Response to editor

Dear authors,
Thank you for carefully responding to all referee comments and for your proposed improvements to the manuscript. All referees see a great value in your work but also raised numerous points to address. I believe that if the referees comments are addressed adequately, as indicated in most of your responses, the paper will be indeed a valuable puzzle piece for understanding surface-atmosphere water exchange. In addition to the changes you proposed, could you consider the following?

Dear Stan, we appreciate your feedback.

1) Referee 1 critices that the mechanisms resulting in modelled NWL were not explained, while reference is made to an alleged under-estimation of nocturnal stomatal conductance in the models without going into details. Even though a detailed analysis of how NWL is simulated in the different models may be out of scope for this paper, it would be helpful if you provided NWL results for each model in addition to the multi-model mean values, or at least a ranking of the models, so that the readers could verify for themselves what might cause the spread in the simulations. The CMIP5 data does actually distinguish between water_evaporation_flux_from_soil, water_evaporation_flux_from_canopy and transpiration_flux, so you could at least verify what proportion of simulated NWL comes from transpiration as opposed to evaporation in the models. I think that this would be within the scope of the study, which is to provide a "general overview of NWL across the globe from observations and climate models".

We expanded the discussion about model discrepancies in the text indicating which models tend to have systematically high and low values of NWL, and also added Fig. S2 showing the ranking of all analyzed models.

We agree that it would be relevant and interesting to disentangle the different fluxes contributing to NWL in the models, however, these data are not available in the CMIP5 archive with a 3-hour temporal resolution. Therefore, we are not able to compute the contribution of the individual fluxes during the night.

2) The explanation of the process underlying NWL should include an energy balance consideration. You mention the influence of air temperature, VPD and wind speed on NWL, but what about sensible heat flux, soil heat flux (also soil temperature), and longwave radiation?

We modified Fig. 4 and expanded the corresponding text to also analyze correlations of NWL with the suggested variables.

3) Please make sure that all your responses to the referees are also reflected in the manuscript, as the referees' comments likely reflect your future readers' thoughts. For example, your response to Referee #1 that the data does not account for LE storage might also be an important information for the reader.

We appreciate the suggestion and modified the text accordingly.

4) I agree with Referee #1 that Figure 7 does not add much value to the paper and could be *removed, unless you would like to make a strong point that the models do not only disagree about the magnitude of NWLf but also its trend.*

We removed two panels from Fig. 7 and modified the text. We convey two main points about future projections of NWL: (i) NWL is projected to increase everywhere with an average of 1.8 %, although with a substantial inter-model spread. (ii) Changes in NWL contribute substantially to projected changes in total ET.

5) In your response to Referee #3, you propose that possible ecological advantages of NWL include capacitance refilling, embolism removal and hydraulic redistribution, among others. Hydraulic redistribution, capacitance refilling and embolism removal may explain nocturnal sap flow, but not water loss. The difference between sap flow and NWL sensed by EC towers should be emphasized more prominently throughout the text.

We now clarify that these possible advantages are for nocturnal sap flow, and not necessarily NWL. We modified the text to emphasize the difference between nocturnal sap flow and NWL.

6) Your response to Referee #3 about P7L1: It should be easy to verify if these sites include more gap-filled data than the average, and to mention this in the text.

We now include this information in the text.

7) Data availability and reproducibility of results: Thank you for providing the original lysimeter data. However, for your analysis to become reproducible, it would be important to also provide the scripts that were used to analyze both the Fluxnet and the CMIP5 data. In addition, when I opened the link given for the CMIP5 data, I had to click on CMIP5 in the list of data, create an account and eventually landed on a search page for data. Could you please provide accurate instructions on how to access the exact data you used for the study? Is there a specific search query that would take the reader to the right data? Same for the Fluxnet data: which 99 stations did you use, and which years of each station?

We updated our data availability statement to clarify these points about the specific FLUXNET and CMIP5 data used in the study. Reproducibility of the analysis should be feasible based on the information provided in the manuscript. No software or model code was developed. We do not consider relevant to provide several customized scripts for data selection and manipulation, e.g. computing climatologies, plotting, or computing correlations.

List of main changes to the manuscript

- The introduction was rewritten, including the addition of Table 1 summarizing results from previous studies.
- Addition of uncertainty estimates for the FLUXNET observations of NWL: Changes to text and Fig. 2.
- Addition of temperature, radiation, sensible and ground heat flux to the analysis of factors influencing NWL in Fig. 4.
- Addition of one paragraph about model discrepancies in NWL and Fig. 7 (previously Fig. S2) showing the relation between model differences in NWL and model differences in nocturnal temperature.

Response to reviewers

The initial point-by-point response to the reviewers during the interactive discussion is included below.

Reviewer 1:

The overall focus of this paper is interesting; nocturnal evapotranspiration is an under-appreciated part of the hydrologic cycle that represents water loss without accompanying carbon gain (something that many resource managers might like to avoid). Thus, the result showing that nocturnal water loss (or NWL) represents a significant fraction of total ET across a wide range of biomes is likely of interest to a wide audience. The comparison of observed and modeled NWL rates is interesting in that, while the total magnitude of NWL is relatively similar between data and models (6.3 versus 7.9%), the relationship between modeled and observed NWL rates is virtually non-existing across sites (e.g. Fig 8a). This suggests some process-level room for improvement in the models.

We appreciate the positive opinion about the relevance of our manuscript.

Overall, I found that the study was largely exploratory; the mechanistic explanations were limited to a simple spearman correlation analysis (e.g. Fig 4) of observations, and little discussion of how mechanistic representation of key processes in the models might affect the inter-model variability. While purely objective-oriented exploration of network level data can be useful, at the same time, better closing the gap between observations and models requires that underlying mechanisms be understood and carefully linked.

Towards that end, I have a few suggestions below for enhancing the mechanistic perspective of the paper that could ultimately leave the reader with a better understanding of not only how much water is lost at night, but also why this happens at different rates across ecosystems and models.

1. Much of the introduction reads like a list of previously published papers on the topic. While it is important to acknowledge this prior work, it would also be quite helpful to review for the reader the various mechanisms that could contribute to high NWL (e.g. not only incomplete stomatal closure, but also non-negligible cuticular conductance, and nocturnal evaporation from soils and canopies, snow sublimation). From there, it may even be possible to craft some expectations about in which ecosystems, and when, NWL should be especially prominent in the observations.

The introduction is modified and extended according to the suggestion.

2. Likewise, some discussion about how the different models treat relevant processes and parameters could allow for a more informed understanding of why they differ so widely in their estimation of NWL. The authors suggest that most of the models employ the Ball-Berry stomatal conductance model (e.g. Page 2 Line 23). . . Is this true for the models studied here, and do they adopt similar formulations for the intercept of this model? Knowing precisely how these models treat nocturnal conductance would go a long way towards understanding if the cross-model differences are linked to model ecophysiological representation.

We completely agree. We expanded the discussion on factors affecting inter-model variability and introduced a new figure (previously Fig. S2 in the Supporting Information). Yes, we note that most of the analyzed climate models' stomatal conductance formulations are based on the Ball-Berry model. Note that the complexity of CMIP5 models, and the fact that not all models are equally well documented, hinders a simple explanation of inter-model variability. In addition to how individual models represent nocturnal conductance, other factors such as planetary boundary evolution and soil parameterizations might also influence the inter-model variability. Thus, we consider this more detailed analysis to be outside the scope of our study, but nonetheless an interesting topic for a follow-up article.

3. Related to (2), I found it quite interesting that model differences were related to near surface temperature (page 12, line 6); unfortunately, this result is buried in the SI. I would urge the authors to bring this result into the main text, and also expand the discussion about why this correlation exists.

We appreciate the suggestion. We now include this as Figure 7 in the revised manuscript and expanded the discussion.

4. The mechanistic analysis of the data is limited to correlations between NWL rates and VPD, wind speed, and soil moisture. I agree that these are important drivers of ET. However, even though incident solar radiation is zero at night, energy is still required to drive ET at night. The paper would strongly benefit from a discussion of where this energy comes from, which would require consideration of sensible and ground heat fluxes. . . and thus provide additional mechanistic insight.

We appreciate the suggestion. We now include in Fig. 4 also the relation of NWL with net radiation, downward longwave radiation, sensible and ground heat flux. We additionally expanded the discussion accordingly.

I also had a few concerns about the treatment of the flux data.

1. The analysis relies on datasets that are largely gapfilled. While gapfilled data are necessary for estimating annual sums, they are not required for exploring relationships between ET observations and meteorological drivers. Can the authors repeat the analysis for Figure 4, but using only data that pass the quality control test?

This was already the case for Figure 4. We now clarify this in the text and figure caption.

2. The flux observations have been corrected so that the energy budget is fully closed. This correction is quite controversial in the flux community, especially since the mechanisms causing the lack of energy balance closure are still not fully known (and at least one school of thought suggests that much of the problem could be linked to sensible heat flux). Thus, I urge the authors to repeat the analysis without the energy balance correction, and include a summary of those results (at least in the SI).

We appreciate the insights. We now include this also in the manuscript and provide more information on the uncertainty of the EC fluxes. See modified version of Fig. 2 and corresponding changes to the text.

A few other comments:

Page 1, Lines 15-20. Much of the first paragraph is not well written. It states that ET is an important process but does not tell us specifically why we should be concerned about NWL specifically. Moreover, the logic is not clear: the authors tell us that VPD, temperature and wind speed affect ET, and that half of the diurnal cycle is night, therefore NWL can be important. This conclusion does not follow from the premise (missing is a discussion about the prevalence of VPD, temperature and wind speed conditions that could generate substantial nocturnal ET).

We reformulated the paragraph.

Page 3, Lines 1-5: This paragraph, which discusses the overall objective of the study, is quite short and lacks detail. Here would be an excellent place to discuss some expectations as to how NWL relates to "different meteorological and land cover conditions." The model-data comparison should also be mentioned here, and perhaps expectations offered as to which models are best equipped to accurately describe NWL patterns.

We reformulated and expanded the paragraph. In addition, note that our study follows an exploratory approach rather than specific hypothesis testing, which is why we do not provide any assumptions besides the known influence of abiotic factors like temperature, VPD and wind speed on evaporation/sublimation from the soil or canopy.

Section 2.1.2: Are the Fluxnet2015 data corrected for LE storage terms at night? Is this important?

The relevant data processing is described in the text and the referenced FLUXNET website. To our knowledge the FLUXNET2015 data does not account for LE storage in the air between the ground and measurement level.

Page 7, Line 4: The relationship between VPD and NWL may not be linear if stomatal conductance decreases when VPD is high, even at night.

We now also explicitly mention this in the text.

Page 11, lines 20: The discussion of nocturnal stomatal conductance here is interesting; it strikes me as a bit of a missed opportunity not to explore patterns of nocturnal surface conductance from the data (it is relatively straightforward to invert flux tower ET measurements with the Penman-Monteith equation to obtain half-hourly surface conductance, e.g. see Wever et al. 2002 https://doi.org/10.1016/S0168-1923(02)00041- 2). Doing so would illuminate whether cross-site differences in NWL are driven largely by biotic versus abiotic factors.

We find this suggestion very interesting and an excellent idea for a more specific study on surface conductance. Our main goal here is to provide a first more general overview of NWL across the globe from observations and climate models.

Figure 7: Considering that the models and data don't agree at all on the site level, can we really have much confidence in these future projections?

The inter-model variability of future NWL_f *projections is indeed large as shown in Fig. 7d and acknowledged on page 9 lines 10–12. Future studies could aim at reducing inter-model spread and constraining future projections.*

Reviewer 2:

Padrón and others analyze nocturnal evapotranspiration measurements from eddy covariance and estimates from models. The analysis is interesting and certainly novel although a few methodological points need to be reconsidered in my opinion, and the text could be improved in multiple instances.

We appreciate the positive opinion about the relevance of our manuscript.

Sentences like 'Lombardozzi et al. (2017) compiled evidence of this from 204 species' aren't particularly instructive. What did they find? In the paragraph at the bottom of page 1 try to make the scientific findings, not the authors, the subject of the sentences. For a discussion of this see https://schimelwritingscience.wordpress.com and the associated book.

We appreciate the suggestion. We modified the text to improve the focus and readability.

A more powerful way to synthesize the literature, which would make the present manuscript more citable, would be to synthesize existing studies in a table to help further motivate the present analysis and be more comprehensive.

We appreciate the suggestion. We now introduce Table 1 in the revised manuscript to summarize nocturnal water loss estimates from the literature.

The points about dew and hoar frost are great.

Thank you.

P 2 line 22: disentangle aerodynamic vs. surface conductances more clearly. The surface has both stomatal and boundary-layer resistances.

We clarified this. We now provide a more complete description of the resistances included in models to compute latent heat flux.

2.1.1: Why is the 10 W m-2 threshold used to differentiate between day and night? Sensors have uncertainty but the solar zenith angle can be calculated with extreme accuracy for environmental science applications. Are results sensitive to the 10 W m-2 threshold? I see that a zenith angle-based analysis is done in section 2.1.2 (sun up and sun down). Why are different approaches used? What are the 'cases described by Hirschi et al. (2017)'?

Here we use this simple threshold because the focus is on the comparison of the lysimeter and EC data, and we wanted to be consistent with the comparison from Hirschi et al. (2017). The results are hardly sensitive to the 10 $W\ m^{-2}$ *threshold.*

We extended the sentence to clarify the meaning of 'cases described by Hirschi et al. (2017)'. It corresponds to cases when the tower is upwind of the sensor and thus disturbing the air flow.

P 3 line 30: using a static value for the latent heat of vaporization is fine, but it's easy to add its temperature sensitivity to add a bit more accuracy in the latent heat to water flux conversion.

Yes, we are aware of this, but for simplicity and to avoid dealing with possible missing temperature data, we assume a value of λ corresponding to a temperature of approximately 12 °C. We trade simplicity for a very small loss in accuracy. In addition, note that we do not incur in a highly biased error, given that temperatures are likely to be sometimes greater and sometimes less than 12 °C.

2.1.2: The Bowen-ratio-based assumption is a bit problematic; there is extensive evidence that undermeasured sensible heat flux from large eddies plays a large role in lack of energy balance closure. That being said, these factors are less important at night where low-level jets and decoupling of the eddy covariance sensors and the canopy often dominate.

We appreciate the insight. We now analyze the uncertainty of NWL estimates with and without the Bowen ratio assumption in Fig. 2.

2.1.2: instead of emphasizing caution, perhaps don't use gap-filled fluxes for the analysis. This is a hard thing to do at night when eddy covariance data are often less reliable than many people believe.

Gap-filled fluxes are required in order to obtain the total NWL estimates shown in Fig. 2. An alternative would be to estimate a mean hourly NWL rate from the non-gap-filled observations and obtain total sums by multiplying the mean by the total number of nighttime hours. However, this has its own disadvantages. Nonetheless results are rather similar with both options.

When analyzing the correlation of NWL with environmental conditions in Fig. 4 we do not employ gap-filled data.

Thinking broadly, is 'nocturnal water flux' better than NWL given that water can be both lost and gained (but is admittedly a net loss over the time scales mostly investigated here).

In a first draft we also used nocturnal water flux but decided that NWL is more appropriate to communicate our results.

3.1: why is the second threshold chosen? Is it appropriate for the site or just simply half of the previous threshold?

In this case is just half of the defined threshold value to provide an estimate of the sensitivity. We revised the text to make this clearer.

Fig. 2 and elsewhere: what are representative uncertainties of the site-level NWL measurements/estimates?

Figure 2 now also includes uncertainties of NWL estimates from FLUXNET sites. The text accompanying the analysis was modified to convey this point more clearly.

This statement should be in the Methods: "These annual mean values are computed from monthly climatologies obtained by omitting months with half or more of missing latent heat flux data."

Note that there is no specific "Methods" section in the structure of our manuscript. We thus think the location of the statement is appropriate.

In general, the assumptions made in the flux processing for NWL for the FLUXNET2015 database needs to be explained in more detail.

We expanded the text. Note also that a full description of the processing is provided at https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/data-processing/, as indicated in the text.

The statement 'Nonetheless, deciduous broadleaf forests (DBF) have an overall lower NWLf, whereas evergreen needleleaf forests (ENF) include most cases with higher NWLf' suggests to me that perhaps difficulties in measuring the surface-atmosphere flux is partly responsible here. ENF needles are more closely coupled to the atmosphere on account of their smaller dimensions and I can't think of a discernable reason why DBF would have particularly low NWL. Although perhaps relative NWL given that they are frequently found in mesic regions.

We appreciate the insight and now include it in the text. Note that cross correlations and confounding factors might also be relevant.

Figure 4 is tricky to look at. I'm curious to know if there is a more logical way of presenting these complex data.

We increased the size of the symbol representing the mean to convey the main message. We expect that the text also helps to understand the Figure.

The analysis of models is interesting, and the degree of discrepancy is surprising.

Thank you.

Reviewer 3:

The paper is handling an important topic in ecohydrology – the nocturnal water loss of ecosystems.

We appreciate the positive opinion on the relevance of the manuscript.

The tools used in comparison are appropriate but not convincingly comprehensive. The processes that might cause differences in derived NWL between EC measurements and modelled data should be investigated more thoroughly by diving e.g. into variable footprints, processes handled in the models, gap-filling problems for ET from EC during night, and general night-time problems present in EC data.

We expanded our discussion of these points. Note that differences between EC and modelled data are expected due to the stark difference in spatial resolution. This was mentioned on page 10 lines 6–7, and now also in the introduction of the revised manuscript.

I clearly would desire uncertainty estimates for NWL especially as we are dealing with very low fluxes. Fortunately, NWL can only take place under well mixed conditions which gives trust in the nocturnal EC data used for the analysis. But we have to consider that ET (measurements and post-processing) has unfortunately hardly been the main focus of the FLUXNET data set. So, we should be aware that so far, we do not have well established gap filling procedures for ET at night, especially under stable conditions. Thus, the paper lacks uncertainty estimates for the nocturnal fluxes determined by EC.

We appreciate the insight. We acknowledge the difficulties to adequately measure latent heat flux during the night with EC systems, as mentioned on page 4, lines 12–16. The relatively good agreement of NWL climatology from EC and lysimeter data suggests that meaningful estimates can be obtained with EC measurements.

We now include some uncertainty estimates of EC NWL in Figure 2, based also on comments from the other reviewers.

Specific comments: Introduction: What are the processes causing nocturnal water loss? Which kind of energy is converted into ET at night? And why is it so important to deal with? It should be mentioned that a water loss is accepted (during day-time) by gaining carbon. Is there any advantage for the plants or the ecosystem to lose water at night? Or just no possibility to avoid? The authors mainly summarize previous work here.

We expanded the introduction to include the suggested points. It now includes the following statements: "Nocturnal water loss may occur as evaporation from soil and canopy, snow sublimation, or plant transpiration through stomatal and cuticular conductance. It is also recognized that vapor pressure deficit, temperature, wind speed, longwave radiation and surface resistance influence nocturnal ET (Monteith, 1965; Penman, 1948)" and "Possible advantages of nocturnal sap flow include capacitance refilling, embolism removal, nutrient uptake, hydraulic redistribution and oxygen supply (Zeppel et al., 2014), whereas it remains unclear if Tr with no associated carbon gain has any benefits for vegetation or is simply unavoidable".

Page 2, Line 18/19: 'Both ET and dew correspond to a latent heat flux and can prove difficult to disentangle depending on the temporal resolution of the data.' These fluxes are in opposite direction, even if the net ET might comprise a combination of both, for energetic reasons these processes hardly occur simultaneously. Could you describe more clearly what exactly is meant?

We reformulated the sentence to clarify this. We agree that it is likely that they do not occur simultaneously, but they are likely to co-occur during e.g. the 3-hour temporal resolution of the modelled data. Thus, for simplicity and conciseness, we focus on the net flux.

Page 3, Line 21: if weight increase without rain measured is considered as rain or snow, we have to ask how reliable are the rain measurements? Or otherwise you should provide any further explanation for the procedure. And maybe the frequency of occurrence or the amount of water switched from dew to rain.

We include one additional explanatory sentence. It is possible that because of the 0.1 mm resolution of the rain gauge, no precipitation is recorded, while the lysimeter mass increases.

Also, dew formation might be more favored to occur over vegetation than rain gauges. Moreover, it is also possible that the registered weight increase was due to something different than water input, e.g. a bird. In any case, the frequency is ~4 % of the hourly intervals when the dew was estimated, and the amount is ~4 mm yr^{-1}.

Page 3, Line 27ff: we have to consider that ET has never been the main focus of the FLUXNET data set. This statement should not imply that all ET data from FLUXNET are less reliable. But we should be aware that so far, we do not have well established gap filling for ET at night, especially under stable conditions. Fortunately, NWL can only take place under well mixed conditions which gives trust in the nocturnal EC data used for the analysis. Most probably the majority of the data used for the analysis were measured anyway. But it would be quite interesting to see the relation of measured and gap-filled data used for the data-analysis, not only for the Rietholzbach site but also for the FLUXNET analysis. This information gives also a hint related to the uncertainty of the derived nocturnal fluxes.

We appreciate the insights. As indicated in the text, on average across all analyzed FLUXNET sites, latent heat flux is measured in 60 % of all nighttime intervals, whereas gap-filling is required in the remaining 40 %.

An alternative to gap-filled fluxes would be to estimate a mean hourly NWL rate from the non-gap-filled observations and obtain total sums by multiplying the mean by the total number of nighttime hours. However, this has its own disadvantages. In any case, results are rather similar with both options.

Page 4, Line 8: for night-time data?

We expanded the text. The energy balance correction is applied to both daytime and nighttime data. It uses only half hours with timestamps between 22:00–02:30 and 10:00–14:30. See full details at https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/data-processing/

Page 4, Line 14-15: move this sentence to the acknowledgements, even though appreciated by myself.

Ok.

Page 5, Lines 4ff: this section should be improved by quantitative uncertainty values.

We expanded the text and modified Fig. 2 to include information about the uncertainty of the NWL estimates from the FLUXNET data.

Page 6, Line 14: '. . .across sites cannot easily be explained by annual average. . ..'

We modified the text.

Page 7, Line 1: can you be sure that EC data are reliable under 'snowy and windy conditions'? EC assumption might not be fulfilled, sonic data are often disturbed under such conditions.

Our intention here is to point out that conditions at these specific sites are in general snowier and windier than at other sites. We expanded the text to clarify and address this concern.

Page 10, lines 1ff: for EC estimates no uncertainty is considered. How large are the uncertainties related to the fluxes under consideration?

We now include uncertainty information within Figure 2 and the corresponding text.

Page 11, lines 5ff: here it is correctly said that nocturnal measurements can be affected by low turbulence conditions. But nocturnal fluxes are not treated by the energy-balance correction, as also correctly said before. In the discussion part, also the uncertainty of EC data should be discussed.

We now also refer to the uncertainty of NWL from EC data here.

Figure 1, caption: should include the site name.

We added the site name to the caption.

Figure 2: caption to be extended. What exactly is show? Always consider that reader often concentrate on the figures of a paper only and thus need more information. In addition, in c), the colors of the tiny dots are difficult to distinguish with normal page size. But I also fear, this is not a 'spatial distribution' but rather a 'distribution of sites with . . ..'

We modified Figure 2 and the caption as well.

Terrestrial Water Loss at Night: Global Relevance from Observations and Climate Models

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Abstract. Nocturnal water loss (NWL) from the surface into the atmosphere is often overlooked because of the absence of solar radiation to drive evapotranspiration and the measuring difficulties involved. However, growing evidence suggests that NWL – and particularly nocturnal transpiration – represents a considerable fraction of the daily values. Here we provide a global overview of the characteristics of NWL based on latent heat flux estimates from the FLUXNET2015 dataset, as well as from simulations of global climate models. Eddy-covariance measurements at 99 sites indicate that on average NWL represents 6.3 % of total evapotranspiration. There are six sites where NWL is higher than 15 %; these are mountain forests with considerable NWL during winter related to snowy and windy conditions. Higher temperature, vapor pressure deficit, wind speed, soil moisture and downward longwave radiation are related to higher NWL, although this is not consistent across all sites. On the other hand, the global multi-model mean of terrestrial NWL is 7.9 % of total evapotranspiration. The spread of the model ensemble, however, is greater than 15.8 % over half of the land grid cells. Finally, NWL is projected to increase everywhere with an average of 1.8 %, although with a substantial inter-model spread. Changes in NWL contribute substantially to projected changes in total ET. Overall, this study highlights the relevance of water loss during the night and opens avenues to explore its influence on the water cycle and the climate system under present and future conditions.

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1 Introduction

Water is lost from the surface to the atmosphere through evapotranspiration (ET). This process interlinks the water, energy and carbon cycles, and hence influences climate, ecology, agriculture, and economy (e.g. Betts et al., 1996; Fisher et al., 2017; Zhang et al., 2015). Although daytime ET, mainly driven by solar radiation, represents the majority of the contribution to total water loss, nighttime ET is likely non negligible. Nocturnal water loss may occur as evaporation from soil and canopy, snow sublimation, or plant transpiration through stomatal and cuticular conductance. It is also recognized that vapor pressure deficit, temperature, wind speed, longwave radiation and surface resistance influence nocturnal ET (Monteith, 1965; Penman, 1948). The prevalence of nocturnal water loss and its significance for the surface water and energy balance, however, remains overlooked and unclear.

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In recent years there has been a growing body of evidence about the occurrence of nocturnal ET, with a specific focus on transpiration (Tr). Observations of nocturnal stomatal conductance across hundreds of species have challenged the assumption of stomatal closure in the absence of photosynthetically active radiation (e.g. Daley and Phillips, 2006; Dawson et al., 2007; Lombardozzi et al. 2017; Snyder et al., 2003). Possible advantages of nocturnal sap flow include capacitance refilling, embolism removal, nutrient uptake, hydraulic redistribution and oxygen supply (Zeppel et al., 2014), whereas it remains unclear if Tr with no associated carbon gain has any benefits for vegetation or is simply unavoidable. Total water loss through ET, however, is more relevant than Tr from a water balance perspective since it additionally includes evaporation or snow sublimation from the ground and canopy. Nocturnal ET can be measured with lysimeters or eddy-covariance (EC) flux systems. A summary of previously reported nocturnal water loss estimates of both Tr and ET is provided in Table 1.

Table 1. Nocturnal transpiration (Tr) and evapotranspiration estimates (ET) reported in the literature.

Nocturnal water loss	Measurement type	Vegetation type	Setup	Location	Reference
Tr (rate): 5–15 % of daytime rates typically, max: 30 %	Porometer, gas exchange, sap flow, lysimeter	Multiple C_3 and C_4 species	Field, lab, growth chamber, greenhouse	Multiple	Caird et al. (2007)
Tr: 10–25 % of total	Estimate from published literature	Typical plant functional types	Not available	Not available	Zeppel et al. (2014)
ET (annual): 3.5–9.5 % of daytime total	Lysimeter	Grass (plus shrub and moss)	Field	Western Germany	Groh et al. (2019)
ET: 12–23 % of daytime total	Lysimeter	Bean and cotton row-crops	Ecotron: controlled conditions	Montpellier (France)	de Dios et al. (2015)
ET: 6 % of total	Eddy-covariance	Oak - grass savanna	Field	California (US)	Fisher et al. (2007)
ET: 1 % of total	Eddy-covariance	Pinus Ponderosa forest	Field	California (US)	Fisher et al. (2007)
ET: 8–9 % of daytime total	Eddy-covariance	Grass field, Pine plantation, and hardwood forest	Field	Co-located sites in North Carolina (US)	Novick et al. (2009)

Water is not only lost from the surface during night, but it can also be gained by dew formation. For example, dew and hoar frost amounts to 4.2–6.4 % of annual precipitation in three humid grass sites in Austria and Germany (Groh et al., 2018, 2019), and was found to occur in approximately 30 % of the nights in a forest in central Colorado (Berkelhammer et al., 2013) and 70 % of the nights in a grassland in the Netherlands (Jacobs et al., 2006). ET and dew formation correspond to a latent heat flux and might both occur for example within an hour, proving difficult to disentangle them if the temporal resolution of the data is insufficient. In the present study, we therefore focus on the net latent heat flux or net nocturnal water loss (NWL) defined as ET minus dew formation.

Climate models generally represent latent heat flux as a function of the air-surface gradient in specific humidity and a resistance to water vapor transfer. This total resistance can include an aerodynamic resistance, a resistance to diffusion through the soil, a leaf boundary layer resistance and stomatal resistance. Stomatal resistance or conductance is

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Deleted: 2007; Snyder et al., 2003) – Lombardozzi et al. (2017) compiled evidence of this from 204 species. A review by Caird et al. (2007) estimated nocturnal transpiration to be typically 5 % to 15 % of daytime rates, but sometimes as high as 30 %, based on studies using gas exchange measurements of individual leaves, whole-plant sap flow, and field scale lysimetry. More recently, Zeppel et al. (2014) refer to the ubiquity of nocturnal water fluxes and estimate nighttime transpiration to be 10–25 % of total daily transpiration. The above-mentioned publications stem from the plant physiology community, and the relevance of their results for hydrological and climate studies is yet to be fully explored. …

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parameterized in most large-scale land surface models similarly to the Ball–Woodrow–Berry model (Ball et al., 1987; Ball, 1988; Collatz et al., 1991; Leuning, 1995; Medlyn et al., 2011; Sellers et al., 1996), i.e. as a linear function where the intercept is assumed to represent nocturnal conductance (see explanation in Lombardozzi et al., 2017). Meanwhile, new evidence suggests that nocturnal stomatal conductance is an actively controlled process, and that it is not equivalent to minimum conductance (Duursma et al., 2019). Underestimation of nocturnal stomatal conductance would lead to lower transpiration, and hence lower NWL. Previous research has noted that land surface models, dynamic global vegetation models and ecophysiological models continue to commonly assume that virtually no transpiration takes place at night, despite evidence suggesting otherwise (e.g. Lombardozzi et al., 2017; Zeppel et al., 2014). By adjusting the nocturnal stomatal conductance of the Community Land Model (CLM) version 4.5 based on empirical evidence, Lombardozzi et al. (2017) obtain an increase of up to 5 % in global transpiration, as well as significant effects on soil moisture availability and carbon uptake. In another study, Vinukollu et al. (2011) reported a mean nocturnal ET from the VIC land surface model of 9.6 % relative to daytime ET. It is also known that simple land evaporation models are not well suited for nocturnal conditions (Ershadi et al., 2014). Finally, to our knowledge, there have not been any studies analyzing NWL estimates from an ensemble of global climate models.

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The goal of this study is to provide an overview of the magnitude and variability of NWL across the globe, as well as to explore its relationship to different meteorological and land cover conditions. An improved understanding of this overlooked flux is relevant for the surface water and energy balance. Until now most research about NWL stems from the plant physiology community, whereas the relevance of their results for hydrological and climate studies is yet to be fully explored. Here we analyze observations of NWL from a lysimeter and a global network of EC measurements, together with estimates from a climate model ensemble for present and projected future conditions. We conclude with a comparison of the observed and modeled data, while keeping in mind the stark difference in spatial resolution.

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2 Data

2.1 Observations

2.1.1 Co-located lysimeter and EC station

Water fluxes are measured by a co-located weighing lysimeter and EC tower (2 m height) at the Rietholzbach pre-alpine catchment in Northeastern Switzerland (47.38° N, 8.99° E; 795 m a.s.l.; see Seneviratne et al., 2012 for site details). The sensors are thoroughly described by Hirschi et al. (2017). Given that in this case the focus is on sensor comparison, day and night are distinguished using a simple threshold of 10 W m^{-2} for measured incoming solar radiation below which it is assumed that no photosynthesis occurs (Hirschi et al., 2017). Data from 2010 to 2018 are used for comparing NWL estimates from these two independent measurement techniques.

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For the lysimeter, changes in the total system mass (i.e. its weight plus accumulated seepage) are quantified every 5 minutes and correspond to water lost as ET or gained by precipitation, including dew. We apply an adaptive window and adaptive threshold (AWAT) filter to the total system mass of the lysimeter to reduce noise in the timeseries (Peters et al., 2014; Ruth et al., 2018). A minimum of 5 minutes and maximum of 45 minutes are assumed for the moving-average window, as well as a minimum of 0.01 mm and a maximum of 0.25 mm for the threshold values to distinguish signal from noise. A piecewise cubic Hermitian spline is used to interpolate between points of significant mass change (Peters et al., 2016), after applying an 85th percentile "snap routine" at inflection points (Peters et al., 2017). We estimate dew formation from hourly weight increases in the lysimeter when a co-located rain gauge does not record precipitation in that hour or the next. Note that very light precipitation might not be recorded due to the 0.1 mm rain gauge resolution. In those rare occasions when estimated dew surpasses a maximum formation rate of 0.07 mm h^{-1} (Monteith and Unsworth, 1990), it is instead attributed as rain or snow. NWL is calculated as ET minus dew. Lysimeter data from December to March are discarded because the quality is strongly affected by formation of snow bridges and the occurrence of snow drift. In addition, data from the following months are also omitted due to cases with unrealistic lysimeter weight and/or seepage measurements: July–September 2017, August 2014 and 2016, and November 2010, 2011 and 2016.

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The EC data are processed with EddyPro (Fratini and Mauder, 2014; LI-COR, 2018) to obtain a latent heat flux time series with a temporal resolution of 30 minutes. Values are discarded for intervals when rain occurs, when the tower is in the upwind direction affecting the air flow (see Hirschi et al., 2017), and for cases with too low turbulence (median threshold for friction velocity) based on Wutzler et al. (2018). The resulting gaps are filled according to Reichstein et al. (2005). Latent heat flux is converted into water volume by dividing over the latent heat of vaporization; here we assume $\lambda = 2.472E6$ J kg^{-1}.

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2.1.2 Global network of EC stations

To obtain a broader picture of NWL across the globe we employ the FLUXNET2015 Tier 1 dataset, which provides EC measurements of latent heat flux together with numerous other meteorological variables from a global network of 166 sites. We further select only those stations that contain at least 3 years of data to obtain a more accurate climatology of NWL. The temporal resolution of the data is 30 minutes. There are implemented tailored steps for quality assurance and quality control (Pastorello et al., 2014). A quality flag at each time interval indicates whether the data were measured or gap-filled based on marginal distribution sampling (Reichstein et al., 2005). Moreover, there is an energy balance closure correction factor applied to the data based on the assumption that the Bowen ratio is correct. A *joint uncertainty* estimate that combines a *random uncertainty* component and an energy balance closure component is provided at each timestep. Full details of the data processing are available at https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/data-processing/. Even though the dataset distinguishes between daytime and nighttime intervals based on potential incoming solar radiation, we additionally determine the total number of nighttime hours by calculating the sunset and sunrise time of each day (see

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https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html). Finally, this study uses data from 99 sites (see Table A1) that include energy balance corrected measurements of latent heat flux, as well as the uncorrected fluxes.

Here we assume that the provided uncertainty for latent heat flux at each timestep i is the standard deviation (σ_i) of a normal distribution, and thus propagate it to obtain the uncertainty of the accumulated flux (σ_{sum}) over n timesteps as follows:

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$$\sigma_{sum} = \left(\sum_{i=1}^{n} \sigma_i^{\,2} + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} 2\rho_{jk}\sigma_j\sigma_k\right)^{0.5} \qquad (1),$$

where ρ_{jk} corresponds to the Pearson correlation between the estimates of timesteps j and k. Because there is no information available to compute this correlation, we assume an average $\rho_{jk} = 0$ in accordance with the FLUXNET2015 data processing. In addition, note that EC measurements do not account for latent heat storage in the air between the ground and measurement level. Lastly, it is important to be aware that the reliability of EC measurements decreases during the night due to low and intermittent turbulence (e.g. Baldocchi, 2003; Moffat et al., 2007). Nonetheless, on average across all analyzed sites, latent heat flux is measured in 60 % of all nighttime intervals, whereas gap-filling is required in the remaining 40 %.

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2.2 Climate models

Sub-daily climate model output is required to study NWL. Here we analyze an ensemble of climate model simulations of the fifth phase of the Coupled Model Inter-comparison Project (CMIP5) that provide 3 hourly estimates of latent heat flux. As for the EC data, we obtain NWL by dividing it over the latent heat of vaporization λ. For present conditions we use data from historical simulations during the period 1976–2005, whereas for the future period 2081–2100, we use data from simulations with the "business as usual" RCP8.5 emissions scenario (Moss et al., 2010). The employed ensemble comprises 26 different models (or model configurations) with one initial condition simulation (see Table A2). Data from all models are bilinearly interpolated to a common 2.5° × 2.5° grid. Grid cells with data from less than 2/3 of all models are not considered.

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To estimate total NWL we obtain the average flux from all 3 hourly intervals that are exclusively night, and then extrapolate this value based on the complete number of nocturnal hours. To achieve this, we compute the time of sunset and sunrise for each day at the center of each individual grid cell using the solar time equations without accounting for topography. Note that this extrapolation approach could lead to inaccuracies if the NWL rate from periods immediately following sunset or just prior to sunrise systematically differ from the NWL rate during the middle of the night.

3 Results

3.1 Observed nocturnal water loss

Monthly NWL from the co-located lysimeter and EC system show a Pearson correlation of 0.5 or 0.57 depending on how dew is estimated from the lysimeter data (L1 vs. L2, see Figs. 1a and 1b). For L1 (Fig. 1a), the default threshold of 0.07 mm

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h-1 is used (Section 2.1.1). In the case of L2 (Fig. 1b), we select here as a sensitivity test a second threshold of 0.035 mm h^{-1}, i.e. half of the defined value of 0.07 mm h^{-1} for maximum dew formation, when processing the lysimeter data. Note that the correlations may be affected by the difference in the footprint of the sensors and periods with gap-filled EC data. Also, in this case there is no energy balance closure correction factor applied to the EC data. The agreement between EC and lysimeter improves if the NWL monthly climatology is analyzed. Moreover, in months when one of the lysimeter estimates of NWL is either too high or too low relative to the EC data, the other lysimeter estimate generally has a much better agreement. Overall, these results suggest that EC measurements can provide meaningful estimates of NWL. The annual climatology of EC-based NWL at this particular grassland site in Switzerland is 34.3 mm, equivalent to 5.8 % of annual ET.

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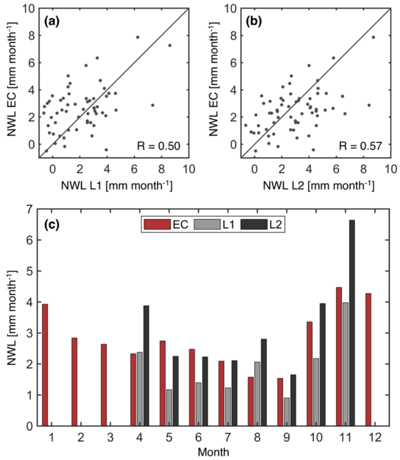
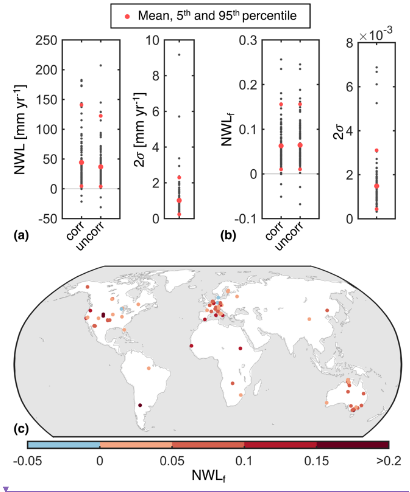


Figure 1. Comparison of nocturnal water loss (NWL) measured by the co-located lysimeter and EC system at Rietholzbach. Comparison of individual months is shown in (a) and (b) with the Pearson correlation coefficient denoted as R, whereas a comparison of the climatology from the period 2010–2018 is shown in (c). L1 corresponds to the lysimeter estimate with a maximum dew formation threshold of 0.07 mm h^{-1}, and L2 with a threshold of 0.035 mm h^{-1}. Lysimeter data from December to March are discarded because of measurements issues when snow is present.

An overview of observed NWL at the analyzed FLUXNET sites is presented in Fig. 2. Mean annual NWL based on energy balance corrected fluxes is 44.2 mm on average over all 99 stations, whereas the 5th and 95th percentiles of the distribution are 4.5 mm and 140.9 mm. There is a positive Spearman correlation coefficient of 0.61 between total ET and NWL, indicating generally higher NWL at sites with higher ET. The net nocturnal water loss as a fraction of total ET, i.e. NWL_f = NWL / ET, provides more insight on the relevance of the nocturnal water flux. Average NWL_f across all stations is 6.3 %, the 5th percentile is 1 %, and the 95th percentile is 15.6 %. These annual mean values are computed from monthly climatologies obtained by omitting months with half or more of missing latent heat flux data. There is practically no difference in the distribution of NWL_f with and without energy balance closure correction, whereas NWL is generally smaller when based on uncorrected fluxes. Furthermore, the uncertainty of annual mean NWL$_f$ per site, given by 2σ (~95 % confidence interval), is rather small with an average of ± 0.15 %. When assuming a more conservative value of ρ_{jk} = 0.1 in equation 1, the average uncertainty across sites increases to ± 1.7 %.

Interannual variability of NWL$_f$, represented by the standard deviation, is 2.4 % on average from all sites. To analyze seasonality, we compute NWL for the trimesters December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON) at all 81 sites located above 30° N, where seasonal differences are clearer, and data are available. The most common season with the highest NWL is winter (35.8 % of the sites) followed by autumn (25.9 %), summer (23.5 %) and spring (14.8 %); whereas for the lowest NWL, the most common is summer (37 %) and the least common is autumn (13.6 %). Note that this is partly related to an increase in the total nocturnal hours as we go from summer to autumn and winter.



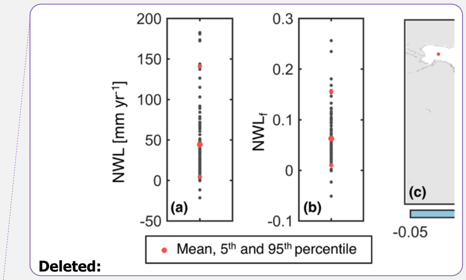


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Figure 2. Nocturnal water loss at 99 FLUXNET sites as the annual NWL (a), and as the fraction of total evapotranspiration NWL$_f$ (b). Values from individual sites are shown in black, whereas the mean, 5th percentile and 95th percentile are shown in red. Both energy balance corrected values (corr) and uncorrected values (uncorr) are shown. Uncertainty estimates are given by 2σ, which correspond to a confidence interval of approximately 95 %. The uncertainty of total ET is small and therefore neglected when computing the uncertainty of NWL$_f$. (c) Location of sites with their estimated NWL$_f$.

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The variability in NWL$_f$ across sites cannot be easily explained by annual average climate conditions (temperature and precipitation) or land cover (Fig. 3). Nonetheless, deciduous broadleaf forests (DBF) have an overall lower NWL$_f$, whereas evergreen needleleaf forests (ENF) include most cases with higher NWL$_f$. An ANOVA test (differences in the mean) for the

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land cover categories has a p-value of 0.038, and a Kruskall-Wallis test (differences in the distribution) a p-value of 0.055. The three sites with negative NWL$_f$ (dew is greater than nocturnal ET) are Hainich (Germany), Soroe (Denmark), and Willow Creek (WI, USA). These are all DBF with typically lower vapor pressure deficit and higher soil moisture than approximately 75 % of all sites. Moreover, it may be more difficult to accurately measure EC latent heat flux at DBF sites with large trees that reduce the ground-atmosphere coupling. On the other hand, there are six sites with NWL$_f$ > 15 %: GLEES (WY, USA), GLEES Brooklyn tower (WY, USA), Niwot Ridge Forest (CO, USA), Lavarone (Italy), Wallaby Creek (Australia), and San Luis (Argentina). These are four ENF, an evergreen broadleaf forest (EBF) and a mixed forest (MF) in mountainous areas. Winter contribution to annual NWL approximately doubles that of summer in the four ENF sites. Snowier and windier conditions at these sites may suggest a considerable contribution of sublimation to NWL. The percentage of gap-filled data for these sites with relatively high or low NWL is not particularly different than for all other sites.

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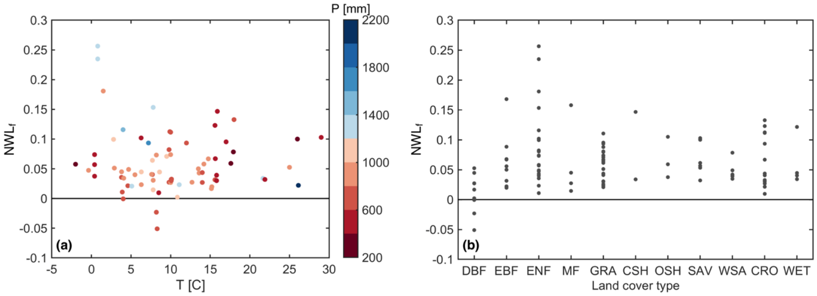

Figure 3. Relation of NWL$_f$ with (a) mean annual temperature (T) and precipitation (P), and with (b) land cover type at FLUXNET sites. Precipitation and temperature data are available for 73 of the 99 FLUXNET sites. Land cover types are deciduous broadleaf forest (DBF), evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), mixed forest (MF), grassland (GRA), closed shrubland (CSH), open shrubland (OSH), savanna (SAV), woody savanna (WSA), cropland (CRO), and wetland (WET).

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At most sites there is a positive correlation of NWL with local air temperature (T), vapor pressure deficit (VPD), wind speed (WS), soil moisture (SM) and downward longwave radiation (LWd) for the 30-minute non-gap-filled data (Fig. 4). Correlations with net radiation (Rn) and ground heat flux (G) are also positive on average, but smaller. As expected, higher incoming energy (LWd, Rn, G), evaporative demand (T and VPD), aerodynamical conductance (related to WS) and water supply (related to SM) generally favor higher NWL. In addition, there is a tendency to have less NWL (i.e. latent heat flux) when sensible heat flux (SH) is higher, which is consistent with the partition of available energy. However, Spearman correlations at the majority of sites are smaller than 0.3. Reasons for this may include confounding effects among the analyzed drivers of NWL, observational uncertainty and a possible physiological control on nocturnal transpiration; e.g. the relationship of VPD with NWL might not increase monotonically if stomatal conductance decreases when VPD is high. Although there is no clear dependency of the correlations on land cover, we note that croplands (some of them irrigated)

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often exhibit higher correlations with VPD and WS, while higher correlations with SM and LWd often correspond to short vegetation types. When analyzing data from summer months only, we find that correlations with VPD increase at forest sites, in particular at DBF. Also, the four sites with the highest correlations with SM are located in southern Arizona, an arid zone.

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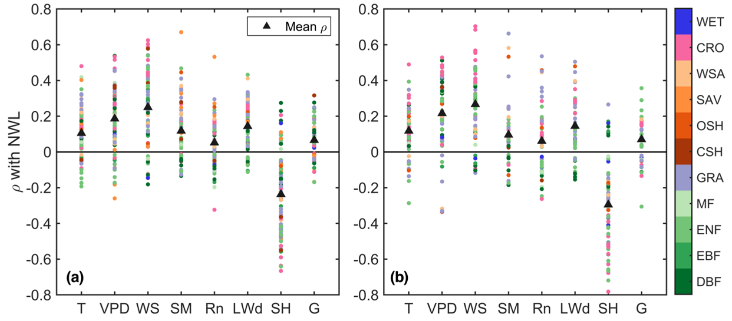

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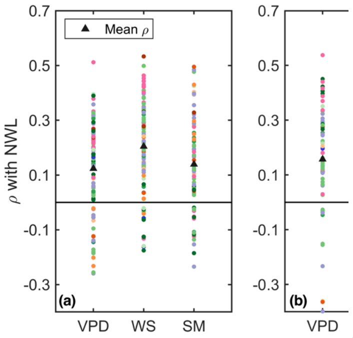

Figure 4. Spearman correlation (ρ) of 30-minute non-gap-filled nocturnal water loss (NWL) with air temperature (T), vapor pressure deficit (VPD), wind speed (WS), soil moisture (SM), net radiation (Rn), downward longwave radiation (LWd), sensible heat flux (SH) and ground heat flux (G) at FLUXNET sites. Panel (a) is for all data and (b) for summer months (JJA) at sites located above 30° N. Land cover types are deciduous broadleaf forest (DBF), evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), mixed forest (MF), grassland (GRA), closed shrubland (CSH), open shrubland (OSH), savanna (SAV), woody savanna (WSA), cropland (CRO), and wetland (WET).

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3.2 Climate model estimates of nocturnal water loss

The multi-model mean depicts an average NWL$_f$ of 7.9 % across all land grid cells excluding desert regions and Greenland (Fig. 5). The 5th percentile of the spatial distribution without deserts and Greenland is 1.8 %, and the 95th percentile is 13.2 %. In tropical regions NWL$_f$ is generally below the global average, even though NWL can e.g. surpass 80 mm yr^{-1} in parts of the Amazon. Central and northern Europe, USA, China and India show similar regional averages of approximately 9 %. The models also suggest a high relevance of nocturnal water fluxes in Australia with an average NWL$_f$ of 13.1 %, and in the Mediterranean with 12 %. In most of Greenland and parts of Egypt the amount of dew or hoar frost is greater than the water lost through ET during the night. Interannual variability of NWL$_f$, given by the standard deviation of the 30-year time series from the multi-model mean, is below 2 % on 95 % of land grid cells excluding deserts and Greenland. Finally, we focus in the northern midlatitudes (30–60° N) to analyze seasonality. The multi-model mean indicates that autumn (SON) is the season with highest NWL on average (50.4 % of grid cells), whereas the lowest NWL typically corresponds to winter (DJF) (73 % of grid cells).

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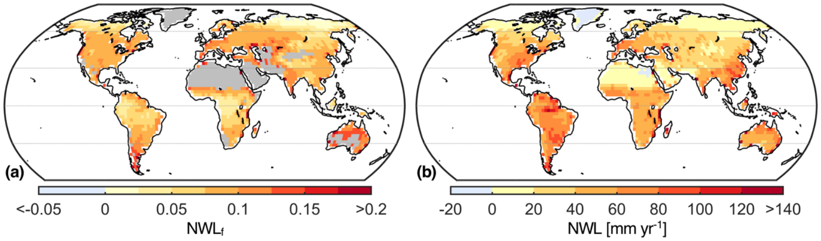


Figure 5. Map of multi-model mean NWL$_f$ (a) and NWL (b) on average over the period 1976–2005. Desert regions and Greenland are masked in (a) because of division by small numbers.

There are large discrepancies in NWL$_f$ between the different climate models (Fig. 6). The 95th percentile of the model ensemble is higher than 15 % in most of the globe, whereas the 5th percentile even shows negative values (i.e. dew is greater than nocturnal ET) in parts of the tropics and high latitudes. The central 90 % spread of the ensemble is almost everywhere larger than 10 %, and even greater than 20 % in southern South America, eastern Africa, India and Australia. This means that at certain locations some models simulate NWL$_f$ to be approximately zero, whereas estimates from other models are higher than 20 %. Even though the model differences in NWL$_f$ can originate from differences in total ET (e.g. in India), we also find differences in NWL generally ranging from 50 to 150 mm yr^{-1} (see Fig. S1).

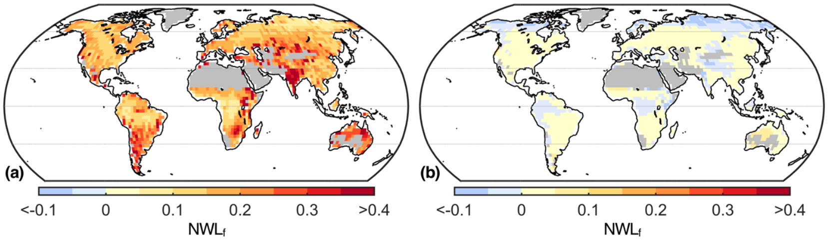
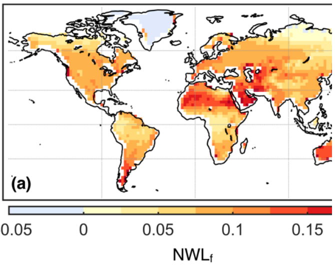


Figure 6. NWL$_f$ uncertainty within the climate model ensemble. (a) Map of the 95th percentile of the ensemble. (b) Map of the 5th percentile of the ensemble. Desert regions and Greenland are masked because of division by small numbers.

The complexity of CMIP5 models, together with the fact that not all models are equally well documented, hinders a straightforward assessment of potential factors contributing to the large inter-model differences in NWL. Nonetheless, we find a positive relation of climatological NWL and nighttime near-surface air temperatures across models (Fig. 7), indicating that models with high temperatures also tend to simulate high NWL. This correlation is present throughout the world and during the different seasons, although it decreases substantially in the Northern Hemisphere during summer (JJA). Furthermore, we note that inmcm4, EC-EARTH, NorESM1-M and CNRM-CM5 are models with systematically low values



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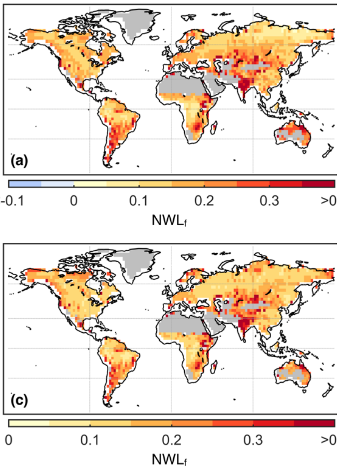

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of NWL throughout the globe; whereas GISS-E2-R, GISS-E2-H and MIROC5 tend to simulate the highest values of NWL (see Fig. S2).

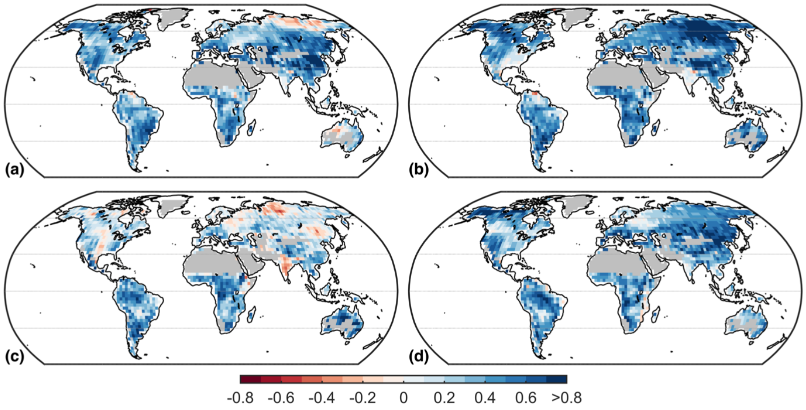
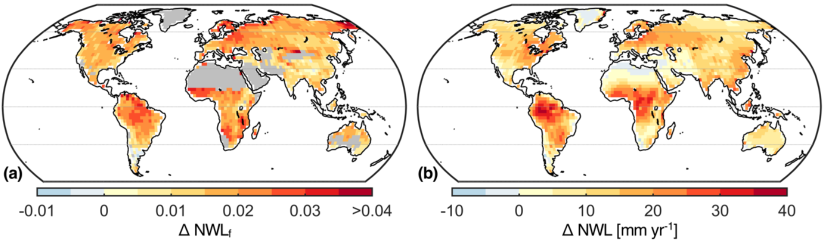


Figure 7. Pearson correlation at each grid cell between average NWL and nocturnal near-surface air temperature of climate models. Data corresponds to the period 1976–2005 from historical simulations. Correlations are computed separately for each season: (a) December–February, (b) March–May, (c) June–August, and (d) September–November. Desert regions and Greenland are masked for consistency.

Terrestrial NWL$_f$ is projected to increase towards the end of the century throughout the globe (Fig. 8). The average increase in the multi-model mean is 1.8 %, neglecting deserts and Greenland. Whereas NWL is projected to increase almost everywhere, this is not the case for total ET. The increase in NWL$_f$ in the Amazon, Central America, southern Africa and the Mediterranean is favored by a projected decrease in total ET. It is important to note that the spread of the model ensemble reduces confidence even in the sign of projected changes in NWL and total ET (Fig. S3). Lastly, we highlight the contribution of the nocturnal flux to projected changes in total ET. In more than half of all land grid cells, the projected change in NWL corresponds to 20 % or more of the absolute change in ET.



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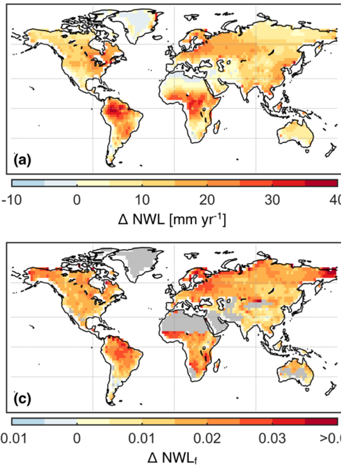

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Figure 8. Multi-model mean of projected changes in NWL$_f$ (a) and NWL (b) for the period 2081–2100 relative to the period 1976–2005. Desert regions and Greenland are masked in (a) because of division by small numbers.

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3.3 Comparison of observed and simulated nocturnal water loss

We compare the site-level EC observations to model estimates from the corresponding grid cells, despite the large difference in spatial resolution. Modelled NWL$_f$ generally shows an overestimation, although there are a few exceptions (Fig. 9a) – the average from the considered grid cells is 10.6 %, whereas the observational average is 7 %. Note once again the large discrepancies between individual models with an average spread of 20.5 % across locations calculated as the difference between the 97.5th percentile and 2.5th percentile. On the other hand, the estimated 95 % confidence interval of the EC observations is ± 0.15 % on average across sites. Interestingly, the multi-model mean has a smaller spread across sites than observations. This is partly explained by strong local discrepancies between individual models causing little variability in the multi-model mean; nonetheless, it could also be related to smoothing of cross-site differences in the much coarser spatial resolution of the models. At locations above 30° N, where most stations are found and seasonal differences are clearer, the simulated seasonal behavior agrees generally well with that of the EC data (Fig. 9b, see also Fig. S4). However, there is a noteworthy overestimation of the cases where the multi-model mean shows the lowest NWL to occur in summer, which is compensated by an underestimation for autumn and spring.

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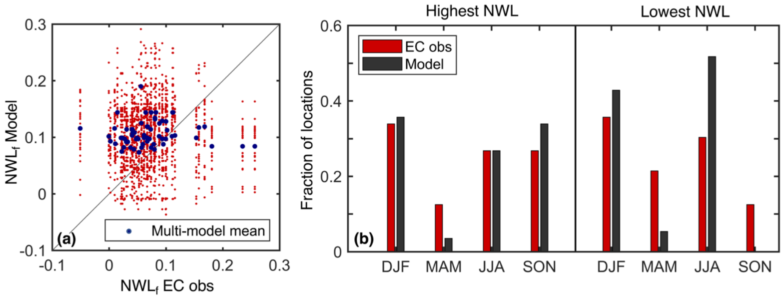

Figure 9. Comparison of observations with climate model simulations at the corresponding grid cells. (a) NWL$_f$ from EC observations versus model simulations at 64 locations. (b) Fraction out of 56 locations (i.e. FLUXNET sites or grid cells) above 30° N where each season has the highest or lowest NWL on average. Seasons are defined by the trimesters December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON).

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4 Discussion and conclusions

Our average estimate of net nocturnal water loss relative to total evapotranspiration from 99 FLUXNET sites is 6.3 %. This is smaller than reported values around 10–25 % from published physiological studies (Zeppel et al., 2014). However, it is important to distinguish that our focus is on the net flux, i.e. evapotranspiration minus dew, whereas physiological studies refer only to transpiration. The results agree with the expectation of lower NWL$_f$ when dew is taken into account. In addition, we recall that nocturnal measurements at FLUXNET stations can be affected by low-turbulence conditions, and therefore gap-filled and energy-balance-corrected data are used in the analysis. Future work could help to disentangle the distinct fluxes of transpiration, evaporation from soil and canopy, sublimation and dew during the night.

We find that higher air temperature, vapor pressure deficit, wind speed, soil moisture and downward longwave radiation tend to favor higher NWL, although the correlations are rather low. Similar results were reported by Groh et al. (2019) at two sites in Germany. Dawson et al. (2007) also found these conditions to favor higher nocturnal sap flow in woody plant species from different ecosystems, but in their case the relationships are much clearer. Meanwhile, Zeppel et al. (2014) point to plant functional type, ecosystem type, and biotic temporal characteristics like leaf or stand age, as possible additional factors influencing NWL. On the other hand, de Dios et al. (2015) found no temporal relation with vapor pressure deficit because of endogenous circadian regulation in an experiment with crops under controlled environmental conditions. Additionally, an increase in nocturnal sap flow and stomatal conductance was reported in two tree species under increased atmospheric CO_2 concentration, given sufficient soil moisture (Zeppel et al., 2011, 2012). Further research about the controls of NWL, and in particular nocturnal transpiration, is required.

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The climate model ensemble provides an average NWL_f of 7.9 % over land, which is slightly higher than the observational estimate. Moreover, the overestimation is greater when considering only grid cells that contain FLUXNET sites. These relatively high multi-model mean estimates of NWL_f are surprising given the literature that suggests models underestimate nocturnal stomatal conductance (e.g. Lombardozzi et al. 2017; Zeppel et al., 2014). Note that increasing model nocturnal stomatal conductance would likely lead to even higher values of simulated NWL_f. Thus, it is possible that even if the mean simulated magnitude of nocturnal water loss is relatively accurate, the underlying processes may be misrepresented.

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Our analysis indicates strong discrepancies between individual models in simulated NWL_f, which are much larger than the spatial and inter-annual variability. These discrepancies are related to differences in average nighttime temperature between models. Simulations that disentangle nocturnal transpiration, evaporation (sublimation) from soil and canopy, and dew would be highly relevant to study the inter-model differences. Note that differences in NWL can represent a substantial fraction of model differences in total ET. Furthermore, these biases could affect boundary layer evolution and precipitation timing in models. Inter-model uncertainty also reduces confidence in the direction of change in NWL under global warming, despite the multi-model mean showing a projected increase throughout the world.

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In conclusion, our study provides a comprehensive global overview of NWL – defined as nocturnal evapotranspiration minus dew formation – from observations and climate models. The magnitude of this flux suggests it can be important for the surface energy and water balances, and therefore relevant to consider in hydroclimate analyses. Future research about NWL focused at seasonal and shorter timescales could address its influence on climate impacts during extreme conditions

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(e.g., Duarte et al., 2016; Groh et al., 2019). Finally, ongoing development and expansion in sensing water and energy fluxes are expected to help address the uncertainties we have highlighted around NWL through continued research on this topic.

Data availability. The FLUXNET2015 Tier 1 dataset is available at https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/. Table A1 indicates the specific sites considered for the analysis. The CMIP5 data used in this study are available at https://esgf-node.llnl.gov/projects/esgf-llnl/. Detailed inputs for the search query are as follows: Model (see Table A2), Experiment (historical, rcp85), Time Frequency (3hr), Ensemble (see Table A2), Variable (hfls, tas). Processed hourly data from the co-located lysimeter and EC tower at Rietholzbach, as well as accompanying meteorological data, are available at https://doi.org/10.3929/ethz-b-000370968.

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Appendix A: List of FLUXNET sites and climate models used in the analysis

Table A1. FLUXNET sites from the FLUXNET2015 dataset employed for the analysis. Included sites provide energy balance corrected measurements of latent heat flux during at least three years. The SITE_ID is indicated here, whereas a full description of each site is available at https://fluxnet.fluxdata.org/sites/site-list-and-pages/. Additionally, the number of years of data and average energy balance corrected NWL_f for each site is provided.

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SITE_ID	# of years	NWL_f	SITE_ID	# of years	NWL_f	SITE_ID	# of years	NWL_f
AR-SLu	3	0.158	CN-HaM	3	0.026	IT-Tor	7	0.051
AT-Neu	11	0.023	CZ-wet	9	0.040	NL-Hor	8	0.074
AU-ASM	4	0.081	DE-Geb	14	0.010	NL-Loo	18	0.082
AU-Ade	3	0.042	DE-Gri	11	0.031	RU-Fyo	17	0.011
AU-Cpr	5	0.057	DE-Hai	13	-0.051	SD-Dem	5	0.100
AU-Cum	3	0.067	DE-Kli	11	0.041	SN-Dhr	4	0.103
AU-DaP	7	0.023	DE-Lkb	5	0.116	US-AR1	4	0.111
AU-DaS	7	0.053	DE-Obe	7	0.040	US-AR2	4	0.088
AU-Dry	7	0.061	DE-RuR	4	0.064	US-ARM	10	0.067
AU-Emr	3	0.081	DE-RuS	4	0.112	US-Blo	11	0.023
AU-Fog	3	0.122	DE-Seh	4	0.112	US-Cop	7	0.044
AU-Gin	4	0.041	DE-SfN	3	0.045	US-GBT	8	0.256
AU-How	14	0.035	DE-Tha	19	0.073	US-GLE	11	0.235
AU-RDF	3	0.049	DK-Sor	19	-0.023	US-KS2	4	0.034
AU-Rig	4	0.067	ES-LgS	3	0.105	US-Los	15	0.034
AU-Stp	7	0.061	FI-Hyy	19	0.036	US-MMS	16	0.002
AU-Tum	14	0.056	FI-Jok	4	0.021	US-Me2	13	0.102
AU-Wac	4	0.168	FR-Gri	10	0.093	US-NR1	17	0.181
AU-Whr	4	0.068	FR-LBr	13	0.043	US-Ne1	13	0.032

AU-Wom	3	0.088	FR-Pue	15	0.050	US-Ne2	13	0.030
AU-Ync	3	0.041	IT-BCi	11	0.133	US-Ne3	13	0.033
BE-Bra	19	0.027	IT-CA2	4	0.044	US-Prr	4	0.058
BE-Lon	11	0.027	IT-CA3	4	0.027	US-SRG	7	0.095
BE-Vie	19	0.015	IT-Col	19	0.045	US-SRM	11	0.078
BR-Sa3	5	0.022	IT-Cp2	3	0.020	US-Syv	14	0.045
CA-Qfo	8	0.047	IT-Cpz	13	0.031	US-Ton	14	0.039
CA-SF1	4	0.057	IT-Lav	12	0.153	US-Twt	6	0.123
CA-SF2	5	0.074	IT-MBo	11	0.021	US-Var	15	0.030
CA-SF3	6	0.038	IT-Noe	11	0.147	US-WCr	16	-0.001
CH-Cha	10	0.071	IT-PT1	3	0.027	US-Whs	8	0.059
CH-Dav	18	0.099	IT-Ren	16	0.049	US-Wkg	11	0.067
CH-Fru	10	0.093	IT-Ro2	11	0.017	ZA-Kru	11	0.032
CN-Cng	4	0.080	IT-SRo	14	0.058	ZM-Mon	10	0.053

Table A2. Climate models or model configurations employed for the analysis. Note that there are slightly variations depending on time period / scenario and on variable under consideration.

Model	Simulation	1976–2005: Historical		2081–2100: RCP8.5
		Latent heat flux	Temperature	Latent heat flux
ACCESS1-0	r1i1p1	X	X	X
ACCESS1-3	r1i1p1	X	X	X
bcc-csm1-1	r1i1p1	X	X	X
bcc-csm1-1-m	r1i1p1	X	X	X
BNU-ESM	r1i1p1	X	X	X
CCSM4	r6i1p1	X	X	X
CMCC-CM	r1i1p1	X	X	X
CNRM-CM5	r1i1p1	X	X	X
EC-EARTH	r2i1p1	X	X	X
FGOALS-g2	r1i1p1	X	X	X
FGOALS-s2	r1i1p1	X		
GFDL-CM3	r1i1p1	X	X	X
GFDL-ESM2G	r1i1p1	X	X	X
GFDL-ESM2M	r1i1p1	X	X	
GISS-E2-H	r6i1p1	X	X	X
GISS-E2-R	r6i1p1	X	X	X
HadGEM2-ES	r2i1p1	X	X	
inmcm4	r1i1p1	X	X	X

IPSL-CM5A-LR	r1i1p1	X	X	X
IPSL-CM5A-MR	r1i1p1	X	X	X
MIROC-ESM	r1i1p1	X	X	X
MIROC-ESM-CHEM	r1i1p1	X	X	X
MIROC5	r1i1p1	X	X	X
MRI-CGCM3	r1i1p1	X	X	X
MRI-ESM1	r1i1p1	X	X	
NorESM1-M	r1i1p1	X	X	X

Author contributions. RSP, LG and SIS conceived the idea and designed the study. SIS acquired the funding to carry out the research. DM collected and processed the co-located lysimeter and EC data from the Swiss site. RSP processed the FLUXNET2015 and CMIP5 data. RSP performed the analysis and wrote the manuscript with contributions from all authors throughout the study. All authors discussed the results, read and reviewed the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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