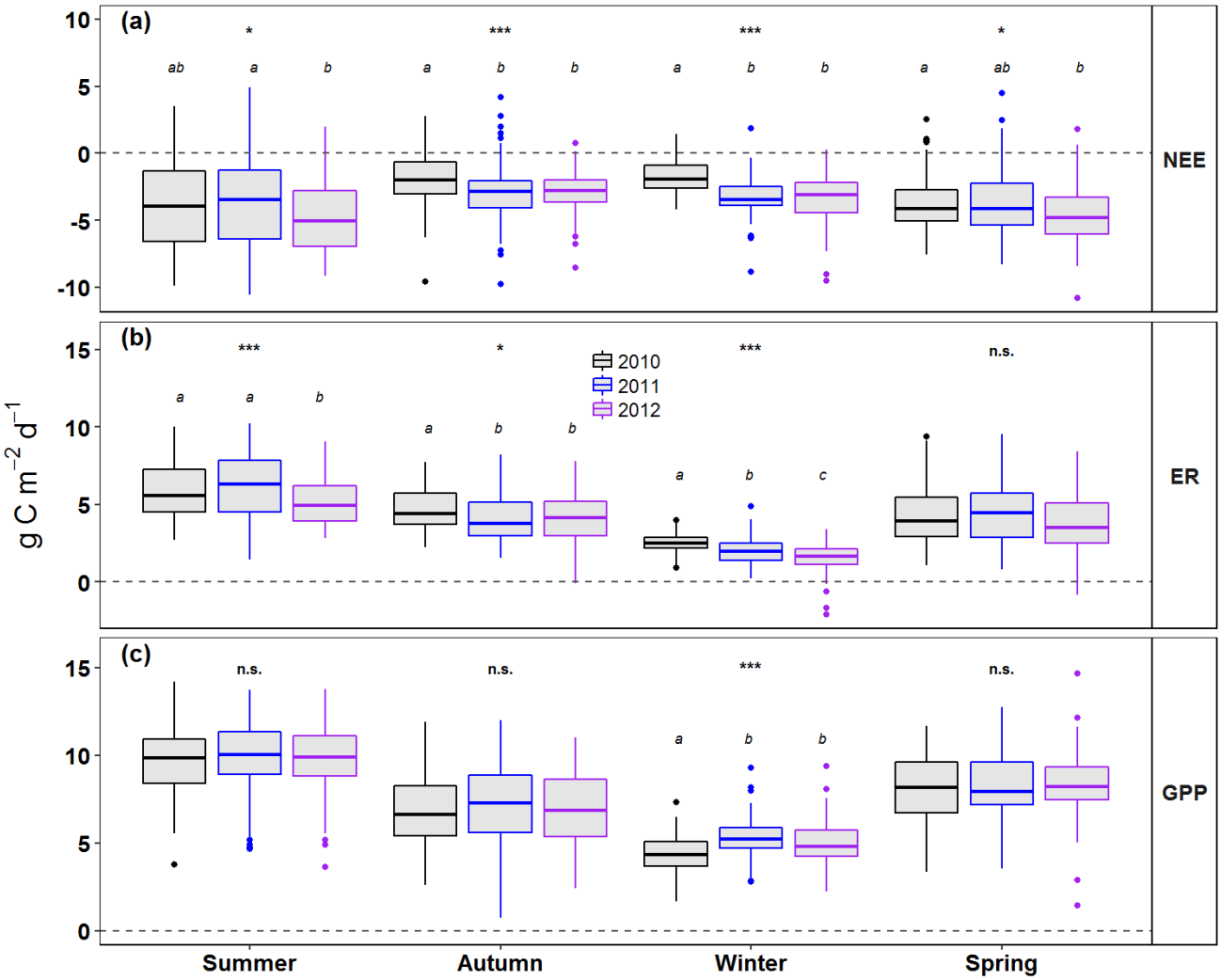

Figure 4: Box- and whisker plots of daily averages of a) -NEE, b) ER and c) GPP for years and seasons; inter-annual differences are displayed for each seasons with p-values (significance level p <0.05), letters indicate year to year differences

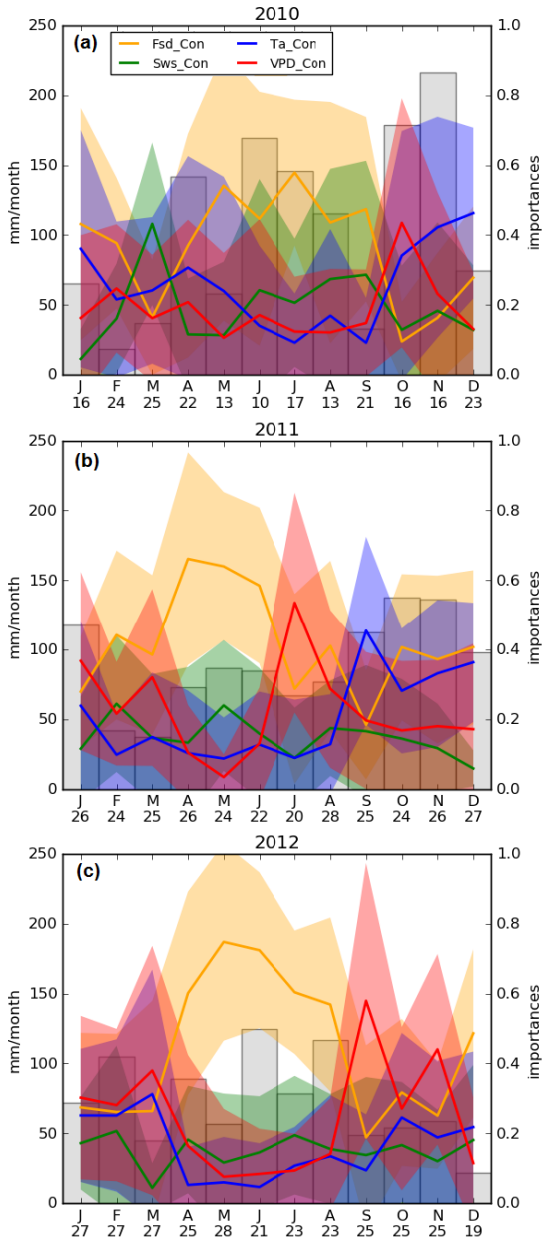

Figure 5: Seasonal importance of the environmental variables ~~incoming solar radiation (Fsd, yellow line), air temperature (Ta, blue line), vapour pressure deficit (VPD, red line) and volumetric soil water content (SWC, green line)~~ to explain variability in ~~gross primary productivity (GPP)~~daily averages of non gap-filled midday NEE (11:00-13:00) for (a) 2010, (b) 2011 and (c) 2012 ~~ecosystem respiration (ER) and net ecosystem carbon exchange (NEE)~~; environmental variables are: incoming solar radiation (Fsd, yellow line), air temperature (Ta, blue line), vapour pressure deficit (VPD, red line) and volumetric soil water content (SWC, green line) thick lines and shading represent the average ± 1 standard deviation of the importance across 1000 decision trees; grey bars indicate average monthly rainfall over the period 2010-2012.

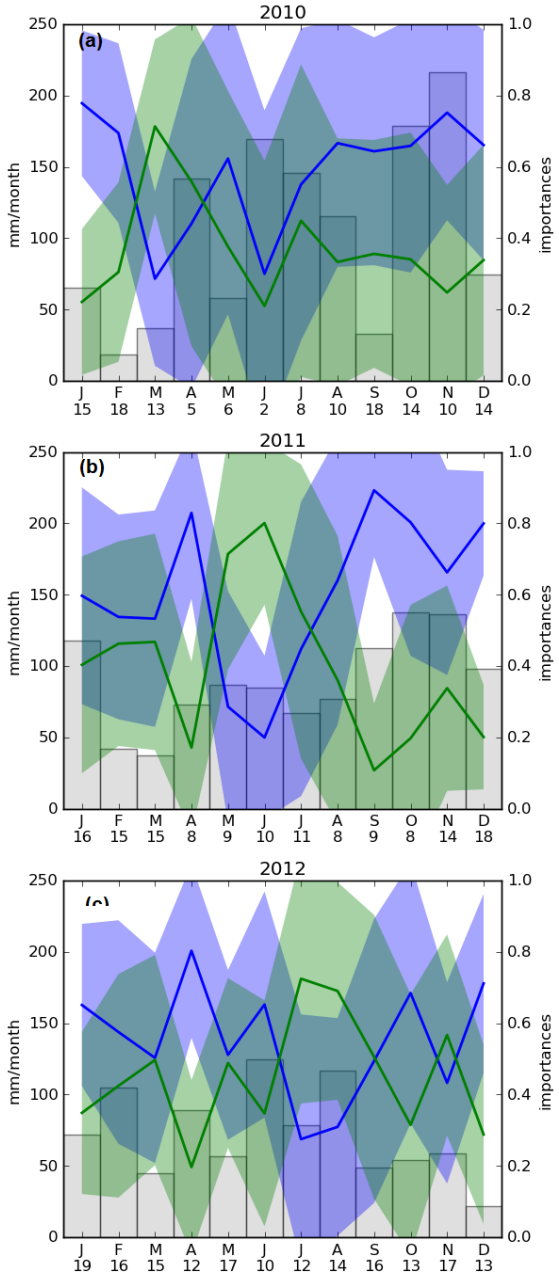

Figure 6:- **Seasonal** ~~**Annual**~~ **importance of the environmental variables** ~~**incoming solar radiation (Fsd, yellow line), air temperature (Ta, blue line), vapour pressure deficit (VPD, red line) and volumetric soil water content (SWC, green line)**~~**to explain variability in** ~~**gross primary productivity (GPP), ecosystem respiration (ER) and net ecosystem carbon exchange (NEE)**~~**daily averages of u* filtered night-time NEE (a) 2010, (b) 2011 and (c) 2012; environmental variables: air temperature (Ta, blue line) and volumetric soil water content (SWC, green line) thick lines and shading represent the average ± 1 standard deviation of the importance across 1000 decision trees; grey bars indicate annual precipitation over the period 2010-2012**~~**.**~~

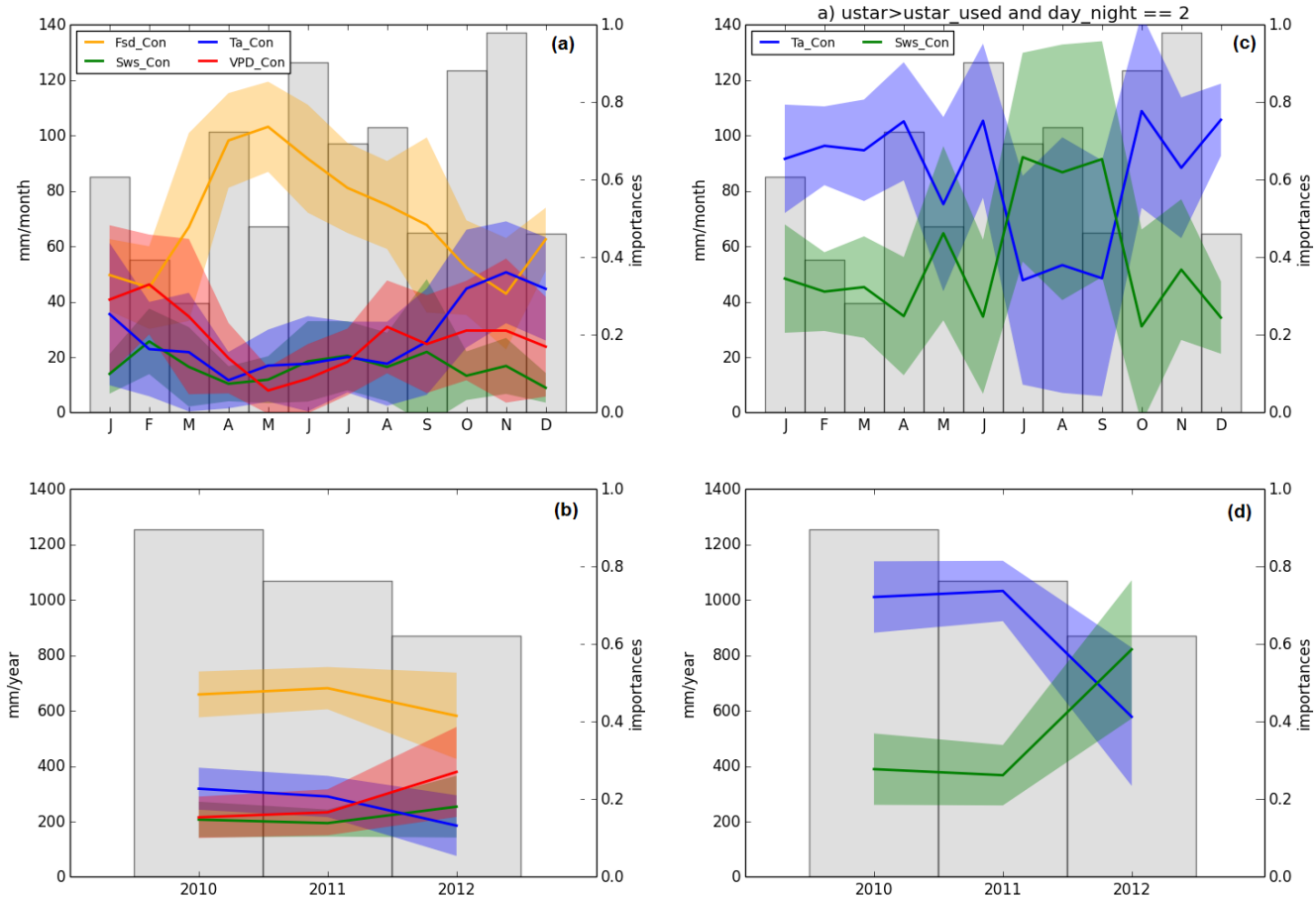

Figure 7: Seasonal (a, c) and inter-annual (b, d) importance of the environmental variables to explain variability in daily averages of non gap-filled midday NEE (11:00-13:00) (a,b) and u* filtered night-time NEE (c, d); environmental variables: incoming solar radiation (Fsd, yellow line), air temperature (Ta, blue line), vapour pressure deficit (VPD, red line) and volumetric soil water content (SWC, green line); thick lines and shading represent the average ± 1 standard deviation of the importance across 1000 decision trees; grey bars indicate annual precipitation over the period 2010-2012

Table 1: Site and tower characteristics for the Wombat State Forest OzFlux-site

Location	37° 25' S, 144° 05' E
Elevation a.s.l. (m)	706
Forest size (ha)	70 000
Tower height (m)	30
Canopy height (m)	22^~~25-27~~
Canopy species	*Eucalyptus obliqua*, *E. rubida*, *E. radiata*
Understorey species	*Pteridium esculentum*, *Tetrarrhena juncea*, *Poa sieberiana*, *Lomandra* spp.
Mean annual air temperature (°C)	11.0 ± 0.1
Mean annual rainfall (114 yrs, mm)#	879 ± 18
LAI (leaf area index m^2 m^{-2})	1.81*
Tree density (ha^{-1})	1316*
Tree dbh (cm)	18.6*
Litterfall (g m^{-2} yr^{-1})	1120 ± 52
Soil type	acidic-mottled, dystrophic, yellow Dermosol
Soil depth (cm)	50cm
pH	4.83 ± 0.02
Bulk density (0-10 cm, kg m^{-3})	0.94 ± 0.02
C/N	30.9 ± 0.5
Sand (%)	45.4 ± 1.8
Silt (%)	27.9 ± 1.9
Clay (%)	26.7 ± 0.4

where applicable: mean of n = 3 ± 1SE; # BoM station Daylesford, 11 km N of study site), ^ Griebel et al. (2015), * Moore (2011)

Table 2: Annual averages of incoming solar radiation (Fsd), air temperature (Ta), soil moisture content (SWC), vapour pressure deficit (VPD), annual sums of rainfall (P), net ecosystem productivity (NEE), ecosystem respiration (ER) and gross primary productivity (GPP) at the Wombat State Forest from 2010 to 2012; CV – coefficient of variation for inter-annual variation, inter-annual differences are indicated with * (p<0.001), ** (p<0.01) or *ns* (not significant), letters indicate year to year differences**

Year	Fsd (MJ m^{-2} d^{-1})	Ta (ºC)	Ts (ºC)	SWC (v/v)	VPD (kPa)	P (mm)	NEE (g C m^{-2})	ER (g C m^{-2})	GPP (g C m^{-2})
2010[a]	15.0	11.0	12.1	0.25*a*	0.36*a*	1254	-1046~~-976~~*a*	1603~~1475~~*a*-	2649~~2451~~
2011	15.3	11.1	11.8	0.27*b*	0.32*a*	1070	-1231~~-1053~~*a*~~*a*~~*b*	1534~~1502~~*a*-	2764~~2555~~
2012	15.8	11.1	11.8	0.24*a*	0.47*b*	872	-1424~~-1158~~*b*~~*b*~~*c*	1346~~1399~~*b*-	2770~~2557~~
CV (%)	2.5 *ns*	0.5 *ns*	1.2 *ns*	6.6 ***	20.0 ***	17.9	15.3~~8.6~~ ***~~*~~	8.9~~3.6~~ ***~~*ns*~~	2.5~~2.4~~ *ns*

[a] includes extrapolated values until 21st of January, estimates without extrapolation, i.e. 344 days:
P (mm): 1229, NEE (g C m^{-2}): ~~-896~~958, ER (g C m^{-2}): 1476~~346~~, GPP (g C m^{-2}): 2434~~243~~