Reply to Reviewer 1

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1 General Comments

I think this paper deserves publication because the dataset is particularly interesting. As said by the authors, it is the first time that one year of turbulent atmospheric fluxes measured by the eddy-correlation (EC) method has been presented for the specific area of the Dead Sea. The data have been professionally processed. They can efficiently be used to assess several parameterizations generally used for long-term measurements when the EC method is not available. The originality is that the authors provide several levels in the parameterizations, according to the measurements that can be performed. However the paper requires some important corrections before being published. I try to describe them below. Some corrections, related to the methodology, are essential. Other are secondary and consists in numerous details that could be improved.

Thank you for the very detailed and insightful review. Your comments helped to improve the paper. Responses to individual comments are provided below. Reviewer's comments are in italic.

2 Specific Comments

Methodology : I think the difficulty comes from the fact you make a local measurement over ground (with the EC method) while you would like to include the close environment in the driving parameters of the turbulent fluxes, considering that the air that is advected on the measurement site is (most of the time) characterized by the water surface temperature and water surface vapor partial pressure. I am not against the idea, but I think the way you deal with this assumption is not always correct. I am aware that you want to prove that measuring on the headland, very close to the seashore is equivalent to measuring with a raft in the middle of the sea, but I am not totally convinced. Another issue is the fact that you address different time scales for the energy budget you consider, without saying accurately which timescale you refer to.

C1) When measuring the latent heat flux LE at level 6m with the EC, the Lv value (kJ/kg) that has to be used to change the evaporation rate $\overline{w'a'}$ into a flux is that of the air, i.e. 3148.4-2.37 Ta and not Tw as you use in Eq. 3. Ta is the air temperature in K. Even if the evaporation takes place at the water surface as you mention p 6, line 3, LE is assumed to be constant in the surface layer (in fact, not to vary more than 10% of its surface value).

A) Thank you for this comment. As Lv is a water specific variable and defined by the temperature of the liquid, in our opinion Tw is the appropiate variable to calculate Lv. The literature equation $Lv = 3148.4 - 2.37 \cdot T$ is derived via the Clausius-Clapeyron equation, by measuring water temperature and saturation vapour pressure. This results in the enthalpy of vaporization. Dividing the enthalpy of vaporization by the molar mass of water gives us the latent heat of vaporization. So it does not include air temperature measurements and is only a function of water temperature.
When using Lv to convert the evaporation rate $\overline{w'a'}$ into LE, which is the energy used to evaporate the water at the surface, from a physical point of view, the water surface temperature and not air temperature has to be used as Lv is a water specific variable Lv=fct(Tw).

This unique Lv value should be used for both offshore and onshore winds. In fact an internal boundary layer develops either inland or offshore, depending on the wind direction. Perhaps you should mention it and clarify *the parameters you use in both situations. [The only opportunity to use Lw as you define it, would be to take into account the heat loss of the water due to water evaporation, as shown by Giadrossich et al., 2015 in their eq (2). This eq. applies to the energy budget of the whole sea, and not the local energy budget that you quantify at the EBS].*

A) As in this paper we are only interested in fluxes from the water surface only fluxes measured during onshore wind conditions are used, because then the source area of the flux is over water. All flux measurements for offshore wind conditions are neglected as they represent the fluxes from the land surface. To fill the so created gaps in the time series the regression model is used.
At this point we take advantage of the very periodic wind systems at the Dead Sea. There are only very short time frames with westerly offshore winds where the flux measurements have to be neglected and therefore a large data set with onshore wind conditions is available to establish the regression of the latent heat flux from the water surface with wind velocity and water vapour pressure deficit. With this so gained regression we calculate evaporation from the water surface for the time steps with westerly winds as no measurements of the fluxes from the water surface for this conditions are available. With this procedure we get the full diurnal cycle of the evaporation from the water surface, just as it would be measured with a raft station in the lake. As only flux data for onshore wind conditions are used, $\overline{w'a'}$ is always converted into LE with Eq. 4:

$$Lv = 5150.6561 - 13.9530 \cdot T_w + 0.0162 \cdot T_w^2$$

(This equation is slightly different to Eq. 3, which is for pure water, as the salinity of the water also influences the latent heat of vaporization.)

For the investigation of the energy balance of the land surface no data from this station is used as we have another station further inland, which is not affected by the water surface. The results of the energy balance of the land surface are not discussed here as they are beyond the scope of this paper.

C2) When discussing the various models you apply to your data, you use Tom-Ta or Ew-Ea. The latter should be replaced by E_{surf} - Ea, with E_{surf} (or another name) standing for the water vapor partial pressure at the surface (water or ground). The former, by T_{surf} - Ta:

- *For onshore winds, as the source area is over water, we think that the similarity profile you use in Appendix B, p26, to deduce the water surface temperature is not appropriate since the regressions you wish to establish in the following will depend on this profile. We suggest that you'd try to find independent remote-sensed measurements of the Dead Sea surface temperature instead, which is not exactly the air temperature at the surface, but is the closer you can find. If you do so, we am almost sure that the discrepancy between panels 2 and 3 in Fig. 2 will be larger. In that way, the models you will apply in the following will include independent measurements (since the temperature difference will not result from the similarity profile).*

  A) We agree that remotely sensed water surface temperature would be favourable as it is independent from the air temperature measurements. This was also considered and discussed when analysing the data but it was discarded because of the following reasons:

  - Nehorai et al. (2009) used Meteosat Second Generation (MSG) data to estimate water surface temperature from the Dead Sea. For retrieving the water surface temperature from the satellite data the operational SST algorithms could not be applied as they are calibrated to mean sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. They derived the water surface temperature by calibrating their algorithm against in-situ measurements. Unfortunately, we did not have the necessary in-situ measurements of the water surface temperature to follow their procedure to derive the water surface temperature from satellite data.
  - Furthermore, Nehorai et al. (2009) raised concerns, that on days where the Mediterranean Sea Breeze, a strong westerly wind, enters the valley in the afternoon the enhanced evaporation causes enhanced water vapour and thus a stronger absorption of thermal IR radiation which leads to a screening of the Dead Sea surface and thus incorrect estimates of the water surface temperature. For their studies they

excluded all data with these conditions. This would lead to data gaps in the time series of water surface temperature during westerly (offshore) wind conditions, meaning that no water surface temperature data would be available for the timesteps where it is actually needed to estimate evaporation from the water surface, as the station measures evaporation from the land surface for offshore wind.

– Another point why satellite data was not used is the need of a continuous time series. Satellite data can not be used for cloudy conditions. So especially for the winter months cloud cover would reduce data availability strongly.

– Because of the aforementioned problems with satellite data we followed the advice of another paper from Nehorai et al. (2013), which shows that "SST is highly correlated to air temperature ($R^2 = 0.93 - 0.98$) in all seasons". Based on these results the similarity approach was used to calculate water surface temperature from air temperature.

– Of course there is dependence in the data, but we also checked the results of the similarity approach with a short term experiment of about 5 days, where longwave and shortwave radiation was measured directly over the water surface. From the outgoing longwave radiation radiation temperature of the water surface was calculated and compared to the calculated Tw using the similarity approach. A correlation of 0.8 was achieved. This is quite good, considering the uncertainty of the radiation measurements, as the radiation sensor was getting covered with salt through the spray over the course of the 5 day experiment.

Following paragraph was added to the paper:
T) For the surface water temperature, T_S, no in-situ measurements were available. Also remotely sensed surface water temperature products could not be used as operational SST algorithms are calibrated to mean sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. Nehorai et al. (2009) showed that a calibration of satellite data with in-situ measurements is necessary. Furthermore, Nehorai et al. (2009) raised concerns that enhanced water vapour input into the atmosphere through evaporation causes stronger absorption of thermal IR radiation, which leads to a screening of the Dead Sea surface and thus incorrect estimates of the surface water temperature. Following the results of Nehorai et al. (2013) , which showed that "SST is highly correlated to air temperature ($R^2 = 0.93 - 0.98$) in all seasons" the Monin-Obukhov similarity approach was used to calculate surface water temperature from the measured air temperature (see Appendix A), and referred to as T_{MO} in the following.

For offshore winds, the source area is partly over water, partly over land. The ΔT *estimation should be a combination of ground surface temperature and water surface temperature. There again, an estimation of the ground surface temperature (perhaps after some assumptions of the emissivity) would be appropriate. You could perhaps also use the upward longwave radiation flux measured at the neighbouring ground station.*
A) For the multiple linear regression approach, data from offshore winds are excluded. So land surface temperature is not needed. As the regression model is used to calculate the evaporation from the water surface for offshore wind conditions, the water surface temperature is needed and can be calculated with the MO Theory.
T) Through the installation of the EBS at the shoreline flux data from the water surface are only available for onshore wind conditions and all data for offshore wind conditions, i.e. wind directions between 230° and 330°, ~~have to be rejected for further~~ are rejected for the analysis

- *For offshore winds, I do not know any mean to deduce* E_{surf} *, unless you make assumptions on the water vapour at the ground surface. You could use the similarity profile, but meanwhile you would make the choice of a model and Sections 3.3 and 4.4 would become useless. For onshore winds,* $E_{surf} = 0.65 \cdot Ew(Tw)$ *could be an appropriate estimation,* Tw *being the satellite sea surface temperature, instead of* Tmo*. A sensitivity study of the regressions to the error in* Tw *(which determines* ew*) could also be informative.*

  A) This paper focuses only on the energy balance of the water surface. The energy balance of the land surface is not discussed and beyond the scope of this paper. For investigating the energy balance of the

land surface we have a different station which is further inland and therefore not influenced by the water. Therefore there is no need to deduce E_{surf} from the data set. We explain this point in the introduction:
T)That is why, in the framework of the international DESERVE project (Kottmeier et al., 2016), a new concept of assessing lake evaporation from onshore measurements was applied. ~~Therefore, long-term~~ Long-term eddy covariance measurements ~~are~~ were conducted at the Dead Sea shore~~to measure the latent and sensible heat fluxes, as well as temperature, humidity, precipitation, radiation, wind speed, and wind direction. The measurement location directly at the shoreline provides flux data from the water surface~~ , which provided evaporation data for onshore wind conditions. ~~The station is complemented by two additional eddy covariance stations in close vicinity to provide additional data from the homogeneous desert land surface and from a vegetated area.~~ These measurements were combined with a statistical model to calculate evaporation for offshore wind conditions.

C3) If we consider the 3 objectives you propose to fulfill : i) is fulfilled by the EC method, but you do not need to use any multiple regression model to quantify the offshore conditions : you directly measure them. The way you can link these flux measurements with local air or surface parameters is another issue.
A) Yes the offshore conditions are measured but not the fluxes from the water surface for offshore conditions. For offshore wind conditions the source area of the measured flux is the land surface. As the aim is to get the full diurnal cycle of the flux from the water surface (which would be measured if the station would be located on a raft), it is necessary to apply the multiple regression model and estimate the flux values for offshore wind conditions.
T) (i) ~~Providing~~ Provide an applicable method for measuring ~~evaporation from the Dead Sea water surface~~lake evaporation, using a station located at the shoreline.

ii) I think you cannot totally achieve this aim since you can only access to the local terms of the energy budget and make assumptions on the terms you have to neglect.
A) We fully agree. We can only get the local evaporation at the measurement site and not the evaporation for the whole lake. This point is rephrased that it becomes clear that these are local values.
T) (ii) Evaluate the ~~actual~~ local evaporation rate of the Dead Sea at the measurement location and its diurnal and intra-annual variability,

iii) OK if you define what 'evaporation' is. You could also add that you want to assess the capacity of these models to retrieve the 'evaporation' term, in the future, when the EC sensors are not available any more (you suggest this in the conclusion).
A) we added your suggestions to point iii.
T) (iii) evaluate the applicability of the commonly used indirect methods to calculate evaporation rates for different time scales, from sub-daily to biweekly time intervals, from the Dead Sea, and assess the capacity of the methods to retrieve the evaporation term, in the future, when eddy covariance measurements are not available.

3 Other Remarks

Thank you very much for the detailed and helpful remarks. First, we provide answers to the questions raised by the reviewer. Afterwards we list the comments about readability and linguistical problems. We considered all of these comments in our revised version of the paper and revised the text accordingly.

3.1 Questions

13 - p2, line 7 : during which period this decrease happened ? And 60-400 denotes a very large variability. Can you explain why ? (variability among the authors ?)
A) The decrease was caused by the construction of dams and canals along the Yarmouk river and Lake Tiberias/Kinneret mainly between 1955 and 1964. Since then only about 10% of the natural discharge of the Jordan river enters the Dead Sea. The variability of the inflow results from variability among the authors.
T) The main water inflow to the Dead Sea is the Jordan river, but through anthropogenic interferences the

discharge of the Jordan river into the Dead Sea decreased by 90 % down to $60 - 400 \cdot 10^6\,\mathrm{m^3\,a^{-1}}$ (Asmar and Ergenzinger, 2002; Holtzman et al., 2005) compared to its natural discharge before 1955.

17 - p2, line 16 : ←'shifting of the fresh/saline groundwater interface' ('of the' has been added). Please define sinkholes, I did not know this phenomenon.

A) Sinkholes are holes or depressions in the ground formed by subsurface erosion or removal of soluble bedrock and the collapse of the surface layer.

18a - p2, line 25 : why westerly winds would be harmful, compared with easterly winds ? You could also delete 'the' at the end of the line, before '1940'. I suppose this harm comes from the fact that easterlies carry drier (continental) air, whereas westerlies carry moister air. But this cannot be guessed from what you wrote here.

A) The westerly winds have often high wind velocities enhancing the evaporation and thus accelerating the lake level decline.

T) Furthermore, it increases the diurnal penetration of the westerly winds into the valley in the afternoon. These westerly winds have often high wind velocities enhancing the evaporation and thus accelerating the lake level decline.

29 - p5, line 5 : is it a tipping bucket rain gauge ?

A) Yes, it is a tipping bucket rain gauge.

34 - p5, eq (2) and line 24 : usually, $LE = \rho_a Lv\overline{w'r'}$ *or* $LE = \rho_a Lv\overline{w'q'}$ *where r and q are the water vapour mixing ratio and specific humidity, respectively. Brutsaert (which you refer to in the following) uses the latter definition for the evaporation rate :* $Ev = \rho_a\overline{w'q'}$*. In addition, if I remember well, the hygrometer converts the absolute humidity in water vapour mixing ratio, using T=20°C and P=1013.25 hPa. Perhaps you could consider using r or q instead of a.*

A) We decided to keep eq(2) as in our calculations of the turbulent fluxes with the EC software we use absolute humidity as this is the raw output of the IRGASON.

39- p6 or before (p5) : did you use a constant calibration coefficient for the IRGASON (when was the calibration done ?) or did you calibrate the hygrometer measurements against the low frequency humidity measurements ?

A) The IRGASON was calibrated before the experiment but not in between, so constant calibration coefficients were used.

41- p6, line 29 : 'when the variability of the signal' . Could you define the variability (standard deviation/average ?) ? I think it is 0.6 and not 0.6%

A) This means that if 10 min averaged normalized signal strength varied from one time step to the next more than 0.006, which is 0.6%, the corresponding 30 min flux value was excluded. This procedure was introduced due to the fact, that we found an increasing variation of the signal strength with the decrease of the total signal strength. Most likely due to contamination of the glass window of the instrument.

T) To assure data quality of the flux measurements, several quality criteria were applied. Latent heat flux data were rejected when the signal strength of the radiation source to measure the water vapour was below ~~0.5~~50%, when the variability of the signal from one 10 min average to the next one was higher than 0.6 % within ~~a~~ the 30 min time interval, and during precipitation events, as a disturbance of the water vapour measurements was expected for these conditions. Due to these quality criteria 10 % of the latent heat flux data were rejected.

46 - p7, subsection 3.2 : once you have made the corrections indicated in point 2, I suggest that you keep on calculating the multiple regressions, but not with the aim of parameterizing the offshore conditions. Rather, to show how the classical relationship between the latent heat flux and the wind and/or vapour pressure deficit behaves, under the specific conditions of a semi-arid area that is influenced by sea breeze, slope breeze or both. The multiple regressions should be done for onshore and offshore data separately (provided that 19% of the dataset is enough to apply your method to the offshore data). Note that the regressions you examine *are similar to the aerodynamic (or bulk model) from Brutsaert. That is why I am not surprised by the good correlations you obtained in Table 4 for V0. That is also the reason why I do not agree with the idea of using these multiple regressions to calculate offshore winds. I also think that the presentation of the simple regressions should be shorter since they are known to fail to represent the flux but they can serve as a base to compare the multiple regression $H = f(U;\Delta T)$, to the regression $H = f(U\ \Delta\Theta)$, and the same with LE, U and Δe. Please also think of using $\Delta\Theta$ instead of ΔT, although the difference will be very small. You may have noticed that I added a multiple regression $H((U;\Delta T)$. The reason is because the BREB method is partly based on this correlation.*

A) We think that the reviewer suggested the additional multiple regression for offshore data based on its wrong impression of our work flow at the beginning (also discussed in C1+C2). As we already clarified in our answer to C1+C2 that we do not use the offshore data for any calculations, there is, in our opinion, no need to establish a regression model for this part of the data.

The second point of the reviewer was to shorten the results of the simple regression results (P.13 l.1-6) and add a comparison of the multiple regression with the simple regressions. We went over the paragraph and added the following conlcusion to it: it can be seen from the comparison that wind speed has a much stronger impact on evaporation that the vapour pressure deficit (VDP) in spring, summer and winter, but that in autumn the VDP has an considerable impact as well.

The third point raised in this comment was a regression for the sensible heat flux with different variables. This was already done during the analysis. The multiple regression of H=f(U,ΔT) achieved a correlation of 0.93. These results were not presented in the paper as we wanted to keep the focus on the latent heat flux.

50 - p8 : I would substitute 'aerodynamic method' for 'aerodynamic or mass transfer method'. In fact it is the bulk method, frequently used to estimate surface fluxes over the sea, where the EC method or dissipative method are not easy to implement. Brutsaert (1982) refers to it as the 'bulk transfer' method and it is based on similarity profiles assumptions and the relationship between fluxes and wind or scalar gradients (through the Dalton or Stanton numbers). According to Brutsaert (p88 in my edition, reprinted in 1984)

$$Ev = C_e \rho_a v_a (q_{surf} - q_a) = C_e \rho_a v_a (e_{surf} - e_a) \frac{0.622}{p} \tag{1}$$

Without telling it, you assume equal transfer coefficients for evaporation and momentum ($C_e = C_d$). C_e is a mass transfer coefficient for evaporation and C_d is the drag coefficient $= \frac{u_*^2}{v_a^2}$. Introducing the logarithmic wind velocity gradient under neutral conditions, which is a second assumption, Ev becomes :

$$Ev = \frac{k^2}{(ln\frac{Z}{zo})}^2 \rho_a v_a (e_{surf} - e_a) \frac{0.622}{p} \tag{2}$$

So K_E you identify in Table 1 should not contain ρ_w. I suppose you needed to add it since the kinematic flux you calculated is in term of absolute humidity (but you should have divided Ev by ρ_a and not ρ_w).
To conclude, I suggest you add a remark concerning the assumption that Ce = Cd. Perhaps this could be explained in an additional Appendix (3). I also suggest that you move into the present subsection, your sentence from p17, lines 12-13 : 'the aerodynamic approach is the only approach designed for sub-daily time intervals'. And you could add '(typically 30 min in this study)'. I find that you well address this timescale issue in the following, specifically with Table 6 where you show the results. However, it should be also clearly mentioned in subsection 3.3 (for the 4 models).

A) Thank you very much for this comment. We followed your suggestions and added an explanation about the assumptions and steps we made, including Ce=Cd, and the use of the logarithmic wind profile. We also addressed the issue that only the aerodynamic approach can be used for sub-daily calculations. The use of ρ_w is necessary to convert evaporation Ev in mm d^{-1}.

T) An aerodynamic approach also known as mass transfer approach, the energy budget method, and two combination approaches, namely the ~~Penman equation and the~~ Priestley-Taylor ~~equation~~and Penman equation, will be evaluated on time intervals of 1, 7, 14, and 28 days. The aerodynamic approach is the only approach which is also designed for sub-daily time intervals and will thus also be tested for 30 min time intervals. [...] With the assumption of equal transfer coefficients for evaporation and momentum ($C_e = C_d$) under neutral conditions the logarithmic wind profile can be used (Van Bavel, 1966)(Table 1, V0). This is the default version of the aerodynamic method for the sensitivity studies.

57 - The hysteresis model from Duan and Bastiaanssen, $\Delta Q = aRn + b + c\frac{dRn}{dt}$ should be described including the discussion about the term $\frac{dRn}{dt}$. Note also the dependance of c on the range and variability of the water surface temperature. V3 is a specific case of V2 where b=0 and c=0, a being obtained as 'the deviation of the default version from the measurements'. Did you try to determine specific (a,b,c) for your own dataset, just to quantify the deviation relative to Duan and Bastiaanssen's results ? I do not suggest to include them in the models you use, since, doing so, you would invalidate the V5 regressions.

A) Thank you for this comment. We added some additional explanation about the hysteresis model to the paper. We also explain that in our analysis we first used the proposed ansatz from Duan and Bastiaanssen $\Delta Q = aRn + b + c\frac{dRn}{dt}$, and calculated specific a,b,c from our data set. This was done, as Duan and Bastiaanssen stated in their paper that 'a,b, and c vary largely among lakes. [...] and that lake-specific coefficients should be determined'. Then we investigated the special case b=0 and c=0. V5 is an additional 'special' case were we repeated the calculations using the hysteresis model and the coefficients from Kohler and Parmele, which means V2 and V5 are not the same.

T) Duan and Bastiaanssen (2015) proposed a hysteresis approach to calculate the heat storage term, depending only on the net radiation ($\Delta Q = a + b \cdot R_n + c \cdot dR_n/dt$). This approach is applied to the measurement data and the rresulting coefficients (a, b, c) are used in sensitivity version V2 to calculate ΔQ.

58 - Could you please be careful to discuss the assumptions of the other two models and give additional information for Kohler and Parmele's work ? I would not say that Ts has been removed (if I understood correctly) but that it has been estimated from the long-wave radiation flux. This is no-doubt an improvement, relative to your initial estimation from the similarity profile. Please use the same symbol to design the water temperature as the one you have used in the previous section, unless you want to distinguish it on purpose.

A) Thank you for the comment. We revised the description of the sensitivity studies that it hopefully becomes clearer to the reader. Kohler and Parmele did not estimate the surface temperature from longwave radiation but removed T_s by doing following approximation. He used the first two terms of a binominal expansion

$$L \uparrow = \epsilon \sigma T_s^4 = \epsilon \sigma (T_a^4 + 4T_a^3(T_s - T_a)) \tag{3}$$

and then used $T_s - T_a = (E_s - e_a)/\Delta$ to derive following parameters

$$L' = L \downarrow - L \uparrow = \epsilon_w \cdot L \downarrow - \epsilon_w \cdot \sigma \cdot T_a^4 \tag{4}$$

$$\gamma' = \gamma + \frac{4 \cdot \epsilon_w \cdot \sigma \cdot T_a^3}{K_E \cdot \rho_w \cdot L_v \cdot v_a}. \tag{5}$$

T) In V4 the uncertainty caused by the calculated longwave outgoing radiation with T_{MO} was eliminated by using an approximation from Kohler and Parmele (1967) where they calculated the longwave net radiation and the psychromatric constant using air temperature only.

62 - Fig. 2 : Please add 'prec' after 'daily precipitation amount' in the caption. Which temperature is Ta : ultrasonic at 6m, BetaTherm probe at 6m, HC2S3 probe at 2m? Please represent T_{surf} instead of Tmo. You could also show $T_{surf} - T_a$. Please represent $e_{surf} - e_a$, and perhaps also qa. I suppose the air is very dry during summer. It would be interesting to show the annual evolution of the air specific humidity. 200 Wm^{-2} are enough for the H vertical axis. It would be convenient to add a thin line for 0 Wm^{-2} in the lower panel. Did you try to represent the daily average parameters (Rn, H, LE, ΔQ) on the same graph (with a more appropriate scale on the y-axis), to be able to see the phase shift between the annual maxima and also whether the Rn variation relative to the time is linked or not with ΔQ (in relation with the hysteresis model from Duan and Bastiannssen).

A) Ta is 2m temperature. The use of T_{MO} and not T_{surf} was discussed in C2. As explained, there is no way to determine T_{surf} from satellite data and therefore we will keep T_{MO} and e_{MO} in the graph. Specific humidity was added to the graph, but presenting the daily averages made the graph very overloaded and was thus not included.

65 - p10, line 6 : 'the annual precipitation normal of 80 mm' : the word normal is not accurate. What is the period considered by Goldreich, 2003 ?

A) The period which was considered by Goldreich was the climatological standard normal period 1961-1990.
T) The ~~total~~ precipitation amount for the observation period is high compared to the ~~annual precipitation normal~~ mean annual precipitation of the standard normal period 1961 to 1990 of 80 mm (Goldreich, 2003).

68 - p10, lines 14 and 15 : are 32 and 26 % relative to lake breeze or lake breeze+ synoptic conditions ?
A) These values are relative to the total amount of days in winter.
T) In winter, the synoptic conditions gained more influence and often superimposed the local wind field such that a north-easterly lake breeze was only observed ~~at~~ on about 32 % of the days and a south-easterly flow ~~at~~ on 26 % of the days ~~.~~ in winter 2014/15.

76 - p10, discussion on the energy budget : you assume that the energy budget is closed and you never discuss the frequent non-closure energy budget problem that is reported in several studies in the literature (see Foken et al. in Aubinet et al. p108-109). You cannot avoid this discussion, even if there is no mean to estimate the error, especially because your measurements are done at the boundary between the marine and the continental surface layers. Under these conditions, the surface change may generate large scale heterogeneities that are unlikely to be correctly taken into account by the local measurements. You show in Fig. 3, extreme values of ΔQ that are of the order of the net radiative flux in spring and summer. It is unlikely to be true. Anyway, it is known that the shorter the timescale, the larger the non-closure. By contrast, the average ΔQ (daily average) is about 100 Wm^{-2} during summer and decreases down to a few tenth of Wm^{-2} in winter, which are rational values (I remember that LE has to be recalculated, but it should not be very different).
A) Thank you for the comment. We agree with the reviewer that for every EC system there are uncertainties and a possible non closure of the energy balance. The reviewer is right, that we should address this point in context of the calculation of the heat storage as a residuum. We addressed this point in section 2 (Measurement site and Instrumentation.
T) Furthermore, the heat storage of the lake was not measured and was therefore calculated as the residuum of the energy balance equation ($Rn = LE + H + \Delta Q$). Notable hereby is that ΔQ also contains the possible non-closure of the energy balance. Considering the values of common energy balance closure studies (Foken, 2008; Wilson et al., 2002) the heat storage is thus most likely about 20 % smaller than calculated.

3.2 Linguistical Comments

A) Thank you very much for these detailed comments. We considered the comments in our revised version of the paper.

5 - The term 'evaporation' you frequently use is not accurate enough. I will point it out in the following.
A) we revised the paper and either use 'evaporation rates' or 'annual evaporation'.

6 - p1, line 6 : 'total annual amount measured' → 'total annual amount of evaporation measured' (in this case, you do not need to be more accurate since you provide the evaporation unit).

7 - p1, line 7 and further on : 'vapour pressure deficit' ← 'water vapour pressure deficit'
A) rephrased

8 - p1, line 8 : 'Consequently' is not appropriate. Perhaps 'in fact' could be used instead. What do you mean by 'evaporation amounts' ?
A) rephrased
T) ~~Consequently, the local wind systems define the diurnal evaporation cycle~~[...] After sunset, the strong winds cause half hourly evaporation rates which are up to 100 % higher than during daytime...

9 - p1, line 10 could be changed to ← 'during daytime. During nighttime, evaporation rates are also larger than the daytime evaporation rates, due to strong ...'. Why do you use 'evaporation rate' this time ?
Note that this result will perhaps require corrections, in light of what is said in the following (see my final

remarks for instance).
A) rephrased
T) The results show that the diurnal evaporation cycle ~~. In the evening~~is governed by three local wind systems: a lake breeze during daytime, strong downslope winds ~~govern the wind field and cause evaporation amounts~~ in the evening and strong northerly along-valley flows during the night. After sunset, the strong winds cause half hourly evaporation rates which are up to 100 % higher than during daytime~~, and also during the night evaporation rates are accelerated compared to daytime evaporation, due to strong northerly along-valley flows.~~

10 - p1, line 11 : The link 'Furthermore' is somewhat awkward. You should explain here why you calculated the regressions. By the way, I think that the multiple regressions should be established for another purpose (see my remark 46-). A) changed
To account for lake evaporation during offshore wind conditions, a robust and reliable multiple regression model was developed using the identified governing factors

11 - p1, line 14 is clear and nice. I skip lines 15, p1 to the Introduction, p2.

12 - p2, line 6 : you could add 'down' after '90%'.
A) rephrased

14 - p2, line 9 : 'The total amount is about' ←'The total amount of loss is about'
A) rephrased to 'The total loss of water is about'

15 - You could add a budget equation such as : 10^6 (400+240-250)+evaporation = -650 10^6, which gives evaporation = -1060 $10^6 m^3 a^{-1}$, which is in the range 700 - 1400 10^6, indicated by Gavrieli et al., 2006.
A) a budget equation was not added but the sentence was rephrased.
T) The spread of the evaporation estimates ranges from 1.05 to 2 m a^{-1}~~(Stanhill, 1994; Salameh and El-Naser, 1999)~~, comparable to a volume loss of $700 - 1334 \cdot 10^6$ m^3 a^{-1}(Stanhill, 1994; Salameh and El-Naser, 1999).

16 - p2, lines 13-14-15 : I would replace ' Evaporation is not only ....environmental problems.' by something like 'It is important to assess the water budget components of the Dead Sea for a climatological purpose, but it is also a priority for the people and the socio-economic development of the region to anticipate the evolution of these components and the consequence for the environment. For instance, the lake level decline causes severe environmental problems . ' (you may of course change the words).
A) we added following sentence:
T) It is important to assess the water budget components of the Dead Sea for a climatological purpose, but it is also of importance for the people and the socio-economic development of the region to anticipate the evolution of these components and the resulting consequences for the environment. For instance, the lake level decline causes severe environmental problems.

18b - p 2, line 29 (no link with 18a) : I do not understand 'especially' in this context ('In addition' ?). Perhaps you could also mention whether it is a fresh water fish. Ein Feshkha reserve ?
A) it should just be an example so I rephrased it to:
T) endangering the unique flora and fauna in the Dead Sea region , such as the unique fish population of the Ein Feshkha reserve.

18c - p3, line 5 : I would add 'in the evaporation estimations' just before '(Stanhill, 1994'.
A) added
T) To minimise the spread of 1.05 to 2 m a^{-1} in the evaporation estimates (Stanhill, 1994; Salameh and El-Naser, 1999) and reduce uncertainties, direct measurements of the Dead Sea evaporation are required.

18d - p3, lines 6-7 : I would remove : 'Furthermore, the governing factors of the Dead Sea evaporation, e.g. wind velocity, vapour pressure deficit, or net radiation, have to be identified, to validate the indirect methods'. These parameters are governing factors every where in the world and you do not have to prove it. I think this sentence is confusing at this point.

A) The sentence was removed.

T) ~~Furthermore, the governing factors of the Dead Sea evaporation, e.g. wind velocity, vapour pressure deficit, or net radiation, have to be identified, to validate the indirect methods.~~

18e - p3, line 8 : 'with a high temporal resolution' instead of ',in high temporal resolution'.

A) rephrased

The eddy covariance technique is the only method to obtain direct evaporation measurements~~, in high temporal resolution, which can be linked to meteorological variables afterwards. It~~

19 - p3, line 10 : 'continues' ← 'continuous'

A) rephrased

20 - p3, line 12 : according to Wikipedia, it seems that Lake Kinneret is the same as Lake Tiberias mentioned by Kottmeier et al. (2016) (it is only a remark, you choose the name you prefer). You could perhaps add that it is crossed by the Jordan river which partly feeds the Dead Sea. It is not a major piece of information but I find it nice to provide the reader an idea of the geographical environment.

A) You are right. Lake Kinneret and Lake Tiberias refer to the same name and can be used synonymously. But as you suggested I added some information about the Jordan river:

T) 'Assouline and Mahrer (1993) measured evaporation from Lake Kinneret, a freshwater lake north of the Dead Sea, crossed by the Jordan river, and Tanny et al. (2008) measured evaporation from a small reservoir also north of the Dead Sea using eddy covariance systems. '

21 - p3, line 13 : 'to the authors knowledge' instead of 'as to the authors knowledge'.

A) rephrased

However, ~~as~~ to the authors knowledge, ...

22 - p3, line 14 : 'Therefore, long-term eddy covariance measurements are conducted' ← 'That is why, in the frame of the international DESERVE project (Kottmeier et al., 2016), long-term eddy covariance measurements were conducted'

A) rephrased

T) That is why, in the framework of the international DESERVE project (Kottmeier et al., 2016), a new concept of assessing lake evaporation from onshore measurements was applied. ~~Therefore, long-term~~ Long-term eddy covariance measurements ~~are~~ were conducted at the Dead Sea shore~~to measure the latent and sensible heat fluxes, as well as temperature, humidity, precipitation, radiation, wind speed, and wind direction. The measurement location directly at the shoreline provides flux data from the water surface~~ , which provided evaporation data for onshore wind conditions. ~~The station is complemented by two additional eddy covariance stations in close vicinity to provide additional data from the homogeneous desert land surface and from a vegetated area.~~

23 - p3, line 17 : 'provided' and 'was' instead of 'provides' and 'is'

A) rephrased

T) see comment 22

24 - p3, lines 17-19 : I perhaps misunderstood but it seems to me you did not use the data from these stations. Is it useful to quote them ?

A) the sentence was deleted:

T) ~~The station is complemented by two additional eddy covariance stations in close vicinity to provide additional data from the homogeneous desert land surface and from a vegetated area.~~

25 - p3, lines 19-21 : 'Provide', 'Evaluate' and 'Evaluate' instead of the same with 'ing'.

A) rephrased

T) (i) ~~Providing~~ Provide [...] (ii) ~~Evaluating~~ Evaluate [...] (iii) ~~evaluating~~ evaluate [...].

26 - p3, Measurement site : it is difficult to distinguish in Fig. 1, how far the Judean mountains highest submits are from the lake and what their height is (hills or mountains ?). The Moab mountains are clearly

shown.
A) Fig 1 was changed

27 - Fig. 1 : you forgot to write 'Jordan river' in panel (a). Landsat with an L in the caption. The red arrows are a little confusing in panel (b) : simple lines instead of arrows would be enough.
A) Fig 1 was changed

28 - p5, line 4 : Rotronic
A) corrected
T) temperature and humidity at 2 m height (HC2S3, ~~Rototronics~~Rotronic),...

30 - p5, line 7 : please add 'open path' before 'integrated gas analyser'. I suppose that at 6m, it did not suffer from spray, even under strong onshore wind conditions ...
A) 'open path' was added to the text. The instrument did not suffer from spray.
T) With a temporal resolution of 20 Hz, water vapour, CO_2 concentration, sonic temperature and the three wind components were measured with an open path integrated gas analyzer and sonic anemometer (IRGASON) from Campbell Scientific at 6 m height.

31 - p5, line 9 : 'From the 20 Hz data evaporation was calculated using the eddy covariance technique'→ 'The latent heat flux was calculated from the 20 Hz data using the eddy covariance method.'
A) rephrased
T) The latent and sensible heat flux were calculated from the 20 Hz data ~~evaporation was calculated~~ using the eddy covariance ~~technique~~method.

32a - p5, line 9-10 : ←'The principle of the method, the post-processing and data quality control steps are presented in Sec. 3.1'.
A) rephrased
T) The principle of the ~~eddy covariance theory, the applied~~ method, the post-processing ~~steps and the used objective method for~~ and data quality control steps are presented in ~~the following~~ Sec. 3.2.

32b - p5, lines 11-12 : please consider the multiple regressions again (after 46-)
A) see comments to C1

33 - p5, eq (1) and line 23 : the ultrasonic anemometer provides the virtual air temperature and not the air temperature Ta. The Schotanus correction is made, as you say in Sec. 3.1.1, to take this point into account.
A) was corrected in eq (1)
T) $H = c_p \cdot \rho_a \cdot \overline{w' T'_{sonic}}$,

35 - p5, eq (3) and line 27 : as said before, Tw should be Ta.
A) Tw is correct. See answer to C1.

36 - p5-6, lines 27 to 5 : the text should be deleted from 'For salt water ..' to the end of the subsection.
A) See answer to C1.

37 - p6, line 8 : 'measurement limitations' you could add 'of the sensors'
A) changed
T) In particular, measurement limitations of the sensors, non-stationary conditions over the averaging period, as well as horizontal heterogeneity have to be considered (Foken et al., 2012).

38- p6, lines 18 to 24 : it seems to me that the order should be : spectral corrections, Schotanus correction and Webb correction unless you applied an iterative process.
A) thank you for noting the wrong order. The corrections were applied as you said. The order in the text was changed
T) Spectral corrections were performed to account for the loss of energy for high frequencies, due to path-length

averaging and limited sensor frequency response, following the approach after Mauder and Foken (2011).The influence of humidity on sonic temperature plays an important role for the calculation of the sensible heat flux. To account for this influence, the Schotanus correction (Schotanus et al., 1983) was applied. This correction is particularly important for flux calculations ~~for~~ at sites with high humidity fluctuations, such as over the water surface. The water vapour measurements are influenced by temperature and humidity changes, as only the molar density of water vapour is measured and not the mass mixing ratio. To consider the density fluctuations, corrections after Webb et al. (1980) were applied. ~~Finally, spectral corrections were performed to account for the loss of energy for high frequencies, due to path-length averaging and limited sensor frequency response, following the approach after Mauder and Foken (2011).~~

40- p6, line 28 : 0.5 g/kg ?

A) 0.5 in the sense of normalised signal strength. For better understanding it was changed to 50%

T) Latent heat flux data were rejected when the signal strength of the radiation source to measure the water vapour was below ~~0.5~~50%, when the variability of the signal from one time step to the next one was higher than 0.6 % within ~~a~~ the 30 min time interval, and during precipitation events, as a disturbance of the water vapour measurements was expected for these conditions.

42 - p6 line 31 to p7 line 2 : you say too much or not enough. It would be nice to describe the tests and to say what ITC is.

A) As these tests are widely known, and commonly used in eddy covariance processing and also implemented in the TK3 software we decided against describing these tests in detail. The reader is referred to the literature.

T) Further quality control was performed using the steady state test after Foken and Wichura (1996), which analyses each 30 min time interval on stationarity ~~. The~~ and the integral turbulence characteristics (ITC) test after Foken et al. (2012), which checks data on fully developed turbulent conditions~~and, therefore, compares modelled ITC to the actually measured ones, and if the deviation is less than 30 % very good data quality is assumed~~.

43 - p7 and further on : I would replace 'fetch' by 'source area'.

A) 'fetch' is a commonly used word to describe the distance from the tower when describing the flux footprint and will therefore not be changed.

44 - p7, lines 6-7 : please consider again the rejection of these data : I agree that it is important to distinguish them from the onshore measurements data, but the fluxes are what they are and do not have to be rejected.Nevertheless, it is important to quantify this contribution since the source area may be different.

A) as the aim of the paper is to analyse fluxes from the water surface only and the regression model is used to estimate evaporation for offshore wind conditions, this data has to be rejected for the calculations.

45 - p7, lines 7 to 9 : I would replace the 2 sentences 'For southerly wind directions ... 600m away from the headland.' by 'For southerly and northerly wind directions the source area is over water and the average source area contributing to 80% of the flux ranges from 0 to 300 m and 0 to 600 m, respectively, ahead of EBS.'

A) rephrased

T) For southerly and northerly wind directions, the fetch is over water and the average fetch contributing to 80 % of the flux ~~footprint is in the range of~~ ranges from 0 to 300 m ~~away from the headland~~ and 0 to 600 m, respectively.

47 - p8, line 1 : 'Indirect methods to estimate evaporation' ← 'Description of four indirect methods to estimate evaporation'

A) Thank you for the comment, but we keep the shorter heading

48a - p8 : I would move the first two (essential) sentences of subsection 4.4 ('For the calculation of evaporation -please insert a comma here-, several equations, based on .... at least 7 days') to the beginning of section 3.3.

A) Thank you for this remark we moved the sentence to Sec.3.3

T) For the calculation of evaporation, several equations, based on different physical approaches, exist. Each approach connects evaporation to different meteorological parameters and is designed for different time intervals, ranging from sub-daily calculations to a time interval of at least 7 days. Four commonly used indirect methods to estimate evaporation ...

48b - p8, line 5 'an overview of which sensitivity study is performed' (I added 'of').
A) sentence was rephrased to:
T) An overview of the sensitivity studies and to which of the methods it is applied to, is given in Table 2.

49 - Ev is not defined. I suppose it is the evaporation rate defined as Ev=ρ_a w0q0 (Brutsaert, 1982).
A) definition is added:
T) Selection of commonly used equations to calculate evaporation (Ev)

51 - The sensitivity study, referred to as V1, is performed to address the stability issue. The presentation of the stability factors you refer to (Cline 1977) p. 17 should also be moved to the present subsection. I would also describe the new KE (including the stability factor) in Appendix 3. You could also add that the stability functions for wind and heat are expressed in terms of the bulk Richardson number, which allows estimating the stability when the turbulent fluxes are not known.

52 - Energy budget : Here again, ρ_w should vanish if you use the specific humidity instead of the absolute.
A) see answer to comment 50

53 - I suggest that you write down the budget equation as Giadrossich, 2015 did (their eq 1) : Rn + Anet = LE + H +ΔQ , where Anet is the net heat advected into the lake (by stream flow and precipitation minus the heat loss due to evaporation minus the heat transferred at the bottom of the lake) and ΔQ is the heat storage per unit area in the lake (for most cases) or in the ground (for specific cases with strong offshore winds. Under these conditions, Anet can be ignored). This energy balance applies to timescales larger than the day due to the advection term that cannot be known at a short timescale.
54 - With V0, you neglect ΔQ and Anet . [Note that the resulting reduced budget equation can also be applied at a sub-daily scale.] Neglecting ΔQ is a coarse assumption that is valid only under specific and occasional conditions. I think you should mention it at first and say that V0, even unrealistic, is a basis for the BREB method that will be improved by V1 and V2. I mean that V1 and V2 should not only be considered as sensitivity studies for V0, but as 2 alternative methods for V0.
A) we added some explanation:
T) . Because of the aforementioned reasons and the difficulty to obtain these three terms, the net advected heat, the ground heat flux and the heat storage term are neglected in many studies. Thus, for the default version (V0) of the BREB method ~~the net advected heat, the ground heat flux and the heat storage term~~ these three terms are neglected (Table 1)~~. Using this version~~. Even though neglecting the heat storage on the time scales investigated is a coarse assumption it serves as a basis for the sensitivity studies V1 and V2.

55 - p9, line 8 : you forgot to mention the water vapour deficit.
A) thank you for noting this. It was added to the text:
T) Using ~~this version~~V0, only net radiation, surface water temperature, ~~and air temperature~~air temperature, and the vapour pressure deficit have to be known, which are relatively easy to obtain and thus an easy approach to calculate evaporation.

56 - β, the Bowen ratio should be defined as H/LE. When fluxes are unknown, β can be approximated by the expression you give, provided that K_Θ, the Stanton number for temperature = Ce, the equivalent for evaporation. Also, be careful not to use the same symbol for the Bowen ratio and the activity of water in Appendix A (I would keep β for the Bowen ratio).
A) Thank you for noting the duplicate of β. We changed it to Bo. *59 - Table 1 : caption : default versions (V0) in Sec. 3.3 and 4.4. (just add 3.3) Fn and Δt are not used and ρ_w should not be used. Please take into account my remarks in 2- Priestley-Taylor is presented as the 3rd method in Sec 3.3.*
A) the order of Priestley-Taylor and Penman was changed. also the caption was changed to:
T)Selection of commonly used equations to calculate evaporation (Ev) in mm d^{-1}.The original version and the default version (V0) used in Sec. 3.4 and 4.4 are presented.

60 - Meteorological conditions : this subsection will have to be read again after new LE, T_{surf}, Δe values ...

61 - For some parameters, the daily values and their evolution are also interesting to discuss in addition to the extreme values.

63 - p10, line 4 : 'long term annual mean' : during which period ?
A) rephrased to
T) In the Dead Sea valley the measured average annual air temperature was 26.5°C for the measurement period, which was slightly higher than the long term annual mean of 25.9 °C found by Hecht and Gertman (2003) for the period 1992 to 2002.

64 - p10, line 5 : please add 'sometimes' before 'exceeded'
A) was changed to regularly.

66 - p10, line 7 : 'made' instead of 'makes'
A) was changed

67 - p10, line 9 : 'only during the winter seasons a different behaviour was found' ←except during winter, when the wind increased in connection with the convective activity, a different behaviour was found'
A) rephrased to
T) However, during winter, ~~only during the winter seasons~~ a different behaviour was found when the wind increased in connection with the stronger large scale activity (Fig. 2).

68 - p10, lines 14 and 15 : are 32 and 26 % relative to lake breeze or lake breeze+ synoptic conditions ?
A) its relative to the amount of days in winter. Text changed to: T) In winter, the synoptic conditions gained more influence and often superimposed the local wind field such that a north-easterly lake breeze was only observed on about 32 % of the days and a south-easterly flow on 26 % of the days in winter 2014/15.

69 - p10, line 15 : Please indicate the direction of the downslope breeze (north-westerly)
A) changed accordingly: T) In the evening, north-westerly downslope winds, often enhanced by the Mediterranean Sea Breeze (MSB)

70 - p10, line 16 : 'yielded' instead of 'lead to'
A) thank you for the comment. we think in this case 'lead to' is also suitable'

71 - p10, lines 18, 19, 24 : 'exceeding' instead of 'of over'
A) was changed.
T) The downslope winds regularly reached mean wind velocities ~~of over~~ exceeding 10 m s^{-1} (Fig. 3 b). During the night, a northerly along-valley flow prevailed mainly in spring and summer. The along-valley flow also reached wind velocities ~~of over~~ exceeding 10 m s^{-1} (Fig. 3 c). The net radiation reaches maximum values ~~of over~~ exceeding 900 W m^{-2} in summer and about 500 W m^{-2} in winter.
72 - p10, line 22 : 'November a Red Sea Trough with a central axis advected dry and warm air'→ 'November, when a Red Sea Trough advected dry and warm air'
A) changed to:
T)~~at~~ in the beginning of November,when a Red Sea Trough with a central axis advected dry and warm air into the valley over the course of several days.

73 - p10, line 25 : 'However, at' ←'However, on'
A) changed to:
T) However, ~~at~~ on individual days in some winter latent heat flux values even exceed the summer values.

74 - p10, line 26 : 'in winter latent heat flux values' ←'in winter some latent heat flux values'
A) see comment 73

75 - p10, line 27 : the energy balance equation should have been shown in subsection 3.3. You only need to say that at this timescale (24h), Anet is ignored. Do you think it is still correct after rainfall ?
A) The equation is now shown in Table 1

77 - p10, line 31 : please reword 'used for heating the lake, which is stronger in spring than in winter'. This is grammatically false.
A) The sentence was deleted

78 - p10, line 33 : I do not see that ΔQ is negative in winter.
A) There is negative heat storage in winter. However, the net annual amount is positive. Several other studies like (Stanhill, 1990; Anati et al., 1987) already documented this and the thereby caused steady increase of the lake temperature over the last couple of years is also documented (e.g Hecht and Gertman (2003)).

79 - p 12, fig 3 : it is usually required to indicate the delay between the UTC and local time. You can keep LT and indicate, on the first time (UTC +3h). It would be also interesting to add in the caption the approximate time of sunrise and sunset, especially from Spring to Autumn.
A) thank you for pointing that out. UTC deviation was added to the text:
T) Through the predominant local wind systems, these wind directions occur almost exclusively in the evening between 17:30 to 20:30 LT (LT=UTC+2) from spring until autumn (Fig. 3)

80 - p12, line 4 : ←'and, thus, [at] most of the [days] data within this time frame' (remove the [words]).
A) changed accordingly:
T) ~~at~~ most of the ~~days~~ data within this time frame are excluded.

81 - p12, line 6 : ←'also for the study of the intra-annual .... this gap' (instead of these gaps).
A) rephrased

82 - p12, line 6 : 'A multiple regression model was applied ... for offshore conditions' : As said before, I do not agree with this method : I'm waiting for your decision, regarding the suggestions I made in 2-
A) see answer to C1

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Reply to Reviewer 2

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1 General Comment

This a very interesting paper, addressing an important environmental issue (evapora- tion from the Dead Sea), presenting very important data and (apparently for the first time) directly measured evaporation rates and thus adding important new information to our knowledge. There is no doubt, therefore, that the paper should eventually be published in one or the other form. There are three main pillars: first, to measure, directly, the lake's evaporation using an EC station on the shore (therewith employing the footprint of the water surface). This provides direct measurements for about 70% of the time. I think this approach is well motivated, well explained and also 'well executed' (all the necessary data treatment, corrections, QC, etc.). To estimate, as a second pillar, evaporation during the remaining 30% of the time, a statistical model is trained using the onshore wind conditions and the available in- formation during these conditions, to estimate lake evaporation during offshore wind direction. This is very appropriate (and possibly novel) as an approach, and so is the statistical approach, its presentation (and results). However, it has the drawback that the estimated evaporation rates are among the largest during the whole year and thus contribute a substantial fraction of the total (yearly, monthly, daily – the shorter the more variable) evaporation. Therefore, the statistical model does not only have to be tested using the 'usual' tests (cross-validation, etc.) based on the available onshore conditions (what is convincingly being done), but attempts should be made to support the hypothesis that the same statistical model applies (yields the claimed 'good' statistics) when the input data stem from offshore situations (high wind speed in combination with low water vapor pressure deficit). Some suggestions are provided in major comments 2 and 3. As a third pillar, empirical estimates (for evaporation) are compared in their performance to the measured evaporation. This is adding a great deal of value to the paper. Unfortunately, for three out of four methods the comparison is not valid (because net radiation is not measured over water – which basically invalidates all the estimates; see major comment 1). Furthermore, the estimation of heat storage (in the water) is also flawed (see again major comment 1), so that all the different 'versions' tested are not really conclusive (with the exception of V1). Indeed, the results show that all the empirical methods using net radiation give results quite different from the observations (if only measured – and not estimated – values would be considered, this finding would probably be even more pronounced). The only 'reliable' empirical method is the aerodynamic approach (not using Rn). The problem with the different fields of view (for radiation and turbulent fluxes) could somehow be overcome (for example by using satellite – or other – observations [even literature values would be better than nothing] to correct for albedo differences between land and water, and by using the [simultaneously measured] land surface temperature [from the two additional EC sites over land] and the estimated lake surface temperature to correct for different longwave outgoing radiation). To actually estimate heat storage in the water from the available data I con- sider virtually impossible – so that the hysteresis model is possibly the only available source. Overall, the addressed issues call for truly major revisions before this paper can e published in HESS.

We thank the reviewer for the detailed and insightful review. We are sure they will help to improve the paper. Responses to individual comments are provided below. Reviewer's comments are in italic.

2 Major Comments

C1) Heat storage is calculated as the residuum (P10, l. 26): the authors use the same notation (delta_Q) as above for the 'heat storage of the lake' (p9, l. 5). So, is this meant to yield the heat storage of the lake *using the local energy balance? This is not appropriate for two reasons. First of all, the energy balance is based on the turbulent fluxes (which can, in my opinion, be interpreted as reflecting the heat fluxes in the footprint, i.e. over water – of course, if the wind direction is accordingly). Net radiation, however, has a much smaller 'field of view' (a circle with a radius of maybe 2 m a for measurement height of 6 m), so that the albedo is that of the land surface, and the same is true for the longwave outgoing radiation. The considered energy balance, therefore, is reflecting (a combination of) two different surfaces – and the difference cannot be attributed to 'anything' (if not a careful disentangling of the differences between radiation conditions is performed). Second, even if the various sensors would see the same surface, the energy balance (measured at 6 m agl) cannot be expected to be closed. There will be mean advection (possibly even in the vertical – as this location is so close to a step change in surface conditions; water – land), storage (in the air layer between the surface and the sensors!), possibly even vertical flux divergence. Finally, for the local energy balance (still assuming that all the observations correspond to the same surface type), one would also need the ground heat flux. Give the importance of this term (P10, l. 30) the authors need definitely to do something about it*

A) Thank you for this comment. Yes, heat storage was meant to be calculated from the local energy balance. Addressing the first point of the reviewer: it's right that the sensor mounted at the station is located over land and thus, outgoing longwave and reflected shortwave radiation do not represent the water surface. We considered this problem using following approach:
To calculate reflected shortwave radiation, we used literature values of the albedo for the Dead Sea and additionally performed a short-term experiment, with radiation measurements directly over the water surface to confirm the literature values for our site. Stanhill (1987) calculated the albedo of the Dead Sea surface from ship measurements and reports values of 0.06 in the summer months and 0.09 in the winter months and an annual average of 0.07. He also reported albedo values from Kondrat'Ev (1969) for the latitude of the Dead Sea and the cloud cover observed in the northern part of the Dead Sea, which was 0.08 for November and 0.07 as an average annual albedo value. The results of the short-term experiment concurred well with the literature values and thus the annual average of 0.07 was used in our calculations. For the longwave outgoing radiation we used the Stefan-Boltzmann equation with a water surface emissivity of $\epsilon = 0.98$ (e.g. Konda et al. (1994)) and the surface water temperature calculated with the Monin-Obukhov approach. We also compared it with the results of the short-term experiment, where we found a good agreement. We will add a paragraph to the paper where we will explain this procedure.
The second point of the reviewer discussed the problem of energy balance closure. For every EC system there are uncertainties and a possible non closure of the energy balance through e.g. mean advection. The reviewer is right, that through calculating the heat storage as a residuum, the mentioned amount of heat storage on P10 l.30 also includes the possible non closure of the energy balance. It is definitely important to mention it in this context.
T) We added a subsection on radiation calculations to section 3: The measurements of the radiation components of the lower half space are not conducted directly over the water surface, but over the land surface. Therefore, these two components have to be calculated. The reflected shortwave radiation was calculated using literature values of the Dead Sea albedo. Stanhill (1987) calculated the albedo of the Dead Sea surface from ship measurements and reported values of 0.06 in the summer months, 0.09 in the winter months, and an annual average of 0.07. He also reported albedo values from Kondrat'Ev (1969) for the latitude of the Dead Sea and the cloud cover observed in the northern part of the Dead Sea, which was 0.08 for November and 0.07 as an average annual albedo value. To confirm the validity of the literature values for our site, a short-term experiment was conducted in November 2014. Albedo values of 0.08 to 0.09 concurred well with the literature values for winter. As the literature values for summer could not be compared to measurements, the annual average of 0.07 was used for all calculations. The longwave outgoing radiation was calculated using the Stephan-Boltzmann equation

$$Rl \uparrow = \epsilon \cdot k_B \cdot T_S^4, \tag{1}$$

with the water surface emissivity $\epsilon = 0.98$ (e.g. Konda et al. (1994)) and the Stephan-Boltzman constant, k_B. For the surface water temperature, T_S, no in-situ measurements were available. Also remotely sensed surface water temperature products could not be used as operational SST algorithms are calibrated to mean sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. Nehorai et al. (2009) showed that a calibration of satellite data with in-situ measurements is necessary. Furthermore, Nehorai et al. (2009) raised concerns that enhanced water vapour input into the atmosphere through evaporation causes stronger absorption of thermal IR radiation, which leads to a screening of the Dead Sea surface and thus incorrect estimates of the surface water temperature. Following the results of Nehorai et al. (2013), which showed that "SST is highly correlated to

air temperature ($R^2 = 0.93 - 0.98$) in all seasons" the Monin-Obukhov similarity approach was used to calculate surface water temperature from the measured air temperature (see Appendix A), and is further on referred to as T_{MO}.
We also explained the influence of the non closure of the energy balance on the heat storage in Sec.2:
Furthermore, the heat storage of the lake was not measured and was therefore calculated as the residuum of the energy balance equation ($R_n = LE + H + \Delta Q$) using half hourly measurements. Notable hereby is that ΔQ also contains the possible non-closure of the energy balance. Considering the values of common energy balance closure studies (Foken, 2008; Wilson et al., 2002) the heat storage is thus most likely about 20 % smaller than calculated.

C2) Statistical model to estimate latent heat flux during offshore conditions: (P14, l. 8) Values up to 200 Wm-2 ...: Interestingly, the estimated values are larger than the measured values (even on average!). Given the statistical model and the high wind speeds especially during the evening hours – in combination with presumed small water vapor pressure deficit - in spring and summer (Fig. 3), this suggests that the statistical model has possibly been used outside the conditions, for which it has been 'constructed'. In other words, the statistical model is trained for cases of high wind speeds (but possibly not even as high as the downslope winds) in combination with (relatively) small water vapor pressure deficit while it is being used for high wind speed and large delta_e. Since these estimated values are not only to fill some gaps in the measured time series but produce the largest values for characteristic times (i.e., after the evening transition), the authors should try to make a very strong case for these estimated latent heat fluxes. In this sense, the statistical model should not only be evaluated in the 'classical sense' (as it is being done – and very convincingly!), but also the question (hypothesis) should be addressed, whether the onshore (training) and offshore (application) conditions are comparable. In other words, how is delta_e over land related to delta_e over water? For this, potentially the two additional EC sites (p3, l. 17 - they are apparently avail able but not used in this study) could be employed. Similarly, the question should be addressed how the strong downslope winds are related to typical wind speed over water. The question here is therefore whether there is any suitable information (possibly from other studies or sources), which would support the hypothesis that the observed (offshore) wind speed can be used to estimate the wind speed over the [entire] Dead Sea.

A) Thank you for this comment. To assure, that the model is not applied outside the conditions for which it has been 'constructed', the extreme values of offshore wind velocity and vapour pressure deficit, were not considered to calculate evaporation and it was always checked that data were not extrapolated. Extreme values in this case were considered to be the 1st and 99th percentile of the data and with this regulation wind velocity and vapour pressure deficit values, which were used to calculate evaporation were within the model boundaries. Evaporation values, which could not be calculated because wind velocity or vapour pressure deficit were outside the boundaries were treated as missing values and filled with the corresponding value of the median diurnal cycle. We know that this might lead to an underestimation of evaporation, but with this procedure we took care that training and application data were comparable and that the model was not used outside the training conditions.
The wind velocity measured at the station is a point measurement, so it is not valid for the entire Dead Sea water surface. However, the offshore wind velocities measured at the station are in our opinion suitable for the water area, and thus the fetch around the station. This is also confirmed by wind lidar measurements, which were performed during the DESERVE project. The measurements showed that westerly winds in the evening regularly reached several km over the lake without loosing its strength. Furthermore other studies from Weiss et al. (1988) and Hecht and Gertman (2003), evaluated data aquired in the middle of the lake. They both observed westerly winds in their data and listed strong wind events with hourly averaged velocities between 8 to 9 $\mathrm{m\,s^{-1}}$ in the study of Weiss et al. (1988) and 10 to 12 $\mathrm{m\,s^{-1}}$ in the study from Hecht and Gertman (2003).
For the vapour pressure deficit we don't have data from the middle of the lake to directly compare it, but we made following observations: 1) We have seen in the data that the strong westerly winds are connected with high turbulence, and even rotor formation was observed. This means that vertical mixing and air mass exchange is enhanced and thus VDP decrease should be low. 2) The fetch of the station is around 600 m. In our opinion the decrease of VDP within such a distance is not very strong considering the turbulent mixing. 3) Evaporation has a stronger dependence on wind velocity than on VDP which makes the influence of VDP variations on the results weaker. But we agree with the reviewer that this is an uncertainty which has to be mentioned and is now

discussed in the discussion chapter. We also agree that the measured evaporation is only valid for the footprint of the measurement location and that it can vary from other areas of the water surface. Estimates of the entire Dead Sea evaporation are not possible by EC measurements, only by applying models. So for future work, the presented regression model can be used to estimate evaporation for the whole water area, when using model data (wind velocity and vapour pressure deficit) at multiple locations over the Dead Sea water surface.
We added following paragraph to Section 4.2:
T) In summary, the regression model X_{LE} provides a suitable and robust method to calculate the latent heat flux for offshore wind conditions. To assure, that the model is not applied outside the conditions for which it has been constructed, the extreme values of offshore wind velocity and vapour pressure deficit were not considered to calculate evaporation and it was checked that data were always within the model boundaries. Evaporation values, which could not be calculated because wind velocity or vapour pressure deficit were outside the boundaries were treated as missing values.
Furthermore we discussed the so introduced uncertainties in the discussion section:
However, there is still some uncertainty to this method which cannot be accounted for directly. On the one hand, extreme values of wind velocity and water vapour pressure deficit were not used to calculate evaporation when they were outside the model boundaries. This leads most likely to an underestimation of the actual evaporation amount. On the other hand, wind velocity and vapour pressure deficit could decrease with increasing distance from the shoreline, which would lead to an overestimation of evaporation. The comparison with results from measurements in the middle of the lake (Weiss et al., 1988; Hecht and Gertman, 2003) shows that even in the middle of the lake westerly winds with hourly averaged velocities between 8 and 12 m s^{-1} were observed. Also wind lidar measurements confirmed, that the westerly winds regularly reached several km over the lake without loosing its strength (Metzger, 2017). So offshore wind measurement seem representative for the calculation of evaporation. A decrease of vapour pressure deficit has to be considered, but is most likely small due to the following reasons. Firstly, the fetch of the station is quite limited with 600 m, and secondly the westerly winds are connected with high turbulence and thus strong vertical mixing (Metzger, 2017).

C3) The Discussion Section as a whole is, first of all, more a summary than a discussion. Much of what has been stated before is repeated (and the 'discussion' consists to some extent in adding some literature values). The statistical model, for example, is repeated to be good enough (no discussion), rather than addressing potential difficulties (see major comment 2).
The 'problem' with the downslope winds (having a stronger wind speed that over the lake, and (probably much) larger water vapor pres- sure deficit is mentioned - but only mentioned to yield a 'slight overestimation'. Based on what is this called 'slight'? Is it 10% (and would 10% be slight)? Or 50%? (but only occurring during 30% of the hours? – and what is then slight?). I think this would be a discussion.
Another point that apparently needs discussion is the fact that the radiation measurement does not 'see' the same surface as the authors want to probe with their EC system, i.e. the lake surface. In fact, I think that either all the aspects, which include Rn have either to be removed from the paper, or an estimate has to be made to establish a method to estimate Rn over water from measured Rn over land (see major comment 1). The discussion then, would consist of the associated uncertainty and the potential impact on the interpretation of the empirical methods (i.e. their performance). Given the relatively large uncertainty in the statistical model, a useful contribution to the discussion would be to test the empirical relations for only a subset of days (for the 1 day averaging period, say), for which the impact of the statistical regression model is minimal (only a few or no estimated evaporation hours, mostly measured values). If then the comparison to the 4 empirical methods (Tab 6) would be robust, this would indeed be an indication that the conclusions regarding the appropriateness of the empirical relations are supported by data (not the statistical model). This last discussion, of course, would only make sense if the 'radiation problem' had somehow been overcome. Finally, an important point for the discussion seems to be that the empirical estimates are relatively good 'average estimates' (28 days) – but do only have reduced predictive (diagnostic, that is) skill for short time scales

A) Thank you for the detailed remarks about the discussions sections.
We agree that the discussion of the possible uncertainties of the applied method is probably too short. We revised this section and addressed also the 4 points of the reviewer:
1) The first point of the reviewer refers to C2 and if the regression model was used 'outside' its boundaries. As already discussed this was not the case and so an overestimation does not take place but we will discuss the

possible underestimation of evaporation, due to the fact that 'extreme' values of wind velocity and VDP were not used for calculations but instead a median value was used (see also answer to C2). Furthermore, we will discuss the question of overestimating evaporation due to the possibility that VDP decreases with increasing distance to the shoreline. As already mentioned in the answer to C2, in our opinion, the influence on the evaporation results is weak but nevertheless is discussed in the revised version of the paper.
2) Regarding the net radiation measurements, we now explain our methods for calculating net radiation in section 3.
3) We also want to thank the reviewer for the idea to test the empirical formulas on a subset of days to show that the regression model does not influence the results of the empirical relations. We did realise those test and it was found that still the aerodynamic approach V0 (R=0.96) and penman V6 (R=0.94) achieved the best results. However, we did not add the results to the paper as we think that the results are not fully comparable to the regressions for the whole data set (Fig. 6) as the number of days where only onshore wind conditions occurred and, thus, no or less than 2 values (1 h) are missing is limited to 13 days and these days are not equally distributed over the year. So this subset of days does not represent the seasonal variation, which obviously is important for the results.
4) The last point of the reviewer, refers to the reduced predictive skills of the empirical approaches on short time scales. We will discuss the reduced predictive skill of the empirical approaches, especially on the sub-daily time scales and that only the aerodynamic approach can reliably be applied to short time scales.

T) **Discussion and Conclusion**

~~Results from former studies, which investigated Dead Sea evaporation by using indirect approaches, varied strongly. No~~ The eddy covariance method was used for the first-time, high resolution, direct evaporation measurements ~~were performed at~~ of the Dead Sea~~so far to validate these results. Hence, there was a need for such direct evaporation measurements. The eddy covariance method is recognised internationally to be a very accurate method to directly measure evaporation (e.g. Rimmer et al., 2009) and was therefore chosen for this study.~~ . One aim of this study was to present an applicable method to measure evaporation with a shoreline station. The measurement strategy was based on the installation of the station on a headland, which was surrounded by water from 320°. This setup at the shoreline was chosen to avoid influence on the measurements by raft motion and sea spray, where the latter one leads to a serious soiling of the instrument and influences data quality strongly. However, land based eddy covariance measurements have their limitations in measuring evaporation from the water surface, as part of the flux footprint is located over land. Therefore, a novel approach was presented to account for this limitations. A multiple regression model was ~~applied to the data and the results show that evaporation from the Dead Sea water surface is driven by wind speed~~ trained with the onshore wind and vapour pressure deficit ~~. The model was tested using a MCCV, and it was confirmed that the model is reliable for calculating the Dead Sea evaporation and has a small model error of~~ data and with this model lake evaporation for offshore wind conditions was calculated. With this method, 90 % of the missing evaporation data due to offshore wind conditions could be calculated. Considering the high amount of rejected data due to the fetch criteria in this and also in other works, 15-25 % (e.g. Mammarella et al., 2015; Nordbo et al., 2011) this approach can improve data availability considerably. The uncertainty due to this method is also small with a prediction error of the calculated values of only 4.8 % which makes it a very reliable method. However, there is still some uncertainty to this method which cannot be accounted for directly. On the one hand, extreme values of wind velocity and water vapour pressure deficit were not used to calculate evaporation when they were outside the model boundaries. This leads most likely to an underestimation of the actual evaporation amount. On the other hand, wind velocity and vapour pressure deficit ~~for offshore wind conditions is probably higher directly at the shoreline in comparison to the open water surface. Considering these uncertainties the model can be used to calculate evaporation values for offshore wind conditions, enabling, for the first time, the analysis of the full~~ could decrease with increasing distance from the shoreline, which would lead to an overestimation of evaporation. The comparison with results from measurements in the middle of the lake (Weiss et al., 1988; Hecht and Gertman, 2003) shows that even in the middle of the lake westerly winds with hourly averaged velocities between 8 and 12 $m\,s^{-1}$ were observed. Also wind lidar measurements confirmed, that the westerly winds regularly reached several km over the lake without loosing its strength (Metzger, 2017). So offshore wind measurement seem representative for the calculation of evaporation. A decrease of vapour pressure deficit has to be considered, but is most likely small due to the following reasons. Firstly, the fetch of the station is quite limited with 600 m, and secondly the westerly winds are connected with high turbulence and thus strong vertical mixing (Metzger, 2017). From these results we conclude that the approach is also applicable to other lakes, when the measured wind velocity and vapour pressure deficit value range is equally distributed between onshore and offshore conditions to appropriately train the model, and the fetch of the measurements is small enough that the shoreline measurements are representative for the fetch.

The second aim was to evaluate the diurnal and intra-annual ~~cycle~~ variability of Dead Sea evaporation. ~~The results show~~ The results of the measurements showed that the diurnal cycle of evaporation is ~~mainly driven by the diurnal cycle of the wind systems and their related wind velocities. This leads to maximum evaporation rates after sunset, caused by westerly winds with high wind velocities. These westerly winds occur from spring until autumn. The results are consistent with findings for Lake Kinneret, where these westerly winds also occur in the evening (Assouline and Mahrer, 1993; Shilo et al., 2015).However, the daily evaporation rates are notably lower compared to the evaporation at Lake Kinneret through the much higher salinity of the Dead Sea water and thus the reduced saturation vapour pressure. The median daily evaporation ranges from 1.1~~in phase with the wind velocity, which corresponds to findings of other studies in the Jordan valley (e.g. Assouline, 1993; Assouline et al., 2008) and that the strong westerly winds in the evening double evaporation compared to midday values. These findings are also important for other lakes, as there are many places with similar strong and dry wind systems (e.g. Bora, Tramontane, Mistral), which just occur on longer time scales. Bouin et al. (2012) already showed that the Tramontane in France even trebles evaporation from a lagoon compared to normal conditions. In respect to the ongoing climate change these results could motivate a regional study on the impact of climate change on the future evolution of thermally and orography induced wind systems in the Mediterranean region, as there is little information so far, but they are important for the future development of the water bodies. As already expected, evaporation from the Dead Sea is lower compared to other less or non-saline lakes. The ratio to Lake Kinneret, which is located under similar climatic conditions is 0.68 in summer, but only 0.83 in winter. This difference is most likely caused by the different climatic conditions in winter. Lake Kinneret receives a considerable amount of rainfall and more humid air masses as it is Mediterranean climate (Goldreich, 2003), whereas the Dead Sea is located in arid climate conditions where, even in winter, nearly no rainfall occurs. The annual evaporation was found to be 994±88.2 ~~mm~~mm. The uncertainty of 8.8 % results mostly from the gap filling procedure (81.2 mm~~d^{-1} in July, but the absolute maximum of the measured daily evaporation rates was measured in November with 6.9 mm d^{-1}. This is extremely high compared to the median values in winterand highlights the stronger synoptic influence on the region during the wet season (Bitan, 1974, 1976). One of the typical synoptic systems during the wet season is the Red Sea Trough, which can cause high wind velocities and high vapour pressure deficits in the valley and thus leads to very high evaporation rates. This is particularly important as Alpert et al. (2004) found that the frequency of such Red Sea Trough systems nearly doubled since the 1960s from 50 to 100 days per year. The total measured evaporation for the period 1 March 2014 until 1 March 2015 was 994.5 ± 81.2 mm, which agrees~~). It could thus be reduced by improving the system performance or by finding a better method to fill the gaps. However, the annual amount coincids well with previous findings such as Stanhill (1994) with 1005 mm a^{-1} and is close to the results from Lensky et al. (2005) ($1100 - 1200$ mm a^{-1}), which both estimated the evaporation based on theoretical energy balance approaches. However, it is far away from the 2 m from Salameh and El-Naser (1999), who estimated evaporation based on water balance calculations, which could indicate uncertainties in the assessment of the water balance components. A certain degree of differences between the results is natural as the studies, considered different data sets for different years, which also means different salinities and different weather conditions.

~~Eddy covariance measurements provide high resolution and accurate evaproation data but they are costly and need frequent maintenance. Therefore, it is difficult to maintain an operational system in remote areas. Hence, the third aim of this paper was to evaluate the applicability of commonly used indirect evaporation equations, which use standard meteorological measurements. The~~ For the perspective affordable long-term assessment of evaporation different equations to calculate evaporation were tested on their applicability for the Dead Sea. The best suitable, and also the only method applicable on sub-daily time scales, is the aerodynamic approach. It was also shown that the consideration of the atmospheric stability in the calculations has an neglegible effect on the results. This again coincides with results for Lake Kinneret (Shilo et al., 2015; Rimmer et al., 2009) and makes this method easily applicable for evaporation calculations with data from a shoreline station. The other approaches are designed for longer time intervals and are not applicable for sub-daily calculations. The results also confirm the findings from various other studies (Rimmer et al., 2009; Giadrossich et al., 2015; Tanny et al., 2008; Rosenberry et al., 2007) that for the BREB, Priestley-Taylor ~~,~~ and Penman method, ~~are difficult to apply for intra-annual calcuations. The main difficulty is the heat storage term. For these three methods the~~ the knowledge of the heat storage term is essential to achieve reliable results, as neglecting the heat storage results in a strong seasonal bias~~, with an overestimation~~

~~of daily evaporation rates of up to 100 %~~. Using estimates of the heat storage term does not provide acceptable results for the BREB and the Priestley-Taylor method either. For the Penman equation an applicable solution is achieved when ~~a linear function for the heat storage is empirically gained from the data set. We conclude that the BREB and Priestley-Taylor method can only be applied for the Dead Sea if heat storageis measured, which requires a raft station or ship measurements, or for long time periods, i. e. one year, where the heat storage term can be neglected. The Penman equation is applicable for the Dead Sea, if the heat storage is considered using the described approaches. The aerodynamic approach yields the best results with respect to the diurnal and intra-annual calculation of evaporation. They were in best agreement with the measurements. It was also shown that the consideration of the atmospheric stability in the calculations has an neglegible effect on the results. This again coincides with results for Lake Kinneret (Shilo et al., 2015; Rimmer et al., 2009) and makes this method easily applicable for evaporation calculations, as only wind velocity and vapour pressure deficit are required.~~
~~This study focuses on providing an applicable method to investigate the diurnal and intra-annual variability of evaporation from the Dead Sea water surface using an eddy covariance system located at the shoreline. Furthermore, it investigates the application of commonly used indirect methods to calculate evaporation with shoreline data. When using a station located at the shoreline ,~~ using the empirically gained function for the heat storage. Thus, we conclude that the BREB or Priestley-Tayler method are not applicable with a shoreline station only, but the aerodynamic and the ~~use of a new model is proposed to calculate Dead Sea evaporation for offshore wind conditions on sub-daily time scales. It was shown that a model consisting of a linear combination of wind speed and vapour pressure deficit results in a robust model for the calculation of evaporation. This approach can also be applied to other lakes~~adapted Penman method can be used, making expensive raft measurements expendable. ~~From the evaluation of the indirect methods we conclude that for a reliable estimate of the Dead Sea evaporation the aerodynamic method is advisable and that the influence of the atmospheric stability is negligible. Like the new model, the aerodynamic method connects evaporation with its governing variables, which are wind velocity and vapour pressure deficit, and allows the calculation of sub-daily or multi-day evaporation amounts without a seasonal bias. The advantage thereby is clearly the use of~~ For future application it is advisable to use the Penman method only for longer time intervals as its prediction skill improves with increasing time interval and use the aerodynamic method for short time intervals. The use of low-maintenance, cost-efficient measurements ~~, which can be installed on the shoreline,~~ to estimate evaporation ~~values on a sub-daily time scale. This~~ on short time scales is beneficial for economic purposes, such as the production of minerals from the saline water, as well as for further investigations of the water budget of the lake~~, and the resulting environmental changes on a longer time scale.~~ . The results can be implemented into hydrological models to thus study the water budget and its development in the future.

3 Minor comments

P5, l.4 I don't think I have ever heard of a Rototronic sensor
A) that was a typo. The company is called Rotronic.

P5, l. 4 the height of measurement is not given for the radiation, precipitation and pressure sensors. Please specify.
A) The measurement height for radiation is 2 m. Precipitation and pressure at 1 m height. It was added to the paper.
T) temperature and humidity at 2 m height (HC2S3, ~~Rototronics~~Rotronic), temperature at 6 m (100KGA1A, BetaTherm), longwave and shortwave radiation components of the upper and lower half space (CNR4, Kipp&Zonen) at 2 m height, precipitation (tipping bucket rain gauge 552202, Young), and atmospheric pressure (PTR330, Vaisala) at 1 m height.

P5, l. 25 I agree with the present authors (in contrast to the other reviewer) that the appropriate conversion should be based on the water temperature and not the air temperature (the differences will be small, though). ¡w'a'¿ is already an energy flux (i.e., the kinematic flux of absolute humidity), which is only converted into energy units by multiplication with L_v. The corresponding energy (enthalpy) is calculated at the location where the process of evaporation takes place and the relevant temperature is the lake surface temperature (whether this is called T_w, the very top of the water or T_s, the very bottom of the air, is the same). I don't think that the 'constancy of the fluxes' in the SL is a valid argument for using the air temperature (at 6 m

agl in the present case) since the fluxes are only 'constant' within the SL, but not below (note that the SL has also a lower boundary, i.e. the laminar layer with a thickness of some millimeters over water wherein the turbulent fluxes are zero by definition – and rapidly change to their 'atmospheric surface value' at its top). The 'SL theory' (including the constant flux assumption) produces a temperature profile (e.g., eq. 11.12 in the text book of Arya (1988)), which is based on a 'surface temperature, T_o or T_s, which actually corresponds to the temperature at the height of the (thermal) roughness length. If we assume an (ideal) stratified SL, stable or unstable, and perfect measurements with a given 'surface' latent heat flux, each measurement height would have a (slightly) different L_v (because of the temperature profile) and hence a different latent heat flux – which is inconsistent with the 'constant flux'. In order to obtain the 'surface flux' from a measurement at any height (within the SL, of course), we must therefore relate the conversion into energy units to a common height, i.e. the thermal roughness length. The actual task therefore in determining L_v is to find the temperature at the height of the thermal roughness length. I think the water temperature is a better estimate for this than the temperature at measurement height. This 'surface latent heat flux' then can be used to assess how many mm of water had been evaporated (what is one of the primary goals in the present study). In any case, two comments have to be added: first, it is in fact potential temperature that has to be used (more precisely, virtual potential temperature) – again the differences (for a 6 m level) are negligible. Second, if L_v is estimated using eq. (3), latent heat fluxes will be in [kW m-2] (since L_v is is in [kJ kg-1]) and not comparable to the sensible heat fluxes from eq (2).
A) Thank you for your comment. For better comparison of eq. 3 it's changed to $LE = L_v \cdot \overline{w'a'} \cdot 1000$

P6, l.17 … the mean vertical velocity: this could be mixed up with the mean vertical velocity over the averaging period that is zero in the 'double rotation approach'. In PF, it is the mean vertical velocity over the period that is used to define the plane.
A) Thank you for the comment. We added '..over the period that is used to define the plane'.
T) It rotates the coordinate system to the main wind direction and then rotates the system around the y-axis, such that the z-axis is positioned perpendicular to the horizontal plan and that the mean vertical wind ~~is~~ over the period that is used to define the plane is $0\,\mathrm{m\,s^{-1}}$.

P6, l.20…calculations at sites..
A) changed accordingly.
T) This correction is particularly important for flux calculations ~~for~~ at sites with high humidity fluctuations, such as over the water surface.

P6, l. 28 below 0.5 'what'? (units)
A) 0.5 is 50%. This was changed.
T) Latent heat flux data were rejected when the signal strength of the radiation source to measure the water vapour was below ~~0.5~~50%, when the variability of the signal from one from one 10 min average to the next one was higher than 0.6 % within ~~a~~ the 30 min time interval, and during precipitation events, as a disturbance of the water vapour measurements was expected for these conditions.

P7, l.3 …data, which…
A) changed accordingly.
T) Class 1 to 6 describe data, which can be used for the analysis and classes 7 to 9 were rejected.

P7, l. 11 is reasonably good
A) changed accordingly.
T) This is ~~reasonable~~ reasonably good...

P7, l. 28 is built
A) changed accordingly.
T) After each division a regression model is ~~build~~ built with the training data set and then applied on the data of the validation group.

P9, l. 5 on longer time scales (or: on a longer time scale)
A) changed accordingly.
T) On longer time ~~scale~~ scales ...

P8, l. 11ff The presentation of the methods to estimate evaporation is somewhat difficult to comprehend. I try to exemplify this for the Energy balance method. First, one is referred to Tab. 1. The first mentioned aspect of this method is, what is difficult to obtain. I then try to check (find) F_n in Tab 1 (which is apparently difficult to obtain). F_n does not appear in the given equation (but it is 'explained' below in the list of symbols – even if it is not present in any of the given equations). So, I cannot at least judge how this variable appears in the full equation or is related to other variables that do so. The same with the other neglected variables. The 'result' is called V0 (it has an 'X' in Tab 2). Estimating 'somehow' delta_Q produces then 'V2' (why is it V2 for this method, and V1 for the first?). Anyway, it also has an 'X' in Tab 2 (why not a V2?). And some of the other methods also have an 'X' in this table for delta_Q. Overall, I think the overview on the employed approaches should be presented in a much more concise manner. The reader should be able to judge what has actually been done.
P8, l. 15 to make the confusion complete, the 'third method' is then – not the third line in Tab 1 but the fourth.....
A) Thank you for this remark. We revised this section it is now hopefully easier for the reader to follow and identify the different sensitivity tests which were performed. Table 1 was also changed and the original equations with all terms were added.
T) For the calculation of evaporation, several equations, based on different physical approaches, exist. Each approach connects evaporation to different meteorological parameters and is designed for different time intervals, ranging from sub-daily calculations to a time interval of at least 7 days. Four commonly used indirect methods to estimate evaporation (Table 1) will be ~~evaluated~~ tested in this paper by comparing their results to the eddy covariance measurements. An aerodynamic approach, the energy budget method, and two combination approaches, namely the ~~Penman equation and the~~ Priestley-Taylor ~~equation~~and Penman equation, will be evaluated on time intervals of 1, 7, 14, and 28 days. The aerodynamic approach is the only approach which is also designed for sub-daily time intervals and will thus also be tested for 30 min time intervals. Additionally, sensitivity studies are performed to quantify the influence of simplification within the approaches, which are often made in literature. ~~An overview which sensitivity study is applied for the different methods is given in Table 2.~~
The first method is ~~an~~ the aerodynamic approach after Brutsaert (1982), where only wind speed and vapour pressure deficit are required. ~~Brutsaert (1982) used a~~ With the assumption of equal transfer coefficients for evaporation and momentum ($C_e = C_d$) under neutral conditions the logarithmic wind profile ~~and did not consider near surface atmospheric stability (Table 1). A sensitivity study is performed for the aerodynamic approach considering atmospheric stability in the wind function K_E, afterwards referred to as V1.~~ can be used (Table 1, V0). This is the default version of the aerodynamic method for the sensitivity studies. The second method is the energy budget method expressed as the Bowen Ratio Energy Budget (BREB) (Table 1). For this approach several of the input variables are difficult to obtain. The amount of net advected heat into the water body, F_n, meaning the heat advected into the lake by water inflow and precipitation, as well as the loss of heat by water outflow, have to be known. If the in- and outflows are small compared to the size of the water body, or water temperatures are similar the ~~terms~~ term can be neglected (Dingman, 2002; Rosenberry et al., 2007). Moreover, the ground heat flux G, meaning the heat exchange at the bottom of the lake, is required. It can usually be neglected, as the amount for deep lakes is small compared to the other components (Henderson-Sellers, 1986). Another component difficult to obtain is the heat storage of the lake, $\cancel{\Delta Q}\Delta Q/\Delta t$. It requires measurements of lake temperature at different depths from a raft station or a ship. On longer time ~~scale~~ scales it can often be neglected~~, which is used~~. Because of the aforementioned reasons and the difficulty to obtain these three terms, the net advected heat, the ground heat flux and the heat storage term are neglected in many studies. Thus, for the default version (V0) of the BREB method ~~the net advected heat, the ground heat flux and the heat storage term are neglected~~ these three terms are neglected in this study (Table 1). Using ~~this version~~V0, only net radiation, surface water temperature, ~~and air temperature~~air temperature, and the vapour pressure deficit have to be known, which are relatively easy to obtain and thus an easy approach to calculate evaporation. ~~Sensitivity analyses for the BREB method are performed regarding the consideration of the heat storage in the equation. For this purpose Rn is replaced with $(Rn - \Delta Q)$. Duan and Bastiaanssen (2015) proposed a hysteresis model to calculate the heat storage term, depending only on the net radiation. This approach is used in sensitivity version V2. Another approach to~~

~~account for the heat storage term is the simple assumption that the heat storage is directly proportional to the net radiation and that the deviation of the default version from the measurements equals the heat storage term. This is tested as version 3 (V3).~~ The third method to calculate evaporation is the combination approach, considering the energy balance and the aerodynamic influence. Priestley (1972) proposed an equation which considers the aerodynamic influence by using an empirically gained coefficient of $c_{PT} = 1.26$ (Table 1). ~~In this equation the heat storage is also not considered, and hence the same sensitivity studies as for the BREB method are performed. Penman (1948) combined~~ Because of the same reason as mentioned above, the ground heat flux is neglected in the default version (V0) of the Priestley-Taylor equation. Method four is a combination of the energy balance equation with the aerodynamic approach first developed by Penman (1948). In his approach he already neglected net advected heat, the ground heat flux, and the heat storage. Van Bavel (1966) further generalized Penman's equation by replacing the empirical wind function through the logarithmic wind profile, assuming neutral conditions (Table 1). ~~The heat storage can be considered in the Penman equation by replacing Rn with $(Rn - \Delta Q)$ again. Sensitivity studies~~ This equation will be used as the default version (V0) for testing the Penman approach.
In total, six sensitivity studies were performed. An overview of the sensitivity studies and to which of the methods it is applied to, is given in Table 2. Sensitivity study V1 considers non-neutral atmospheric conditions, by incorporating stability correction factors into C_e. As only the aerodynamic and the Penman approach are based on mass-transfer, V1 is applied to these two equations only. Studies V2 and V3 ~~are tested for the Penman equation as well. Furthermore, Kohler and Parmele (1967) presented modified coefficients for L_v and γ to eliminate the need of surface water temperature T_s from the equation.~~ consider the heat storage of the lake $\Delta Q/\Delta t$ and are applied to the BREB, Priestley-Taylor and Penman method. For this purpose Rn is replaced with $(Rn - \Delta Q/\Delta t)$. Duan and Bastiaanssen (2015) proposed a hysteresis approach to calculate the heat storage term, depending only on the net radiation ($\Delta Q/\Delta t = a + b \cdot Rn + c \cdot dRn/dt$). This approach is applied to the measurement data and the resulting equation for $\Delta Q/\Delta t$ is used in sensitivity version V2. To avoid the use of the calculated heat storage from the measurements, in V3 it is assumed that the heat storage term is directly proportional to the net radiation and that the deviation of the default version (V0) from the measurements equals the heat storage term. The last three sensitivity tests were applied to the Penman approach only. In V4 the uncertainty caused by the calculated longwave outgoing radiation with T_{MO} was eliminated by using an approximation from Kohler and Parmele (1967) where they calculated the longwave net radiation and the psychromatric constant using air temperature only. This further reduces the amount of necessary input parameters, which makes the equation more easily applicable~~. The modified parameters are tested in version V4.~~, when net radiation of the water surface is not directly measured. In version V5 ~~they are~~ the approximation after Kohler and Parmele (1967) is applied together with the hysteresis model for the heat storage term (V2). The last sensitivity test (V6) combines the ~~parameters~~ approximation after Kohler and Parmele (1967) with a linear function for the heat storage term, derived from the deviation of V4 from the measurements.

P10, l. 15 on 26% of the days
A) changed accordingly.
T) In winter, the synoptic conditions gained more influence and often superimposed the local wind field such that a north-easterly lake breeze was only observed ~~at~~ on about 32 % of the days and a south-easterly flow ~~at~~ on 26 % of the days ~~.~~ in winter 2014/15.

P10, l. 16 on about 57%...
A) changed accordingly.
T) These downslope winds occurred ~~at~~ on about 57 % of the days in summer,...

P10, l. 18 if the along-valley flow is northerly (with what I concur judging from Fig. 1) the lake breeze would be expected to be perpendicular (easterly on the western shore). Wouldn't this mean that, what was called a 'lake breeze' before (p10, l. 11) is rather a superposition of the along-valley flow and the lake breeze? Can the authors comment on that?
A) We don't think that it is a superposition of the described nocturnal along-valley flow and the lake breeze, as the data showed the following: (1) When we analyse data of the station further inland and a little bit south of the shoreline station, wind during daytime has a much stronger easterly direction. (2) when we look at the third station (which is in the north) data shows a south-easterly flow during daytime. (3) Other studies, e.g. Bitan (1974, 1976); Alpert et al. (1990), all show a lake breeze development during the day, but depending on the

location of the station the exact wind direction of the lake breeze changes. Alpert et al. (1990) analyzed data in the south and found a northerly lake breeze, whereas Bitan (1974) in the north found a south-easterly flow (which corresponds to ()).

So in our opinion the north-easterly flow shown at the shoreline is not a superposition with an along valley flow but rather caused by the specific geographic location of the station, meaning the shape of the shoreline and the nearby orography which modulates the lake breeze.

P10, l. 22 in the beginning
A) changed accordingly.
T) ~~at~~ in the beginning of November

P0, l. 25 on individual days
A) changed accordingly.
T) However, ~~at~~ on individual days...

P12, l. 4 on most of the days ...
A) changed
T) Through the predominant local wind systems, these wind directions occur almost exclusively in the evening between 17:30 to 20:30 LT (LT=UTC+2) from spring until autumn (Fig. 3) and, thus, ~~at~~ most of the ~~days~~ data within this time frame are excluded.

P14, l. 2 what does 'uncorrected' mean? No Webb correction, etc.? Or do the authors refer to 'only measured, no estimated (with the multiple regression model) values'? (same in Fig. 4). I think the term 'uncorrected' is not appropriate.
A) uncorrected means only measured values. To avoid confusion we renamed it to "measured"
T) The comparison of the mean diurnal cycles of the measured fluxes ~~(uncorrected)~~ with the cycles including the calculated values for offshore wind conditions (corrected fluxes) shows that during the day the differences are small (Fig. 4).

P15, l. 1 Maximum values are reached....: see major comment 2.
A) as explained in the answer to comment 2, the values of the model should not overestimate evaporation, as it was only used in the reliable boundaries.
T) see answer to comment 2

P15, l.11 the uncertainty...: so, how large was it found to be?
A) The uncertainty due to the gap filling method was estimated using the corresponding MAD of the used timestep of the respective month. Overall the mean MAD for the different months varied between 0.019 and 0.029 mm 30 min^{-1}. For the total annual evaporation amount the uncertainty due to gap filling resulted in 81.2 mm
T) Summing the evaporation values over the whole measurement period results in a total amount of 994.5±88.2 mm, where 81.2 mm of the uncertainty result from the gap filling method and 7 mm due to the regression model.

P16, l. 10 evaporation rates of 5.1 mm d-1,.... are measured: do these 'extreme days' contain any estimated values (using the statistical model)? How about the other 'large days' throughout the year?
A) Only 3 out of the 72 values for these 3 'extreme' days had to be estimated as northerly winds prevailed. The estimated values were also not the maximum values reached on these days. It's similar for other large days.
T) This case was also used to test the performance of the regression model as on these three consecutive days only 3 out of 72 evaporation values had to be calculated due to the fetch criteria. Applying the regression model to calculate evaporation on these 3 days completely yields good results for day one and three were the difference was only 4-5 % but it also shows the potential underestimation of extreme evaporation rates as the model underestimated the daily evaporation on the second day by 18 %

P16, l. 14 not shown: I think that this 'case' (if it were shown) could serve as a good example to gain some confidence in the statistical model (see major comment 2). Tab 6 'MD' must be defined.
A) Thank you for this comment. Indeed this event serves as a good example to show the performance of the

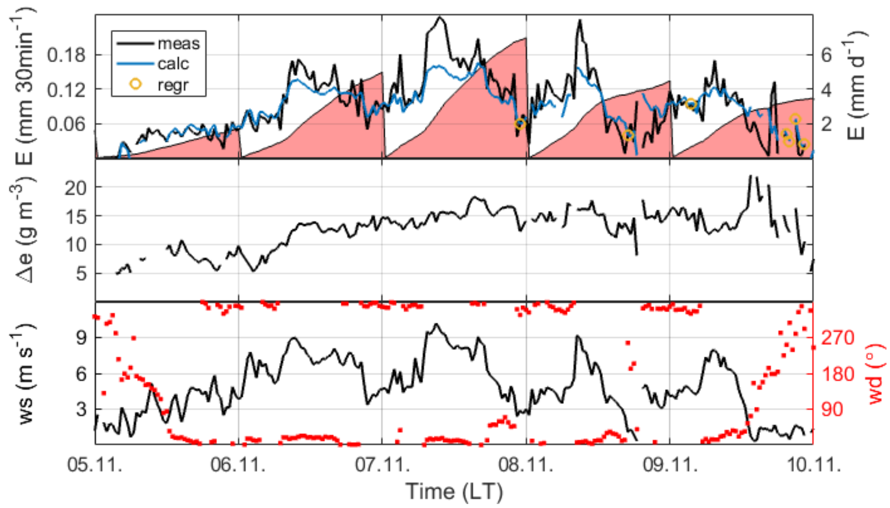

Figure 1: Evaporation, water vapour deficit and wind conditions for 5 to 11 November 2014.

statistical model. As mentioned in the previous comment on these 3 days only 3 out of the 72 evaporation values were estimated. When the model is applied to estimate the evaporation of these days, we get quite a good agreement for day 1 and 3 the model underestimates evaporation by only 4% and 5%. But we also see that the model potentially underestimates the extreme values as on day 2 the value was underestimated by 18% (see Fig. 1 in this document). We added the information about this case to the paper.
T) see answer to comment before

P17, l. 16 MD is probably mean difference, right? Anyway, the mean differences are not given in the table to demonstrate this (for V0 they are essentially the same ...).
A) Thank you for this comment. MD is mean difference. The mean difference for the 30 min interval is only given in the text (P.17, l.14) and not in the table to keep the table clear and better readable. To make the comparison easier we added the value of the mean difference for the 1d interval to the text.
T) The correlation coefficients vary between 0.94 for 1 d intervals and 0.99 for 28 d intervals, mean differences are smaller, 0.02 ± 0.54 mm d^{-1} for 1 d intervals, and the slopes of the regression lines vary around 1.10 (Table 1, Fig. 6 a,V0).

P17, l. 20 I suggest to start a new paragraph for the BREB method.
A) changed accordingly.

P17, l. 25 the largest
A) changed accordingly.
T) and the ~~larges~~ largest offset

P17, l. 30 22%: judging from Fig. 7 this number is probably valid for a 28 d averaging period A) Yes that's right. It was added to the text to make it clear and added another explanation, that the numbers for the other averaging times are comparable.
T) ...Compared to the measured values, this results in ~~a~~ an overestimation of the annual evaporation amount by 22 %~~.~~, calculated from the 28 d averages. For the other time intervals the overestimation of the annual evaporation amount was comparable and is therefore not shown.

p17, l. 31 coefficients
A) changed accordingly.
T) Correlation ~~coefficient~~ coefficients are better...

p17, l. 31 improved the results: I do not really agree. Indeed, the correlation coefficients do somewhat increase (but look at Fig. 6 – both versions would probably serve as examples for 'statistics 101' students for data sets, for which a linear model is not appropriate). At the same time, slope and offset are getting worse (this is why we usually use different statistical measures....). In my view the results of V2 (as compared to V0) simply demonstrate that the calculation of heat storage is not appropriate (see major comment 1)

A) we revised this description.

T) Correlation ~~coefficient~~ coefficients are better and the mean differences are reduced (Table 1). However, the slope and offset shows that the heat storage term is still not represented correctly. The slopes and the offsets indicate an overestimation of the small evaporation amounts and an underestimation of the high amounts (Fig.7 b,V2).

p17, l. 34 11%: same as above (and also in the following) these values seem to apply for the 28 day averages

A) That's right, please see also answer to comment P17,l.30

p19, l. 7 up to 100%: I don't think I can see this from Fig. 7d

A) Thank you for pointing this out. Fig. 7d has to be compared to the measured daily evaporation amounts in Fig. 5. We added the necessary reference.

T) Evaporation values are strongly overestimated from spring until autumn (Fig. 6 d,V0), exceeding the measured daily evaporation amounts by up to 100 % (compare Fig. 7 d,V0 to Fig. 5).

p20, l. 16 with a heat storage term....: in fact, I only now understand what actually V6 does: it fits the Penman equation to account for the missing storage term, right? So, how is this fitting process being done? If it is fitted – as I assume – using the measured evaporation, it does not come as a surprise that a negligible mean difference results. The results from this exercise have to discussed in this light (major comment 3).

A) Thank you for the comment. For the fitting it was assumed that the heat storage term equals the difference between the calculated evaporation amounts using the Penman equation V4 and the measured evaporation amounts and that it can be described as a linear function of the net radiation $\Delta Q = a \cdot Rn$. With this assumption the coefficient 'a' was derived and averaged over the measurement period, which resulted in $\Delta Q = 0.77Rn$.

p21, l. 8 due to the much higher

A) sentence is not longer in the discussion.

p22, l. 12 The BREB, Priestly-Taylor and Penman... All these methods do not employ radiation (which has a different field of view – and does not represent the water surface, see major comment 1). I would hypothesize that this is, in the first place, the reason for their bad performance. Only if the Penman method is fitted to the data, it can also produce some reasonable results.

A) Thank you for the comment. As already explained for comment 1, we considered the different field of view of the radiation measurements. We still think that the strongest influence is the correct representation of the heat storage term, but of course there are uncertainties connected to the calculation of the net radiation.

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Reply to Reviewer 3

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The paper shows, for the first time, results of direct annual evaporation (E) measurements from the Dead Sea (DS) based on eddy covariance (EC) technique. Understanding the annual and the short-term dynamic of the lake evaporation rate is important scientifically in many aspects, for the regional managers and for the future fate of the whole region. The paper is a clearly written, covering both measurements aspects and evaporation modelling aspects over free water body in exceptional conditions, and one can assume that the measurements were carried under very harsh conditions. Last, there are not many E measurements over water bodies that are based on eddy covariance technique and are comparing measurements results versus different evaporation rate models as the Authors presented here. Having said that, there are a few significant points the Authors need to address before any publications.

The authors thank the reviewer for the insightful review. They helped to improve the paper. Responses to individual comments are provided below. Reviewer's comments are in italic.

1 Major Comments

C1) Comparing annual evaporation results with previous estimation. Comparing to previous works need caution which the Authors have to mention and discuss, including; A. The change in the water level likely changed as well the DS surface area between the different estimation years (e.g., in the case of Stanhill 1994 the lake level was probably 30 m higher and surface area much larger). B. Changes of the climatic conditions due to large-scale changes as well as due to the lake shrinkage. The Authors already mentioned the rapid changes in the regional Persian trough frequency. C. Likely salinity changes over the years and possibly also the amounts of water removal to the mineral production pools in those years? And D. This work is based on a single measurement year that the Authors mentioned as a relatively wet one

A) Thank you for this comment. We agree that there are differences between the conditions of the former studies and our study. Climate and weather conditions, salinity and water level obviously influence the evaporation rate. We will point this out in the discussion and take your remarks into consideration when comparing our annual evaporation rate with former studies. Nevertheless, our main goal was not to rate former results of yearly evaporation amounts. Our main aim was to provide information on the short-term and intra-annual variability of evaporation as this was so far not provided by other studies and to provide a measurement concept and post-processing methods with which evaporation measurements at the shoreline can be realised.
T) The annual amount coincides well with previous findings such as Stanhill (1994) with 1005 mm a^{-1} and is close to the results from Lensky et al. (2005) ($1100 - 1200$ mm a^{-1}), which both estimated the evaporation based on theoretical energy balance approaches. ~~However, it is~~ A certain degree of differences between the results is inevitable as the studies, considered different data sets and different time periods, meaning different salinities and different weather conditions. However, the measurements are far away from the 2000 mm from Salameh and El-Naser (1999), who estimated evaporation based on water balance calculations, which could indicate uncertainties in the assessment of the water balance components.

C2) H and L_v calculations (section 3.1) were needed for the energy budget models (as in Tab1). And I assume, though not clearly presented, that ET was derived directly from EC evapotranspiration calculation, not from L_v? However, figure A1 is important in showing that compared with pure water, saline water L_v *is lower for temperature higher than 22C , which likely means that for most times of the year L_v of Dead Sea water is lower than that of a pure water. In this respect, the sentence in L27, page P5 is confusing and future warming and increase water salinity will possibly increase E?*

Yes, the evaporation was derived directly from the EC measurements.
If future warming and an increase in water salinity will increase evaporation can not be concluded from Fig. A1. These measurements were only conducted for the given salinity of the Dead Sea in 2014 and do not capture changes through salinity increase. There are two factors determining the L_v: 1) Temperature. It's correct that the data show that L_v of the Dead Sea is most of the time lower than L_v of pure water in case of water temperatures larger 22°C. 2) Water salinity. It can be assumed that if water salinity increases, L_v increases as well (Salhotra et al., 1987). Yet, it is unkown how these two factors will balance each other in the future. For conclusions about the future development of the evaporation due to L_v changes studies with different salinities, also considering the chemical composition of the Dead Sea water, have to be conducted.

C3) Gap filling model for E values when wind direction is coming from the land enhances considerably the total evaporation, especially during the afternoons. However, this model uses VPD (and wind speed) derived from humidity values of air coming from the lake. While the humidity of the land air is probably lower compared to wind coming from the lake. But, it is likely that RH of this dry air increases as it is blowing over the lake for some distance., Thus VPD and E should decrease. Shouldn't such effects be estimated, considering its large effect on E? Do the Authors have any information on the RH difference between the two sides of the lake (e.g., west vs. east) for wind blowing to either directions?

A) The effect of a possible VDP decrease with increasing distance from the shoreline couldn't be directly estimated, but we made following observations: 1) We have seen in the data that the strong westerly winds are connected with high turbulence, and even rotor formation was observed. This means that vertical mixing and air mass exchange is enhanced and thus VDP decrease should be low. 2) The fetch of the station is around 600 m. In our opinion the decrease of delta_e within such a distance is not very strong considering the turbulent mixing. 3) Evaporation has a stronger dependence on wind velocity than on VDP which makes the influence of VDP variations on the results weaker.
The second question of the reviewer was if we have data from both sides of the lake. We don't have information on the VDP variation over the lake or from the eastern shore to validate our assumption. We agree with the reviewer that VDP variations are an uncertainty, but as stated in the above paragraph we don't think that it has an large effect. We discussed this uncertainty in the new discussion section:
T) On the other hand, wind velocity and vapour pressure deficit could decrease with increasing distance from the shoreline, which would lead to an overestimation of evaporation. However, the comparison with results from measurements in the middle of the lake (Weiss et al., 1988; Hecht and Gertman, 2003) shows that even in the middle of the lake westerly winds with hourly averaged velocities between 8 and 12 $m\,s^{-1}$ were observed. Wind lidar measurements confirmed, that the westerly winds regularly reach several km over the lake without loosing their strength (Metzger, 2017). In conclusion, offshore wind measurement seem representative for lake conditions and reasonable for the calculation of evaporation. A decrease of vapour pressure deficit has to be considered, but is most likely small for the following reasons. Firstly, the fetch of the station is limited with 600 m, meaning that the distance the air mass passes over the water is short. Secondly, the westerly winds are connected with high turbulence and, thus, strong vertical mixing (Metzger, 2017). From these results we conclude that the approach is also applicable to other lakes, in case the measured onshore wind velocity and vapour pressure deficit values are representative for offshore conditions to appropriately train the model, and the fetch of the flux measurements is small enough that the meteorological measurements at the shoreline are representative for the fetch.

C4) Combining or incorporating variables with previous works that have been carried out over the DS in the past to check estimations and assumptions. For example, I found published works on DS surface temperature (Tom) measurements, and others on the lake heat storage on different time scales. I am wondering why the Authors did not refer to this data? Δe is highly dependent on Tom and close to the shore Tom is warmer than in the open sea, thus it would be valuable if the authors could compare their estimations with independent measurements and its effects on E estimation.

A) Thank you for your comment. We used the published works on DS surface temperature as a basis for our method. E.g. Nehorai et al. (2013), showed that "SST is highly correlated to air temperature (0.93-0.98) in all seasons". Based on these previous results we used the Monin-Obukhov approach to calculate DS surface temperature from air temperature. Concerning the heat storage we could not find suitable data to directly use as input for our calculations and a direct comparison to independent measurements over the open sea is unfortunately not possible, as we don't have such measurements or access to such data sets. We added some explanation to Sec. 3.1:

T) For the surface water temperature, T_S, no in-situ measurements were available. Also remotely sensed surface water temperature products could not be used as operational SST algorithms are calibrated to mean sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. Nehorai et al. (2009) showed that a calibration of satellite data with in-situ measurements is necessary. Furthermore, Nehorai et al. (2009) raised concerns that enhanced water vapour input into the atmosphere through evaporation causes stronger absorption of thermal IR radiation, leading to a screening of the Dead Sea surface and, thus, incorrect estimates of the surface water temperature. Based on the results of Nehorai et al. (2013), which showed that "SST is highly correlated to air temperature ($R^2 = 0.93 - 0.98$) in all seasons", the Monin-Obukhov similarity approach was used to calculate surface water temperature from the measured air temperature (see Appendix A), and is further on referred to as T_{MO}.

5. This leads to the last main point: The basis for the uncertainty around E (82.2 mm) is unclear. For ecosystems over land, it is generally assume to be 10%; is it about the same here or? However, although the uncertainty value is about 8% of E it is likely still a substantial large number for water management of the region. Can Authors suggest ways to reduce this in future activities?

A) The uncertainty of the total evaporation amount (88.2 mm) contains the uncertainty due to the gap filling method. Gaps were filled using the median evaporation of the corresponding time step of the respective month and the uncertainty of this method was estimated using the Median absolute deviation (MAD) for the used time step (described in Sec. 4.3). The uncertainty due to the gap filling procedure accounts for 81.2 mm of the 88.2 mm uncertainty. The rest of the uncertainty (7 mm) stems from the regression model. Here, the prediction error given by the MCCV was used. To account for the highest possible uncertainty of the regression model the prediction error of the MCCV with randomly chosen validation sectors $er_s = 4.79\%$ was used.

The uncertainty could further be reduced by finding another method to fill the gaps. The use of a median evaporation cycle naturally results in relatively large MADs, as evaporation varies from day to day. Nevertheless, we choose this method instead of the often used interpolation, as interpolating would in some cases not depict the real diurnal cycle. E.g. if we would use linear interpolation between the 18 LT and 24 LT value in Fig. 4 we would completely miss the diurnal maximum. Another way to reduce the uncertainty would be reducing the gaps in the data set itself. Gaps in the data set were caused by: malfunction of the system (2.4% missing data), precipitation events and problems with the radiation source (signal strength was too low, 10%), and quality control (integral turbulence characteristics and steady state test after Foken (1999), 9.2%). For example, shorter maintenance intervals could reduce the amount of data missing through system malfunction or problems with the radiation source, which were mainly caused by the very harsh conditions (see also answer to minor comment 2). However, precipitation events or conditions were the criteria of the EC method (fully developed turbulence and steady state) are not fulfilled can not be controlled. We also added this information to the discussion section:

T) The annual Dead Sea evaporation was found to be 994 ± 88.2 mm for the measurement period. The uncertainty of 8.8 % results mostly from the gap filling procedure (81.2 mm) and not from the regression model. As gaps result from system malfunction or bad data quality, the uncertainty can be reduced by improving the system performance or by finding a better method to fill the gaps.

2 Detailed Comments

1. L. 9 p. 3. I would look for additional citation(s) for the EC approach reliability to measure E over water bodies.

A) added further citation.
T) The eddy covariance technique is the only method to obtain direct evaporation measurements~~, in high temporal resolution, which can be linked to meteorological variables afterwards. It~~ . Thus, it is considered the most accurate and reliable method to estimate evaporation ~~(Rimmer et al., 2009).~~ (Rimmer et al., 2009; Tanny et al., 2008). All other methods assess evaporation indirectly, which means that all measurement errors accumulate into the estimated evaporation (Assouline and Mahrer, 1993)

2.Is the IRGASON a close or open path IRGA? And generally, did the researcher had any problems with the presumable high rusty environment down there, with salt particles etc.?
T) It is an open path instrument. Through the harsh environment the windows of the IRGASON got dirty in a short time, which influences the signal strength of the radiation source. Through these conditions short maintenance intervals of about 3-4 weeks were necessary.

3.Heat storage in section 4; can the Authors add 'zero' line in Figure 2, ΔQ value. The impression from inspecting that figure is that the annual value deviate considerably from zero? Is it due to negative heat transfer (e.g., by rain)?
T) added the zero line to Figure 2. Yes, there is a positive net heat storage when summing over the whole year. Several other studies like (Stanhill, 1990; Anati et al., 1987) already documented this and the thereby caused steady increase of the lake temperature over the last couple of years is also documented (e.g Hecht and Gertman (2003)).

4.Please add the units for MD and std in Table 6.
T) added accordingly

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Reply to Reviewer 4

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The paper contains very important information on evaporation from the Dead Sea that should be eventually published for the benefit of the scientific and water management communities. The paper presents measured heat fluxes using eddy covariance sys- tem over a year; the eddy covariance data is presented with a solid data analysis. In addition the paper evaluates the validity of common used indirect estimations of evap- oration from the Dead Sea, which is very important for extending the flux estimates when EC is not available. However I think that at the present form the paper cannot be published in HESS due to the following reasons:

The authors state that (end of P3) "To measure the energy budget components of the water surface, a fully equipped energy balance station was installed ... ", however this is not the case. Using eddy covariance - latent and sensible heat are measured directly, but heat storage is not measured nor the net radiation. The radiometer in use is a 4 components CNR4 (P5 L4-5), but as can be seen in Fig 1b the two lower half spaces are directed to the ground not to water surface; this is also acknowledged later on, but this should clearly be stated upfront. Water temperature is calculated not measured, this is found later on in the paper, should appear upfront when declaring for fully equipped energy balance station. In the results it is stated that the heat storage is calculated as the residuum of the energy balance (Rn-LE-H), where Rn by itself is not really measured, again, this is not a fully equipped system. I think the paper should be written with emphasis on the existing data, which are very important and worth publication, but not declaring for measuring energy balance, this gives a wrong impression for the reader. As stated above, water temperature was calculated, not measured, termed TMO. TMO is used for the examining the equations of evaporation versus measured evaporation (e.g. table 1 and large portions of the figures). TMO is also used to determine the saturation vapor pressure at water surface temperature, Ew. Ew is used to determine the vapor pressure deficit and for the evaporation estimates. So both water temperature and Ew are not measured, but they have a very important role in the analysis and the conclusions of the paper. Again, I this think that it would be better to orient the paper to the existing information that was measured and analyzed and not to rely so much on the computed meteorological parameters. Typically, when EC measured evaporation is compared with the evaporation equations it is done based on measured meteorological parameters, not on computed parameters. Overall, due to these weaknesses, there is a gap between the actual measurements and the interpretations and conclusions. The scientific methods and assumptions should be better declared earlier and should appear clearer. I think that the first half of the title "Dead Sea evaporation by eddy covariance measurements" is good and rep- resenting the novel aspects of this work, but the second half of the title represents the weaker part of the paper

The authors thank the reviewer for the insightful review.
The reviewer raised 5 important points: Firstly, a fundamental statement that the comparison to the indirect methods has significant weaknesses, and furthermore four points related to specific parts of the content: 1) There is no fully equipped energy balance station. 2) TMO, which is important in the analysis is not measured but calculated and then used for the calculation of Ew and the vapour pressure deficit. 3) The analysis relies too much on calculated meteorological variables. 4) Methods and assumptions should be better declared.
The responses to the reviewers comments are provided here:

We understand the concerns of the reviewer regarding the indirect methods. There are uncertainties in the calculations of the indirect methods, but as EC measurements are often not available for the long-term assessment of evaporation it was one of the main goals and thus an important part of the paper to provide a reliable and scientifically sound method for long-term flux estimates in the future. Additionally, the results can serve as a

method to calculate the spatial variability of evaporation over the water surface, when using it with an appropriate model, which delivers high resolution information of wind velocity and vapour pressure deficit.
With the first part of the paper alone we would of course publish important and novel data concerning the evaporation of the Dead Sea, but the second part provides an important basis for future studies and work on the topic of Dead Sea evaporation and evaporation of similar land-water configurations. We therefore think that the comparison to the indirect methods should remain part of the paper.

1) With respect to the comment about the energy balance station, we agree with the reviewer that the sentence on P3: "...a fully equipped energy balance station was installed" can confuse the reader, as not all energy balance components of the water surface were directly measured. We changed this sentence and added a paragraph with an explanation what components of the energy balance of the water surface were actually measured and how we calculated the missing variables, like the reflected shortwave and outgoing longwave radiation, and the water surface temperature.
T) To measure the energy balance components of the water surface, ~~a fully equipped~~ an energy balance station (EBS) was installed directly at the shoreline (Fig. 1 b). [....] As the station was located at the shoreline, the radiation measurements of the lower half space represented the land surface conditions. For the water surface they have to be calculated. The applied method is explained in Sec. 3.1. Furthermore, the heat storage of the lake was not measured and was therefore calculated as the residuum of the energy balance equation ($R_n = LE + H + \Delta Q$) using half hourly measurements. Notable hereby is that ΔQ also contains the possible non-closure of the energy balance. Considering the values of common energy balance closure studies (Foken, 2008; Wilson et al., 2002) the heat storage is thus most likely about 20 % smaller than calculated.

Data and methods
Measurement data from March 2014 until March 2015 were analysed. To achieve the research aims, following calculations and methods were applied. The shortwave and longwave radiation components of the lower half space were calculated. This is presented in Sec. 3.1. The latent and sensible heat flux were calculated from the 20 Hz data ~~evaporation was calculated~~using the eddy covariance ~~technique~~method. The principle of the ~~eddy covariance theory, the applied~~ method, the post-processing ~~steps and the used objective method for~~ and data quality control steps are presented in ~~the following~~ Sec. 3.2. Furthermore, a multiple regression model was used to calculate evaporation for offshore wind conditions and it was validated using the Monte-Carlo cross validation (MCCV) technique, which is explained in Sec. 3.3. The indirect methods which are evaluated for calculating evaporation from the Dead Sea water surface and the performed sensitivity studies are presented in Sec. 3.4.

Calculation of radiation components
The measurements of the radiation components of the lower half space were not conducted directly over the water surface, but over the land surface. Therefore, these two components had to be calculated for the water surface. The reflected shortwave radiation was calculated using literature values of the Dead Sea albedo. Stanhill (1987) calculated the albedo of the Dead Sea surface from ship measurements and reported values of 0.06 in the summer months, 0.09 in the winter months, and an annual average of 0.07. He also reported albedo values from Kondrat'Ev (1969) for the latitude of the Dead Sea and the cloud cover observed in the northern part of the Dead Sea, which was 0.08 for November and 0.07 as an average annual albedo value. To confirm the validity of the literature values for our site, a short-term experiment was conducted in November 2014. The measured albedo values of 0.08 to 0.09 concur well with the literature values for winter. As the literature values for summer could not be compared to measurements, the annual average of 0.07 was used for all calculations. The longwave outgoing radiation was calculated using the Stephan-Boltzmann equation

$$Rl \uparrow = \epsilon \cdot k_B \cdot T_S^4, \tag{1}$$

with the water surface emissivity $\epsilon = 0.98$ (e.g. Konda et al. (1994)) and the Stephan-Boltzman constant, k_B. For the surface water temperature, T_S, no in-situ measurements were available. Also remotely sensed surface water temperature products could not be used as operational SST algorithms are calibrated to mean sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. Nehorai et al. (2009) showed that a calibration of satellite data with in-situ measurements is necessary. Furthermore, Nehorai et al. (2009) raised concerns that enhanced water vapour input into the atmosphere through evaporation causes stronger absorption of thermal IR radiation, leading to a screening of the Dead Sea surface and, thus, incorrect estimates of the surface water temperature. Based on the results of Nehorai et al. (2013), which showed that "SST is highly correlated to air temperature ($R^2 = 0.93 - 0.98$) in all seasons", the Monin-Obukhov similarity approach was used to calculate surface water temperature from the measured air temperature (see Appendix A), and is further on referred to as T_{MO}.

2) + 3) both refer to the calculation of TMO and further meteorological variables.
One main goal of this paper was to provide a measurement concept and possible post-processing methods, which includes the common problem of assessing missing variables, with which evaporation measurements at the shoreline can be realised. The problem that not all necessary variables for an analysis are measured is a common problem in the assessment of evaporation (e.g. Lensky et al. (2005) used bulk formulas to estimate longwave radiation, Giadrossich et al. (2015) used a model to estimate stream discharge to the lake). Therefore, we don't see the calculation of e.g. TMO as a weakness of this paper but as part of the possible methods to gain evaporation data from a station on land.

One option to derive the surface water temperature (SST) from satellite data, as suggested from Reviewer 1, was also not possible because of the following reasons:

- Nehorai et al. (2009) used MeteoSat Second Generation data to estimate SST from the Dead Sea. For retrieving the SST the operational SST algorithms could not be applied as they are calibrated to sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. They derived the SST by calibrating their algorithm against in-situ measurements. As we did not have the necessary in-situ measurements of the SST we could not follow their procedure to derive the SST from satellite data.

- Furthermore, Nehorai et al. (2009) raised concerns, that on days where the Mediterranean Sea Breeze enters the valley in the afternoon the enhanced evaporation causes enhanced water vapour and thus a stronger absorption of thermal IR radiation which leads to a screening of the Dead Sea surface and thus incorrect estimates of the SST. For their studies they excluded all data with these conditions. This would lead to data gaps in the time series of SST especially during offshore wind conditions, meaning that no SST data would be available for the timesteps where it is needed as an input parameter for the regression model to calculate evaporation from the water surface.

- Another point why satellite data was not used is the need of a continuous time series. Satellite data can not be used for cloudy conditions. So especially for the winter months cloud cover would reduce data availability significantly.

Because of the aforementioned problems using satellite data, we followed the advice of another paper from Nehorai et al. (2013), which shows that "SST is highly correlated to air temperature (0.93-0.98) in all seasons". Based on these results we used the similarity approach to calculate surface temperature from air temperature.

4) regarding the methods and assumptions we want to refer to answer 1). We will add a better description of the objectives, assumption and methods used to the introduction and section 3 "Data and Methods". We will e.g. explain what data was not measured and how it was calculated (e.g. the calculation of the net radiation.)

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Dead Sea evaporation by eddy covariance measurements versus aerodynamic, energy budget, Priestley-Taylor, and Penman estimates

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Abstract. The Dead Sea ~~water budget is no longer in equilibrium. The lake level decline exceeds 1 m a $^{-1}$ and causes severe environmental problems, such as a shifting of the fresh/saline groundwater interface and climatic changes. As the Dead Sea is a~~ is a terminal lake, located in an arid environment~~, evaporation~~ . Evaporation is the key component of the Dead Sea water budget and accounts for the main loss of water. ~~However, the actual amount of evaporation as well as~~ So far, lake evaporation has been determined by indirect methods only and not measured directly. Consequently, the governing factors of evaporation are unknown. ~~Therefore, for~~ For the first time, long-term eddy covariance measurements were performed at the western Dead Sea shore for a period of one year ~~, starting in March 2014. The total annual amount measured at this location was 994±81 mm a $^{-1}$. The median daily evaporation rate reaches 4.3 mm d^{-1} in July and only 1.1 mm d^{-1} in December. The~~ by implementing a new concept of onshore lake evaporation measurements. To account for lake evaporation during offshore wind conditions, a robust and reliable multiple regression model was developed using the identified governing factors wind velocity and water vapour pressure deficit~~were identified as the main governing factors of evaporation throughout the year. Consequently, the local wind systems define the~~ . An overall regression coefficient of 0.8 is achieved. The measurements show that the diurnal evaporation cycle ~~. In the evening~~is governed by three local wind systems: a lake breeze during daytime, strong downslope winds ~~govern the wind field and cause evaporation amounts~~ in the evening and strong northerly along-valley flows during the night. After sunset, the strong winds cause half hourly evaporation rates which are up to 100 % higher than during daytime~~, and also during the night evaporation rates are accelerated compared to daytime evaporation, due to strong northerly along-valley flows. Furthermore, a robust and reliable regression model is presented to calculate sub-daily and multi-day evaporation values with a linear function of wind velocity and vapour pressure deficit. An overall correlation coefficient of 0.8 is achieved and the cross validation results in a prediction error of 4.8~~. The median daily evaporation is 4.3 ~~%. Finally,~~ mm d^{-1} in July and 1.1 mm d^{-1} in December. The annual evaporation of the water surface at the measurement location was 994±88 mm a^{-1} from March 2014 until March 2015. Furthermore, the performance of indirect evaporation approaches ~~were tested for their applicability for the Dead Sea~~ was tested and compared to the measurements. The aerodynamic approach is applicable for sub-daily and multi-day calculations and attains correlation coefficients between 0.85 and 0.99. For the application of the Bowen-Ratio-Energy-Balance

~~(BREB)~~ method and the Priestley-Taylor method, measurements of the heat storage term are inevitable ~~to calculate evaporation~~ on time scales up to one month. ~~Without the heat storage term, the equations yield~~ Otherwise strong seasonal biases ~~and over- or underestimate daily evaporation rates by up 100 %. The usage of an empirically gained linear function or a hysteresis model depending on the net radiation to estimate the heat storage term was not accurate enough to provide reliable evaporation amounts. The~~ occur. The Penman equation was adapted to calculate realistic evaporation~~amounts~~, by using an empirically gained linear function for the heat storage term~~. The correlation coefficients are above 0.9, the daily mean difference is only 0.5 mm d^{-1} and the estimated annual amount is within the range of the measurement uncertainties. ~~, achieving correlation coefficients between 0.92 and 0.97. In summary, this study introduces a new approach to measure lake evaporation with a station located at the shoreline, also transferable to other lakes. It provides the first directly measured ~~amounts of~~ Dead Sea evaporation ~~and applicable methods to calculate evaporation .~~ rates as well as applicable methods for evaporation calculation. The first one enables to further close the Dead Sea water budget, and the latter one enables to facilitate water management in the region.

1 Introduction

Since several years, the lake level of the Dead Sea declines by over 1 m a^{-1} (approx. $600-700\cdot10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$), meaning that the balance of the Dead Sea water budget is no longer sustained. The main water inflow to the Dead Sea is the Jordan river, but through anthropogenic interferences the discharge of the Jordan river into the Dead Sea decreased by 90 % down to $60-400\cdot10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$ (Asmar and Ergenzinger, 2002; Holtzman et al., 2005) ~~.~~ compared to its natural discharge before 1955. Further natural inflow by groundwater discharge and surface runoff is in the range of $235-243\cdot10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$ (Siebert et al., 2014). As the Dead Sea is a terminal lake, no natural outflow exists, but water is withdrawn from the lake for mineral and potash production. The ~~total amount~~ loss of water is about $250\cdot10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$ (Lensky et al., 2005). Thus, evaporation has to be the main loss of water from the Dead Sea. Even though evaporation is of particular importance for the Dead Sea water balance, the variation in evaporation estimates is high. The spread of the evaporation estimates ranges from 1.05 to ~~2~~2.00 m a^{-1}~~(Stanhill, 1994; Salameh and El-Naser, 1999)~~, comparable to a volume loss of ~~$700-1400\cdot10^6$~~ $700-1334\cdot10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$ ~~(Gavrieli et al., 2006). Evaporation is not only a loss of water from~~ (Stanhill, 1994; Salameh and El-Naser, 1999). It is important to reduce these uncertainties and assess the water budget components of the Dead Sea ~~and an important water balance budget component, the thereby resulting~~ for a climatological purpose, but it is also of importance for the people in the area and the socio-economic development of the region to anticipate the evolution of these components and the resulting consequences for the environment. For instance, the lake level decline ~~also~~ causes severe environmental problems. It influences the adjacent aquifers, their groundwater tables and flow paths (Siebert et al., 2016), and results in a shifting of the fresh/saline groundwater interface (Yechieli et al., 2006), which is connected to the development of sinkholes (Yechieli et al., 2006; Abelson et al., 2006). Since the 1980s, over 4000 sinkholes have formed at the western shore of the Dead Sea, which affect industrial, agricultural, and environmentally protected areas, leading to a substantial economic loss (Arkin and Gilat, 2000). Furthermore, evaporation influences the climatic conditions through a considerable change of the fraction of land and water surface. The changing fraction of water and land surfaces leads to a changing partitioning of the net radiation into sensible and latent heat flux. This results in a weaker horizontal gradient of the air temperature between the air masses over the water and land surface, resulting in a weaker pressure gradient, and thus weakens the lake breeze. As the lake breeze has an attenuating effect on the diurnal temperature amplitude, and advects humidity towards the land, a weaker lake breeze results in higher maximum temperatures and decreasing humidity in the southern part of the valley (Alpert et al., 1997). Furthermore, it increases the diurnal penetration of the westerly winds into the valley in the afternoon. These westerly winds have often high wind velocities enhancing the evaporation and thus accelerating the lake level decline. Alpert et al. (1997) showed that in the ~~1940~~1940s, before the lake level and thus the water surface started to decrease, the much stronger easterly lake breeze delayed the penetration of the westerly winds considerably. The changing atmospheric conditions, together with the changing groundwater tables result in a severe dieback of vegetation and the drying up of springs, endangering the unique flora and fauna in the Dead Sea region~~.~~ ~~Especially~~ , such as the unique fish population ~~around Ein Feshkha (Goren and Ortal, 1999; Lipchin et al., 2009) is affected by the reduced water supply~~of the Ein Feshkha reserve (Goren and Ortal, 1999; Lipchin et al., 2009).

In view of these environmental changes, resulting from the lake level decline, more accurate estimates of the Dead Sea evaporation are required (Kottmeier et al., 2016). Previous studies on the Dead Sea evaporation used indirect methods, such as water budget calculations (Salameh, 1996; Salameh and El-Naser, 2000), the energy balance approach (Stanhill, 1994; Lensky et al., 2005), aerodynamic methods (Salhotra et al., 1985; Oroud, 1994), or the combination of the latter two methods, called combination approach (Calder and Neal, 1984; Asmar and Ergenzinger, 1999; Oroud, 2011). Variations in evaporation estimates between the studies result from assumptions on single water budget components such as groundwater inflow, different lengths of the time series of input variables, different measurement locations, and measurement uncertainties. To minimise the spread of 1.05 to ~~2~~2.00 $\mathrm{m\,a^{-1}}$ in the evaporation estimates (Stanhill, 1994; Salameh and El-Naser, 1999) and reduce uncertainties, direct measurements of the Dead Sea evaporation are required. ~~Furthermore, the governing factors of the Dead Sea evaporation, e.g. wind velocity, vapour pressure deficit, or net radiation, have to be identified, to validate the indirect methods.~~ The eddy covariance technique is the only method to obtain direct evaporation measurements~~, in high temporal resolution, which can be linked to meteorological variables afterwards. It~~ . Thus, it is considered the most accurate and reliable method to estimate evaporation ~~(Rimmer et al., 2009).~~ (Rimmer et al., 2009; Tanny et al., 2008). All other methods assess evaporation indirectly, which means that all measurement errors accumulate into the estimated evaporation (Assouline and Mahrer, 1993). With the high temporal resolution of the measurements, the data can also be linked to meteorological variables afterwards. However, it is quite expensive and difficult to perform such measurements as it requires highly accurate instruments and their ~~continues~~ continuous maintenance. Various studies using eddy covariance measurements have been conducted around the world and also in Israel. Assouline and Mahrer (1993) measured evaporation from Lake Kinneret, a freshwater lake north of the Dead Sea, crossed by the Jordan river, and Tanny et al. (2008) measured evaporation from a small reservoir ~~in the North~~ also north of the Dead Sea using eddy covariance systems. However, ~~as~~ to the authors knowledge, no eddy covariance measurements were performed at the Dead Sea, where the environmental problems are severe. That is why, in the framework of the international DESERVE project (Kottmeier et al., 2016), a new concept of assessing lake evaporation from onshore measurements was applied. ~~Therefore, long-term~~ Long-term eddy covariance measurements ~~are~~ were conducted at the Dead Sea shore~~to measure~~

~~the latent and sensible heat fluxes, as well as temperature, humidity, precipitation, radiation, wind speed, and wind direction. The measurement location directly at the shoreline provides flux data from~~ , which provided evaporation data of the water surface for onshore wind conditions. ~~The station is complemented by two additional eddy covariance stations in close vicinity to provide additional data from the homogeneous desert land surface and from a vegetated area~~These measurements were combined with a statistical model to calculate evaporation for offshore wind conditions. The comprehensive data set ~~of the station~~ is analysed in this paper with the following aims: (i) ~~Providing~~ Provide an applicable method for measuring ~~evaporation from the Dead Sea water surface~~lake evaporation, using a station located at the shoreline. (ii) ~~Evaluating~~ Evaluate the actual evaporation ~~rate~~ rates of the Dead Sea ~~and its~~ at the measurement location and their diurnal and intra-annual variability, and (iii) ~~evaluating~~ evaluate the applicability of the commonly used indirect methods to calculate evaporation from the Dead Sea, and assess the capacity of the methods to retrieve the evaporation term, in the future, when eddy covariance measurements are not available any more.

2 Measurement site and instrumentation

The Dead Sea is a hypersaline terminal lake, located at the lowest point of the Jordan rift valley. It is surrounded by the Judean Mountains to the West and the Moab Mountains to the East (Fig. 1 a). Nowadays, the Dead Sea consists of two basins, the northern basin with approximately 600 km^2 and the shallow artificial evaporation ponds in the south with approximately 280 km^2, which are used for potash and mineral production. Since the 1950s, the lake level of the northern basin dropped by over 30 m, from -395 m AMSL to the current -429.9 m AMSL (Givati and Tal, 2016). The southern basin is held on a constant level by pumping water from the northern basin to the south. The area between the lake and the eastern and western mountain chains is rocky desert. When freshwater springs emerge along the ~~shore line~~shoreline, sufficient water is available for plants to grow. Although the total area of these vegetated areas is very small compared to the area covered by water or desert, these vegetated areas are very important for the diversity of the local ecosystems.

To measure the energy balance components of the water surface, ~~a fully equipped~~ an energy balance station (EBS) was installed directly at the shoreline (Fig. 1 b). The station, was located 3 km south of Ein Gedi on the tip of a headland at the western shore of the Dead Sea (Fig. 1 a). At the time of the measurements, the station was located at -428 m AMSL, the headland was 214 m long and was surrounded by water from 300° to 260° (insert in Fig. 1 b).

3 ~~Data and methods~~

~~To achieve the research aims, measurement data from March 2014 until March 2015 were analysed.~~

At the station the following meteorological variables were measured and averaged over 10 min: temperature and humidity at 2 m height (HC2S3, ~~Rototronics~~Rotronic), temperature at 6 m (100KGA1A, BetaTherm), longwave and shortwave radiation components of the upper and lower half space (CNR4, Kipp&Zonen) at 2 m height, precipitation (tipping bucket rain gauge 552202, Young), and atmospheric pressure (PTR330, Vaisala) at 1 m height. With a temporal resolution of 20 Hz, water vapour,

CO_2 concentration, sonic temperature and the three wind components were measured with an open path integrated gas analyzer and sonic anemometer (IRGASON) from Campbell Scientific at 6 m height.

~~From the~~ As the station was located at the shoreline, the radiation measurements of the lower half space represented the land surface conditions. For the water surface they have to be calculated. The applied method is explained in Sec. 3.1. Furthermore, the heat storage of the lake was not measured and was therefore calculated as the residuum of the energy balance equation ($R_n = LE + H + \Delta Q$) using half hourly measurements. Notable hereby is that ΔQ also contains the possible non-closure of the energy balance. Considering the values of common energy balance closure studies (Foken, 2008; Wilson et al., 2002) the heat storage is thus most likely about 20 % smaller than calculated.

3 Data and methods

Measurement data from March 2014 until March 2015 were analysed. To achieve the research aims, following calculations and methods were applied. The shortwave and longwave radiation components of the lower half space were calculated. This is presented in Sec. 3.1. The latent and sensible heat flux were calculated from the 20 Hz data ~~evaporation was calculated~~using the eddy covariance ~~technique~~method. The principle of the ~~eddy covariance theory, the applied~~ method, the post-processing ~~steps and the used objective method for~~ and data quality control steps are presented in ~~the following~~ Sec. 3.2. Furthermore, a multiple regression model was used to calculate evaporation for offshore wind conditions and it was validated using the Monte-Carlo cross validation (MCCV) technique, which is explained in Sec. 3.3. The indirect methods which are evaluated for calculating evaporation from the Dead Sea water surface and the performed sensitivity studies are presented in Sec. 3.4.

3.1 Calculation of radiation components

The measurements of the radiation components of the lower half space were not conducted directly over the water surface, but over the land surface. Therefore, these two components had to be calculated for the water surface. The reflected shortwave radiation was calculated using literature values of the Dead Sea albedo. Stanhill (1987) calculated the albedo of the Dead Sea surface from ship measurements and reported values of 0.06 in the summer months, 0.09 in the winter months, and an annual average of 0.07. He also reported albedo values from Kondrat'Ev (1969) for the latitude of the Dead Sea and the cloud cover observed in the northern part of the Dead Sea, which was 0.08 for November and 0.07 as an average annual albedo value. To confirm the validity of the literature values for our site, a short-term experiment was conducted in November 2014. The measured albedo values of 0.08 to 0.09 concur well with the literature values for winter. As the literature values for summer could not be compared to measurements, the annual average of 0.07 was used for all calculations. The longwave outgoing radiation was calculated using the Stephan-Boltzmann equation

$$Rl \uparrow = \epsilon \cdot k_B \cdot T_S^4, \tag{1}$$

with the water surface emissivity $\epsilon = 0.98$ (e.g. Konda et al. (1994)) and the Stephan-Boltzman constant, k_B. For the surface water temperature, T_S, no in-situ measurements were available. Also remotely sensed surface water temperature products could

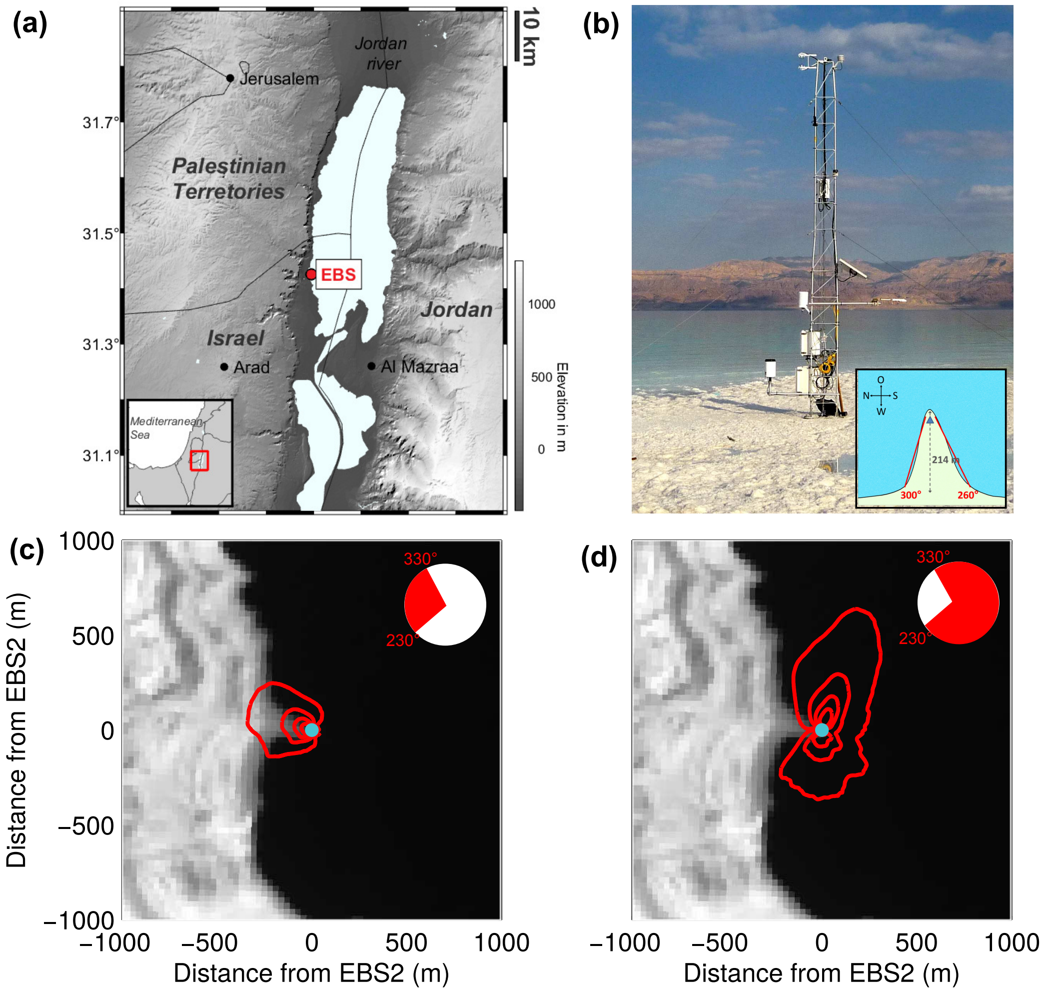

Figure 1. Map of the research area and location of the measurement site (a), image of the measurement site and sketch of the headland (inlet) (b), Landsat 8 images of the headland with location of the EBS (blue dot), containing the results of the footprint analysis (c,d). Contour lines (from inside to outside) represent 20 %, 40 %, 60 %, and 80 % of the flux footprint area calculated with the footprint model of Kljun et al. (2015) for offshore wind conditions with wind direction between 230° and 330° (c) and for the other wind directions (d). Satellite data provided by the U.S. Geological Survey.

not be used as operational SST algorithms are calibrated to mean sea level and do not take the additional 421 m atmospheric layer in the Dead Sea valley into account. Nehorai et al. (2009) showed that a calibration of satellite data with in-situ measurements is necessary. Furthermore, Nehorai et al. (2009) raised concerns that enhanced water vapour input into the atmosphere through evaporation causes stronger absorption of thermal IR radiation, leading to a screening of the Dead Sea surface and, thus, incorrect estimates of the surface water temperature. Based on the results of Nehorai et al. (2013), which showed that "SST is highly correlated to air temperature ($R^2 = 0.93 - 0.98$) in all seasons", the Monin-Obukhov similarity approach was used to calculate surface water temperature from the measured air temperature (see Appendix A), and is further on referred to as T_{MO}.

3.2 Calculation of sensible and latent heat flux

To calculate the sensible and latent heat flux from the wind, temperature, and humidity data measured by the IRGASON, the eddy covariance technique ~~is~~ was used. This method uses the fluctuations of the vertical wind velocity and temperature around a temporal mean, here 30 min, to calculate the sensible heat flux:

$$H = c_p \cdot \rho_a \cdot \overline{w' T'_{sonic}}, \tag{2}$$

and of the vertical wind velocity and the absolute humidity to calculate the latent heat flux:

$$LE = L_v \cdot \overline{w' a'}\cancel{.} \cdot 1000. \tag{3}$$

The overbar represents the time average over 30 min, c_p is the specific heat at constant pressure in J K^{-1} kg^{-1}, ρ_a is the density of the air in kg m^{-3}, w' is the deviation of the vertical wind speed from the mean vertical wind speed in m s^{-1}, $\cancel{T'_a}$ T'_{sonic} is the deviation of the sonic temperature from the mean ~~air~~ sonic temperature in K, and a' is the deviation of absolute humidity from the mean absolute humidity in kg m^{-3}. L_v is the latent heat of vaporisation in kJ kg^{-1},

$$L_v = 3148.4 - 2.37 \cdot T_w, \tag{4}$$

which depends on water temperature T_w in K. For salt water L_v increases with increasing salinity (Steiner, 1948). Therefore, for the calculation of the latent heat flux of the Dead Sea water, the salinity of the water has to be considered. To get the dependency of L_v on ~~surface water temperature of~~ water temperature for the Dead Sea, respective measurements were undertaken. The vapour pressure of the Dead Sea water was measured as a function of water temperature with a calibrated capacitance manometer (see Appendix B). The following equation for the Dead Sea water was derived with the same units as in equation 4:

$$L_v = 5150.6561 - 13.9530 \cdot T_w + 0.0162 \cdot T_w^2. \tag{5}$$

As evaporation takes place directly at the water surface of the lake, in a layer of approximately 10 µm (Emery et al., 2001), surface water temperature $\cancel{T_{0m}}$ should be used for the calculation of L_v. ~~The surface water temperature is not measured directly and is thus calculated using the Monin-Obukhov theory (see Appendix C) and is therefore referred to as~~ Thus, the introduced T_{MO} was used for this purpose.

3.2.1 Post-processing of eddy covariance data

Post-processing of eddy covariance data is essential as field measurements generally do not fulfil all the theoretical concepts and assumptions of the eddy covariance theory. In particular, measurement limitations of the sensors, non-stationary conditions over the averaging period, as well as horizontal heterogeneity have to be considered (Foken et al., 2012). Therefore, the following post-processing steps were applied to the data set using the software package TK3 (Mauder and Foken, 2011). First, data were checked on plausibility using individual thresholds for each meteorological variable. Then, a spike detection, using the algorithm after Mauder et al. (2013), was applied. No fluxes were calculated if more than 10 % of the data in the corresponding 30 min interval were missing. To account for a not perfectly levelled sonic anemometer, meaning that the vertical axis is not perpendicular to the surface, and thus the vertical wind measurements are affected by the horizontal wind components, the coordinate system of the sonic anemometer was rotated using the planar fit method after Wilczak et al. (2001). It rotates the coordinate system to the main wind direction and then rotates the system around the y-axis, such that the z-axis is positioned perpendicular to the horizontal plan and that the mean vertical wind ~~is~~ over the period that is used to define the plane is $0\,\mathrm{m\,s^{-1}}$. Spectral corrections were performed to account for the loss of energy for high frequencies, due to path-length averaging and limited sensor frequency response, following the approach after Mauder and Foken (2011). The influence of humidity on sonic temperature plays an important role for the calculation of the sensible heat flux. To account for this influence, the Schotanus correction (Schotanus et al., 1983) was applied. This correction is particularly important for flux calculations ~~for~~ at sites with high humidity fluctuations, such as over the water surface. The water vapour measurements are influenced by temperature and humidity changes, as only the molar density of water vapour is measured and not the mass mixing ratio. To consider the density fluctuations, corrections after Webb et al. (1980) were applied. ~~Finally, spectral corrections were performed to account for the loss of energy for high frequencies, due to path-length averaging and limited sensor frequency response, following the approach after Mauder and Foken (2011).~~

3.2.2 Quality control and data coverage

The overall performance of the system was very good, and only 2.1 % of the sensible heat flux data and 2.4 % of the latent heat flux data were missing. To assure data quality of the flux measurements, several quality criteria were applied. Latent heat flux data were rejected when the signal strength of the radiation source to measure the water vapour was below ~~0.5~~50%, when the variability of the signal from one 10 min average to the next one was higher than 0.6 % within ~~a~~ the 30 min time interval, and during precipitation events, as a disturbance of the water vapour measurements was expected for these conditions. Due to these quality criteria 10 % of the latent heat flux data were rejected. Further quality control was performed using the steady state test after Foken and Wichura (1996), which analyses each 30 min time interval on stationarity ~~. The~~ and the integral turbulence characteristics (ITC) test after Foken et al. (2012), which checks data on fully developed turbulent conditions~~and, therefore, compares modelled ITC to the actually measured ones, and if the deviation is less than 30 % very good data quality is assumed~~. A combined quality flag considering the steady state test and the ITC test (Foken, 1999) was used to classify the data into nine classes. Class 1 to 6 describe data, which can be used for the analysis and classes 7 to 9 were rejected. After the quality control, data availability was 86.3 % for sensible and 78.5 % for latent heat flux data. Furthermore, the flux footprint ~~has~~ had to be considered. A footprint analysis was performed, using the model after Kljun et al. (2015). Results show that flux data for wind directions between 230° and 330° ~~have~~ had to be rejected as the fetch ~~is~~ was over land, while the aim of this station ~~is~~ was to measure evaporation from the water surface (Fig.1 c). For northerly to southerly wind directions, the fetch ~~is~~ was over water and the average fetch contributing to 80 % of the flux ~~footprint is in the range of~~ ranged from 0 to 300 m ~~away from the headland~~ and 0 to 600 m, respectively. (Fig.1 d). ~~For northerly wind directions the fetch was in the range of about 600 m away from the headland.~~ The amount of flux data rejected due to the footprint was about 19 %. The total available flux data from the water surface was thus 67.1 % for sensible and 59.2 % for latent heat flux. This ~~is reasonable~~ was reasonably good compared to other eddy covariance studies at other lakes~~. Jonsson et al. (2008) reported~~ , where a data availability ~~of 46~~between 36 % and ~~Mammarella et al. (2015) had a data availability of 63~~56 % ~~for sensible and 53 % for latent heat flux data.~~ was reported (eg. Jonsson et al., 2008; Mammarella et al., 2015; Bouin et al., 2012).

3.3 Multiple regression model for the latent heat flux

Through the installation of the EBS at the shoreline flux data from the water surface are only available for onshore wind conditions and all data for offshore wind conditions, i.e. wind directions between 230° and 330°, ~~have to be rejected for further~~ are rejected for the analysis (Fig. 1 c). However, for the analysis of the diurnal and intra-annual variability of the evaporation rates, estimates of the fluxes for these wind directions are important, as otherwise evaporation rates in the afternoon, when westerly downslope winds prevail would be missing. Therefore, a multiple regression model is applied to find a suitable relationship between the turbulent fluxes and governing meteorological variables, such as wind speed, vapour pressure deficit, net radiation, and surface water temperature. ~~Vapour~~ The vapour pressure deficit is calculated using the surface water temperature ~~, which is gained by the Monin-Obukhov theory~~ T_{MO} (see Appendix C). A Monte-Carlo cross validation (MCCV), first introduced by Picard and Cook (1984), is performed to test the model's robustness and get an estimate of the model error. The work flow is as follows: (i) data between 230° and 330° are removed from the data set. (ii) Two approaches are used to divide the data in a training and validation data set. The first approach uses randomly chosen data points of about about 15 % of the total data set as validation data and the second approach uses a randomly chosen wind sector of 45° as validation data. The usage of these two approaches allows the general test of the model on robustness but also its sensitivity on a certain wind sector. (iii) After each division a regression model is ~~build~~ built with the training data set and then applied on the data of the validation group. The deviation of the calculated from the measured flux values ~~yield~~ yields the model error of one realisation. (iv) After multiple applications, in this case 500 times, the model error is averaged and results in the prediction error of the regression model. A large prediction error indicates a dependency of the model on the choice of the training data set and ~~is therefore rejected.~~ therefore has to be rejected.

3.4 Indirect methods to estimate evaporation

For the calculation of evaporation, several equations, based on different physical approaches, exist. Each approach connects evaporation to different meteorological parameters and is designed for different time intervals, ranging from sub-daily calcu-

Table 1. Selection of commonly used equations to calculate evaporation (Ev) ~~. Equations are shown~~ in mm d^{-1}. The original version and the ~~form like they are used for the comparison as~~ default ~~versions~~ version (V0) used in Sec. 3.4 and 4.4 are presented.

Method	Name	~~Reference Equation~~ Original Equation	Default Version (V0)
Aerodynamic/ Mass-transfer	Aerodynamic	~~Brutsaert (1982)~~ [1] $Ev = \frac{0.622}{\rho_w p} C_e \rho_a v_a (E_w - e_a)$	~~$Ev = K_E \cdot v_a \cdot (E_w - e_a)$~~ $C_e = \frac{\kappa^2}{\left(\ln(\frac{z_m - z_d}{z_0})\right)^2}$
Energy Budget	BREB ~~(simplified)~~	~~Dingman (2002)~~ [2] $Ev = \frac{R_n - G - F_n - \Delta Q}{\rho_w \cdot L_v \cdot (1+Bo)}$	~~$Ev = \frac{Rn}{\rho_w \cdot L_v \cdot (1+\beta)}$~~ $\cancel{F}_n, \cancel{G}, \cancel{\Delta Q}$
Combination	~~Penman~~ Priestley-Taylor	~~Van Bavel (1966)~~ [3] $Ev = c_{PT} \frac{\triangle \cdot (R_n - G)}{\rho_w L_v (\triangle + \gamma)}$	~~$Ev = \frac{\Delta \cdot Rn + \gamma \cdot K_E \cdot v_a \cdot \rho_w \cdot L_v \cdot (E_a - e_a)}{\rho_w \cdot L_v \cdot (\Delta + \gamma)}$~~ $\cancel{G}$
Combination	~~Priestley-Taylor~~ Penman	~~Priestley (1972)~~ [4] $Ev = \frac{\triangle \cdot R_n + \gamma C_e v_a \rho_w L_v (E_a - e_a)}{\rho_w L_v (\triangle + \gamma)}$	~~$Ev = c_{PT} \frac{\Delta \cdot Rn}{\rho_w \cdot L_v \cdot (\Delta + \gamma)}$~~ orig. Eq. used
	Bowen ratio	~~$\beta = \frac{c_p \cdot p}{0.622 \cdot L_v} \cdot \frac{T_{0m} - T_a}{E_w - e_a} = \gamma \cdot \frac{T_{0m} - T_a}{E_w - e_a}$~~	$Bo = \frac{H}{LE} \approx \frac{c_p \cdot p}{0.622 \cdot L_v} \cdot \frac{T_S - T_a}{E_w - e_a} = \gamma \cdot \frac{T_S - T_a}{E_w - e_a}$
~~Wind function~~ ~~Brutsaert (1982)~~ ~~$K_E = \frac{0.622 \cdot \rho_a \cdot \kappa^2}{p \cdot \rho_w \left(\ln(\frac{z_m - z_d}{z_0})\right)^2}$~~			

C_e	= transfer coefficient for evaporation	R_n	= net radiation
c_p	= specific heat capacity at constant pressure	T_S	= surface water temperature
c_{PT}	= 1.26=Priestley-Taylor coefficient	T_a	= air temperature
e_a	= vapour pressure at air temperature	v_a	= wind velocity
E_a	= saturation vapour pressure at air temperature	Bo	= Bowen ratio
E_w	= saturation vapour pressure at surface water temperature	γ	= psychometric constant
Ev	= evaporation	$\triangle$	= slope of the saturation vapour pressure versus temperature curve
F_n	= net advected heat flux	ΔQ	= heat storage of the lake
G	= ground heat flux	ρ_a	= air density
L_v	= latent heat of vaporisation	ρ_w	= water density
p	= air pressure		

[1] Brutsaert (1982), [2] Dingman (2002), [3] Priestley (1972), [4] Van Bavel (1966)

lations to a time interval of at least 7 days. Four commonly used indirect methods to estimate evaporation (Table 1) will be ~~evaluated~~ tested in this paper by comparing their results to the eddy covariance measurements. An aerodynamic approach also known as mass transfer approach, the energy budget method, and two combination approaches, namely the ~~Penman equation and the~~ Priestley-Taylor ~~equation~~and Penman equation, will be evaluated on time intervals of 1, 7, 14, and 28 days. The aerodynamic approach is the only approach which is also designed for sub-daily time intervals and will thus also be tested for 30 min time intervals. Additionally, sensitivity studies are performed to quantify the influence of simplification within the approaches, which are often made in literature. ~~An overview which sensitivity study is applied for the different methods is given in Table 2.~~ The first method is ~~an~~ the aerodynamic approach after Brutsaert (1982), where only wind speed and vapour pressure deficit are required. ~~Brutsaert (1982) used a~~ With the assumption of equal transfer coefficients for evaporation and momentum ($C_e = C_d$) under neutral conditions the logarithmic wind profile ~~and did not consider near surface atmospheric stability (Table1). A sensitivity study is performed for the aerodynamic approach considering atmospheric stability in the wind function~~ $\cancel{K_E}$~~, afterwards referred to as V1.~~ can be used (Van Bavel, 1966) (Table 1, V0). This is the default version of the aerodynamic method for the sensitivity studies. The second method is the energy budget method expressed as the Bowen Ratio Energy Budget (BREB) (Table 1). For this approach several of the input variables are difficult to obtain. The amount of net advected heat into the water body, F_n, meaning the heat advected into the lake by water inflow and precipitation, as well as the loss of heat by water outflow, have to be known. If the in- and outflows are small compared to the size of the water body, or water temperatures are similar the ~~terms~~ term can be neglected (Dingman, 2002; Rosenberry et al., 2007). Moreover, the ground heat flux G, meaning the heat exchange at the bottom of the lake, is required. It can usually be neglected, as the amount for deep lakes is small compared to the other components (Henderson-Sellers, 1986). Another component difficult to obtain is the heat storage of the lake, ΔQ. It requires measurements of lake temperature at different depths from a raft station or a ship. On longer time ~~scale~~ scales it can often be neglected~~, which is used~~. Because of the aforementioned reasons and the difficulty to obtain these three terms, the net advected heat, the ground heat flux and the heat storage term are neglected in many studies. Thus, for the default version (V0) of the BREB method ~~the net advected heat, the ground heat flux and the heat storage term~~ these three terms are neglected (Table 1). ~~Using this version~~Even though neglecting the heat storage on the time scales investigated is a coarse assumption, it serves as a basis for the sensitivity studies V1 and V2. Using V0, only net radiation, surface water temperature, ~~and air temperature~~air temperature, and the vapour pressure deficit have to be known, which are relatively easy to obtain and thus an easy approach to calculate evaporation. ~~Sensitivity analyses for the BREB method are performed regarding the consideration of the heat storage in the equation. For this purpose~~ $\cancel{Rn}$ ~~is replaced with~~ $\cancel{(Rn - \Delta Q)}$~~. Duan and Bastiaanssen (2015) proposed a hysteresis model to calculate the heat storage term, depending only on the net radiation. This approach is used in sensitivity version V2. Another approach to account for the heat storage term is the simple assumption that the heat storage is directly proportional to the net radiation and that the deviation of the default version from the measurements equals the heat storage term. This is tested as version 3 (V3).~~ The third method to calculate evaporation is the combination approach, considering the energy balance and the aerodynamic influence. Priestley (1972) proposed an equation which considers the aerodynamic influence by using an empirically gained coefficient of $c_{PT} = 1.26$ (Table 1). ~~In this equation the heat storage is also not considered, and hence the same sensitivity studies as for the BREB method are performed.~~

~~Penman (1948) combined~~ Because of the same reason as mentioned above, the ground heat flux is neglected in the default version (V0) of the Priestley-Taylor equation. Method four is a combination of the energy balance equation with the aerodynamic approach first developed by Penman (1948). In his approach he already neglected net advected heat, the ground heat flux, and the heat storage. Van Bavel (1966) further generalized Penman's equation by replacing the empirical wind function through the logarithmic wind profile, assuming neutral conditions (Table 1). ~~The heat storage can be considered in the Penman equation by replacing Rn with $(Rn - \Delta Q)$ again. Sensitivity studies~~ This equation will be used as the default version (V0) for testing the Penman approach.

In total, six sensitivity studies were performed. An overview of the sensitivity studies and to which of the methods it is applied to, is given in Table 2. Sensitivity study V1 considers non-neutral atmospheric conditions, by incorporating stability correction factors into C_e. As only the aerodynamic and the Penman approach are based on mass-transfer, V1 is applied to these two equations only. Studies V2 and V3 ~~are tested for the Penman equation as well. Furthermore, Kohler and Parmele (1967) presented modified coefficients for L_v and γ to eliminate the need of surface water temperature T_s from the equation.~~ consider the heat storage of the lake ΔQ and are applied to the BREB, Priestley-Taylor and Penman method. For this purpose R_n is replaced with $(R_n - \Delta Q)$. Duan and Bastiaanssen (2015) proposed a hysteresis approach to calculate the heat storage term, depending only on the net radiation ($\Delta Q = a + b \cdot R_n + c \cdot dR_n/dt$). This approach is applied to the measurement data and the resulting equation for ΔQ is used in sensitivity version V2. To avoid the use of the calculated heat storage from the measurements, in V3 it is assumed that the heat storage term is directly proportional to the net radiation and that the deviation of the default version (V0) from the measurements equals the heat storage term. The last three sensitivity tests were applied to the Penman approach only. In V4 the uncertainty caused by the calculated longwave outgoing radiation with T_{MO} was eliminated by using an approximation from Kohler and Parmele (1967) where they calculated the longwave net radiation and the psychrometric constant using air temperature only. This further reduces the amount of necessary input parameters, which makes the equation more easily applicable~~. The modified parameters are tested in version V4.~~ , when net radiation of the water surface is not directly measured. In version V5 ~~they are~~ the approximation after Kohler and Parmele (1967) is applied together with the hysteresis model for the heat storage term (V2). The last sensitivity test (V6) combines the ~~parameters~~ approximation after Kohler and Parmele (1967) with a linear function for the heat storage term, derived from the deviation of V4 from the measurements.

4 Results

4.1 Meteorological conditions

In the Dead Sea valley the measured average annual air temperature was 26.5°C for the measurement period, which was slightly higher than the long term annual mean of 25.9 °C ~~(Hecht and Gertman, 2003).~~ found by Hecht and Gertman (2003) for the period 1992 to 2002. Maximum daily air temperatures regularly exceeded 40 °C in summer (Fig. 2) and the ~~total precipitation amount~~ annual precipitation was 273 mm. (Fig. 2). ~~The total~~ The precipitation amount for the observation period is high compared to the ~~annual precipitation normal~~ mean annual precipitation of the standard normal period 1961 to 1990 of 80 mm

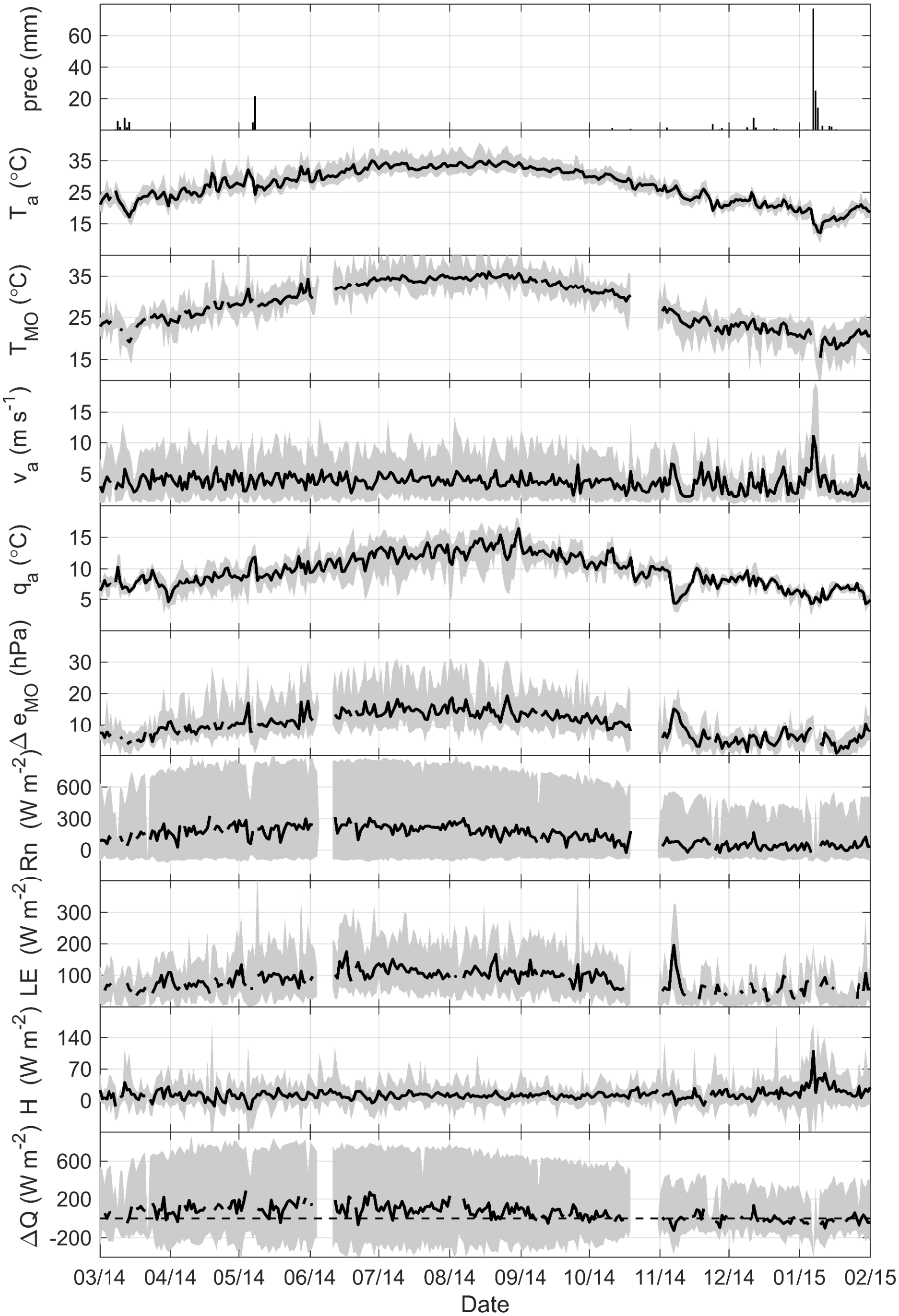

Figure 2. Daily precipitation~~amounts~~, $prec$, 24 h running mean of air temperature, T_a, surface water temperature, T_{MO}, wind velocity, v_a, specific humidity,q_a, vapour pressure deficit Δe_{MO}, net radiation, ~~Rn~~R_n, latent heat flux, LE, sensible heat flux, H, and heat storage ΔQ. The grey shaded area represents the range between daily minimum and maximum values of the respective variable.

Table 2. Overview of the sensitivity studies performed for the evaporation equations. Sensitivity studies applied to a method are marked with an X.

Version	Explanation	Aerodynamic	BREB	Priestley-Taylor	Penman
0	Default (see Table 1)	X	X	X	X
1	Atmospheric Stability	X	–	–	X
2	Heat storage term derived with hysteresis ~~model~~ approach	–	X	X	X
3	Heat storage term derived as a linear function of ~~Rn~~ R_n from V0	–	X	X	X
4	Removal of ~~T_s~~ T_{MO} from R_n calculation	–	–	–	X
5	Removal of ~~T_s~~ T_{MO} from R_n calculation and heat storage term ~~with hysteresis model~~ from hysteresis approach	–	–	–	X
6	Removal of ~~T_s~~ T_{MO} from R_n calculation and heat storage term derived as a ~~fraction of Rn~~ linear function of R_n from V4	–	–	–	X

(Goldreich, 2003). It resulted from a few heavy precipitation events in January 2015, which ~~makes~~ made the observation period 2014/15 a relatively wet year for the area. The wind velocity didn't show a clear annual cycle. From March until October, mean, maximum, and minimum were relatively similar. However, during winter, ~~only during the winterseasons~~ a different behaviour was found when the wind increased in connection with the stronger large scale activity (Fig. 2). The relative uniform wind velocities from spring until autumn resulted from periodic local wind systems, governing the conditions in the valley. Between sunrise and sunset a lake breeze prevailed, leading to north-easterly winds at the ~~western shore~~ station with a median wind velocity of 3 m s^{-1} (Fig. 2 and 3 a). The lake breeze occurred throughout the year, with an occurrence rate ~~of over~~ exceeding 70 % of the days in summer 2014, and 58 % and 48 % of the days in spring and autumn 2014, respectively. In winter, the synoptic conditions gained more influence and often superimposed the local wind field such that a north-easterly lake breeze was only observed ~~at~~ on about 32 % of the days and a south-easterly flow ~~at~~ on 26 % of the days ~~.~~ in winter 2014/15. In the evening, north-westerly downslope winds, often enhanced by the Mediterranean Sea Breeze (MSB) ~~(Alpert et al., 1997; Naor et al., 2017)~~(Alpert et al., 1997; Naor et al., 2017), lead to accelerated wind velocities in the valley (Fig. 3 b). These downslope winds occurred ~~at~~ on about 57 % of the days in summer, and still 28 % of the days in spring and 45 % of the days in autumn. The downslope winds regularly reached mean wind velocities ~~of over~~ exceeding 10 m s^{-1} (Fig. 3 b). During the night, a northerly along-valley flow prevailed mainly in spring and summer. The along-valley flow also reached wind velocities ~~of over~~ exceeding 10 m s^{-1} (Fig. 3 c). The difference between the saturation vapour pressure at the water surface and the actual vapour pressure of the air (Δe) had a mean value of 9.75 hPa. It had a clear annual cycle with maximum values above 30 hPa in summer. Individual peaks in winter were related to special synoptic conditions, e.g. ~~at~~ in the beginning of November, when a Red Sea Trough with a central axis advected dry and warm air into the valley over the course of several days. The annual cycles of the energy balance components are also shown in Fig. 2. The net radiation reaches maximum values ~~of over~~ exceeding 900 W m^{-2} in summer and about 500 W m^{-2} in winter. The sensible heat flux is small throughout the year. The mean latent heat flux values are higher in summer compared to the winter months. However, ~~at~~ on individual days in winter some latent heat flux values even ~~exceed~~ exceeded the summer values. The heat storage ~~is calculated as the residuum of the energy balance equation ($Rn = LE + H + \Delta Q$).As can be seen~~ shown in Fig. 2 shows that a consid-

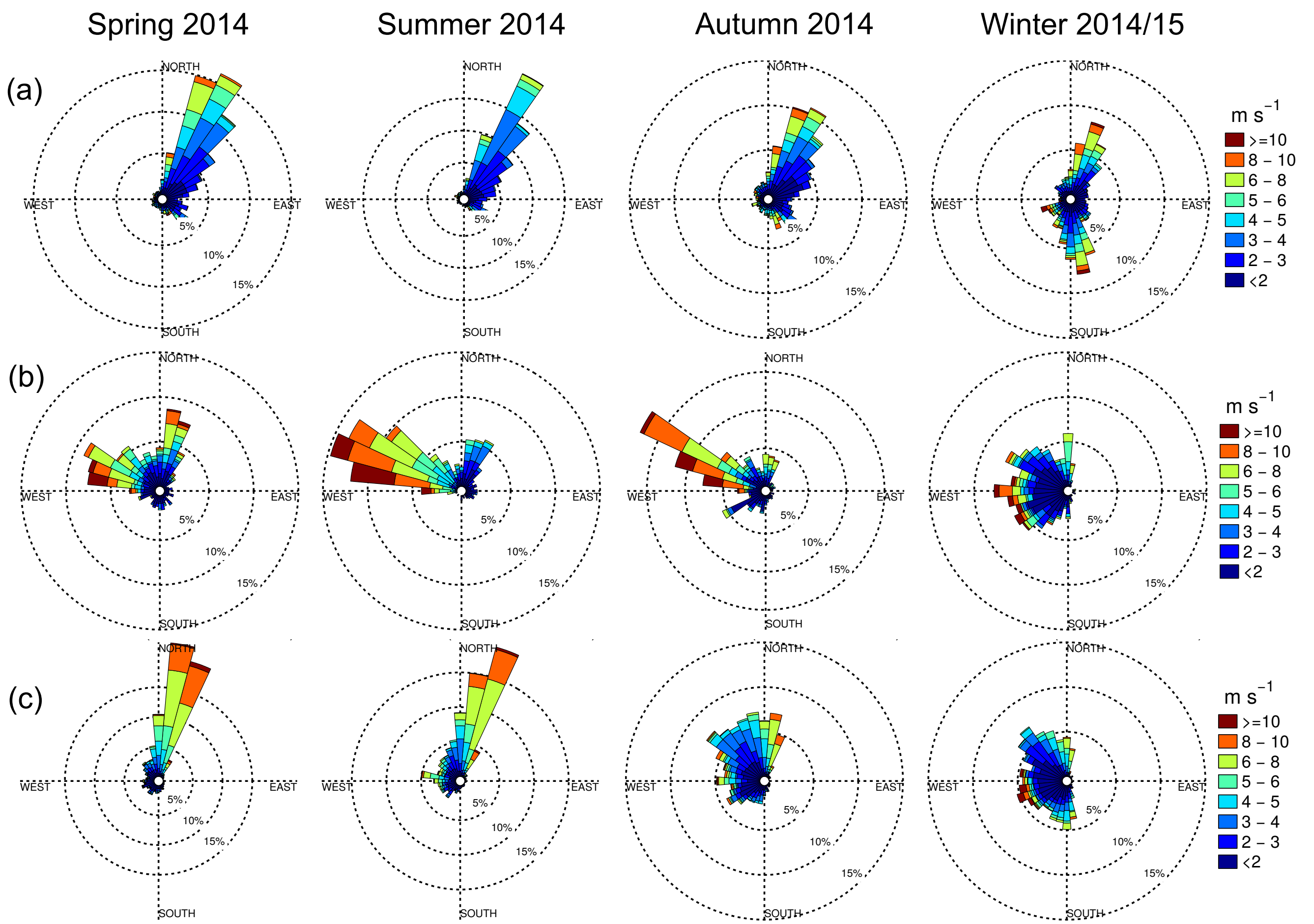

Figure 3. Wind conditions between (a) 6:30 and 17:30 LT, (b) 17:30 and 20:30 LT, and (c) 20:30 and 6:30 LT. Data are shown for spring, summer, autumn, and winter 2014/15.

erable amount of energy is stored, but also released over the course of the day. However, this term also contains the possible non-closure of the energy balance. Assuming common literature values of the non-closure (Wilson et al., 2002; Foken, 2008), the actual heat storage is most likely 20 % smaller than shown here. On a seasonal basis the sensible heat flux accounts for about 5 to 10 % of the net radiation in spring, summer, and autumn, whereas it accounts for nearly 40 % in winter. The latent heat flux accounts for 43 % and 53 % of the net radiation, in spring and summer, leading to a high heat storage amount of 51 % and 42 %, respectively. ~~This energy is used for heating the lake, which is stronger in spring than in summer.~~ In autumn over 74 % of the net radiation is transformed into latent heat flux, such that the heat storage amount is small. In winter, the latent heat flux is in the range of 92 % of the net radiation, meaning that the heat storage term is negative, releasing the heat to the atmosphere, represented through the higher sensible heat flux. Similar behaviour of the flux components was found for other lakes, e.g. Giadrossich et al. (2015).

Table 3. Correlation coefficients for latent heat flux (LE) with wind speed (v_a), net radiation ($\cancel{Rn}R_n$), surface water temperature (T_{MO}), and vapour pressure deficit calculated with surface water temperature (Δe_{MO}). Correlation coefficients over 0.5 are bold. Data are shown for the meteorological seasons 2014/15 and the entire data set.

	v_a	$\cancel{Rn}R_n$	T_{MO}	$\Delta e_{T_{MO}}$
Spring	**0.68**	-0.19	0.07	0.06
Summer	**~~0.72~~0.73**	-0.16	0.00	-0.12
Autumn	**0.53**	0.16	0.36	0.46
Winter	**0.81**	0.27	0.19	**0.56**
Total	**~~0.60~~0.59**	0.03	0.42	0.38

4.2 Multiple regression model for the latent heat flux

The footprint model showed that the fetch of the fluxes is over land for wind directions between 230° and 330°. The affected amount of latent heat flux data is 19 %. Through the predominant local wind systems, these wind directions occur almost exclusively in the evening between 17:30 to 20:30 LT (LT=UTC+2) from spring until autumn (Fig. 3) and, thus, ~~at~~ most of the ~~days~~ data within this time frame are excluded. For the analysis of the diurnal variability of the latent heat flux from the water surface, and also for the intra-annual and annual amounts, it is important to close these gaps. A multiple regression model was applied to calculate the latent heat flux for offshore wind conditions. The choice of the input variables for the multiple regression model was based on the analysis of the linear correlation between the latent heat flux and different meteorological variables. The correlation coefficients for the variables are shown in Table 3. For the latent heat flux highest correlation is achieved with wind speed, with correlation coefficients between 0.53 and 0.81 for the different seasons, followed by the vapour pressure deficit, and finally surface water temperature and net radiation. This is different from cooler climates where highest correlation was found with vapour pressured deficit (Blanken et al., 2000; Nordbo et al., 2011), and also from lakes in Mediterranean climate, where vapour pressure deficit had the same impact as wind speed (e.g. Bouin et al. (2012)). The influence of the vapour pressure deficit varies strongly between the different seasons. In spring and summer no correlation exists between latent heat flux and the vapour pressure deficit, but in autumn, winter, and for the total data set correlation coefficients are between 0.38 and 0.56. Although correlation with individual meteorological variables is already good, none of the variables can fully explain the latent heat flux. A stepwise multiple regression model was applied with the following variables to find the best fitting solution for the latent heat flux:

$$X_{LE} = (v_a, \Delta e_{T_{MO}}, \underline{Rn}R_n, T_{MO}) \tag{6}$$

The model X_{LE} gave the same dependency for all seasons. The latent heat flux depended on a linear combination of wind speed and vapour pressure deficit. The correlation coefficient ranged from 0.77 in spring and summer to 0.85 in winter (Table 4). The aerodynamic approach to estimate evaporation is based on the product of wind speed and vapour pressure deficit (Table 1), instead of a linear combination. For comparison, the correlation of the product of wind speed and vapour pressure deficit with

Table 4. Results of the stepwise linear regression model X_{LE} for the latent heat flux. The corresponding correlation coefficient (R) of the model ~~is shown if~~ after a variable is added to the model ~~. If a variable~~ is ~~not added to the model, it is indicated with a minus sign~~shown. For the model with $v_a \cdot \Delta e_{MO}$, the correlation coefficient (R) is given. The prediction errors yielded by the MCCV with randomly chosen validation data points (er_r) and randomly chosen validation sectors (er_s) are shown for both models. Results are shown for the meteorological seasons and for the entire data set.

	X_{LE}						$v_a \cdot \Delta e_{T_{MO}}$		
	v_a	$\Delta e_{T_{MO}}$	~~Rn~~	~~T_{MO}~~	$er_r(\%)$	$er_s(\%)$	R	$er_r(\%)$	$er_s(\%)$
Spring	0.68	0.77	~~–~~	~~–~~	0.32	8.61	0.79	-0.01	10.57
Summer	0.73	0.77	~~–~~	~~–~~	0.17	2.31	0.76	-0.17	1.60
Autumn	0.53	0.82	~~–~~	~~–~~	-0.16	1.25	0.84	0.42	6.17
Winter	0.81	0.85	~~–~~	~~–~~	2.94	0.02	0.85	4.72	-0.31
Total	0.59	0.80	~~–~~	~~–~~	0.96	4.79	0.83	0.80	6.78

the latent heat flux was calculated additionally and resulted in nearly the same correlation coefficients (Table 4). The results of the ~~MCCV~~ Monte-Carlo cross validation (MCCV) analysis reveal that the model X_{LE} results in small prediction errors. The prediction error varies between -0.16 and 2.94 % for randomly chosen data points and for randomly chosen control sectors between 0.02 and 8.61 %. The model with $v_a \cdot \Delta e_{T_{MO}}$ results in higher model errors varying between -0.17 and 4.72 % for randomly chosen data points and between -0.31 and 10.57 % for randomly chosen control sectors. Even though the correlation coefficients are similar for both models, model X_{LE} was chosen for the calculation of the latent heat flux, instead of the commonly used $\Delta e \cdot v_a$, because of the robustness and the smaller prediction error. The model coefficients are shown in Table 5.

In summary, the regression model X_{LE} provides a suitable and robust method to calculate the latent heat flux for offshore wind conditions. To assure, that the model is not applied outside the conditions for which it has been constructed, the extreme values of offshore wind velocity and vapour pressure deficit are not considered to calculate evaporation and it is checked that data are always within the model boundaries. Evaporation values, which can not be calculated because wind velocity or vapour pressure deficit are outside the boundaries are treated as missing values. With this method 90 % of the originally rejected latent heat flux data due the fetch criteria ~~could~~ can be calculated with the model. The total data availability ~~was thus~~ is increased from 59.2 % to 76.8 %.

The calculation of the latent heat flux for offshore wind conditions is especially important for the analysis of the diurnal cycle of the latent heat flux, and also for its intra-annual variation. The comparison of the mean diurnal cycles of the measured fluxes ~~(uncorrected)~~ with the cycles including the calculated values for offshore wind conditions (corrected fluxes) shows that during the day the differences are small (Fig. 4). As the prevailing wind direction is north-east, caused by the lake breeze, nearly no calculations are necessary, as the flux footprint is located over water (Fig. 1 d). However, in the evening, when downslope winds prevail in spring, summer, and autumn, the differences are quite large (Fig. 4). During this time period, the measured values represent the latent heat flux from the land surface, with values around or below 50 $\mathrm{W\,m^{-2}}$. In contrary the calculated values represent the latent heat flux from the water surface, with values up to 200 $\mathrm{W\,m^{-2}}$ in summer. Hence, the regression model allows a detailed analysis of the diurnal cycle of the fluxes, even though the station is located at the shoreline.

4.3 Diurnal and ~~annual~~ intra-annual variability

The latent heat flux is the dominating turbulent flux at the water surface (Fig. 2). It has a strong diurnal cycle. During daytime, the latent heat flux reaches values of 100 $\mathrm{W\,m^{-2}}$ in summer and autumn, and 70 $\mathrm{W\,m^{-2}}$ in spring and winter (Fig. 4). The maximum values are reached after sunset around 19:00 LT in spring, summer, and autumn. In spring about 105 $\mathrm{W\,m^{-2}}$ are reached, in summer 213 $\mathrm{W\,m^{-2}}$, and in autumn 136 $\mathrm{W\,m^{-2}}$. During the night, the latent heat flux continues to be higher than during daytime and reaches minimum values shortly before sunrise. In winter, this late maximum is not observable and values during nighttime are lower than during daytime. The unusual diurnal cycle with highest latent heat flux values after sunset and during the night are clearly connected to the diurnal cycle of wind speed and vapour pressure deficit, and thus to the wind systems. This is most pronounced in summer. During the day, the lake breeze with relatively low wind velocities, (Fig. 3 a), causes moderate latent heat flux rates. The downslope winds in the evening have generally high wind velocities (Fig. 3 b), and advect drier air into the valley, which results in high vapour pressure deficits and thus high latent heat flux values. The high values during night result from accelerated wind velocities (Fig. 3 c), rather than high vapour pressure deficits.

For the calculation of daily and yearly evaporation~~amounts~~, still existing data gaps were closed, using the median evaporation rate of the corresponding time step of the respective month. The uncertainty due to this gap filling method was estimated using

Table 5. Coefficients of the model equations to calculate latent heat flux (LE). The equations have the general form: $LE = a + b \cdot v_a + c \cdot \Delta e$. Coefficients are shown for the meteorological seasons 2014/15 and the entire data set.

	Spring	Summer	Autumn	Winter	Total
a	-32.52	-25.41	-58.91	-15.29	-36.92
b	13.33	18.41	16.21	11.07	14.31
c	5.51	4.61	7.56	4.46	6.13

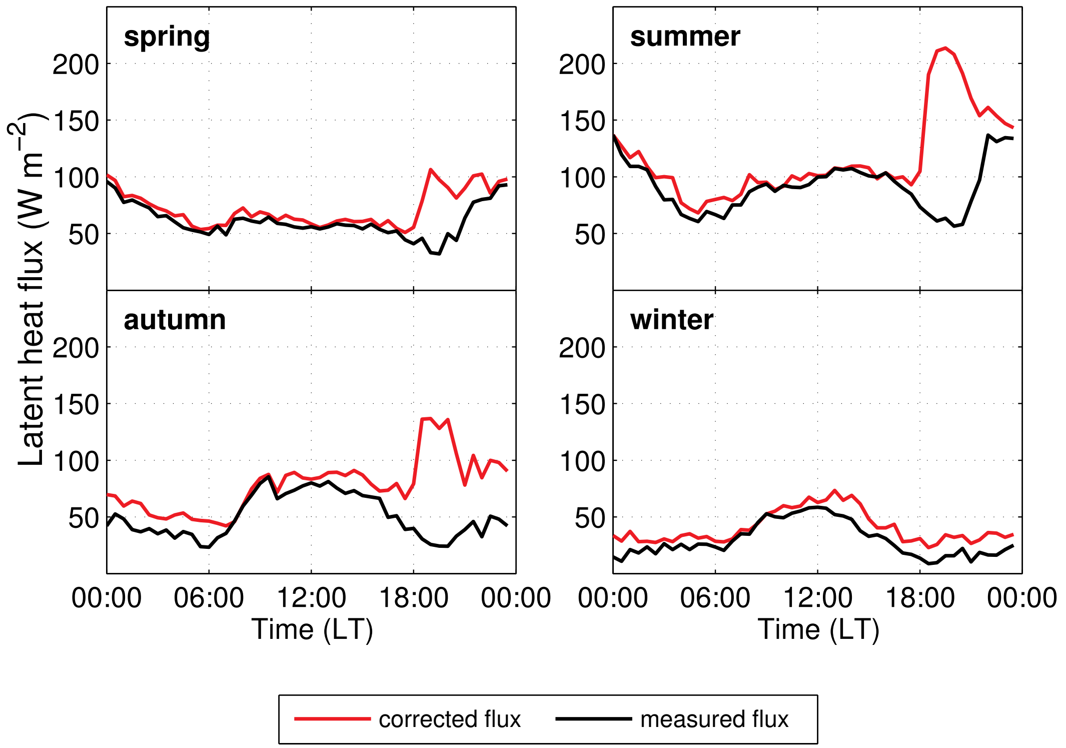

Figure 4. Median diurnal cycles of the measured latent heat flux (black lines) and the ~~calculated~~ latent heat flux ~~for~~ corrected with the ~~water surface (red lines). Latent heat flux values~~ multiple regression model for wind directions between 230 and 330° ~~are calculated with the multiple regression model~~(red lines).

the median absolute deviation (MAD), which is the median of the absolute deviations from the data's median.

In spring, evaporation ~~values~~ rates steadily increase until a maximum median evaporation ~~rate~~ of 4.3 mm d^{-1} is reached in July (Fig. 5). Afterwards, evaporation ~~values~~ rates decrease until a minimum median evaporation ~~rate~~ of 1.1 mm d^{-1} is reached in December (Fig. 5). The annual cycle of evaporation follows the solar cycle with a time lag of about 1 month. Summing the evaporation values over the whole measurement period results in ~~a total amount~~ an annual evaporation of 994.5±88.2 mm, where 81.2 mm ~~.~~ of the uncertainty result from the gap filling method and 7.0 mm from to the regression model. Also visible in Fig. 5 is the higher variation of the daily evaporation ~~amounts~~ rates between November and February. This is the so-called wet season when synoptic patterns gain more influence on the atmospheric conditions in the valley (Bitan, 1974, 1976). The governing factors of evaporation, i.e. wind speed and vapour pressure deficit, are very variable during this time. On the one hand, winter storms with rain and high air humidity can reach the region, which decreases the evaporation rate. On the other hand, winter storms without rain but high wind velocities, which advect very dry air to the Dead Sea, can significantly increase the evaporation rate (Shafir and Alpert, 2011). The highest variability (not considering outliers) can be seen in January, with daily evaporation ~~amounts~~ rates between 0.6 and 3.1 mm d^{-1}. In November, ~~evaporation values vary~~ daily evaporation rates varies between 0.7 and 2.4 mm d^{-1}, but on three consecutive days evaporation rates exceed these values. Evaporation rates of

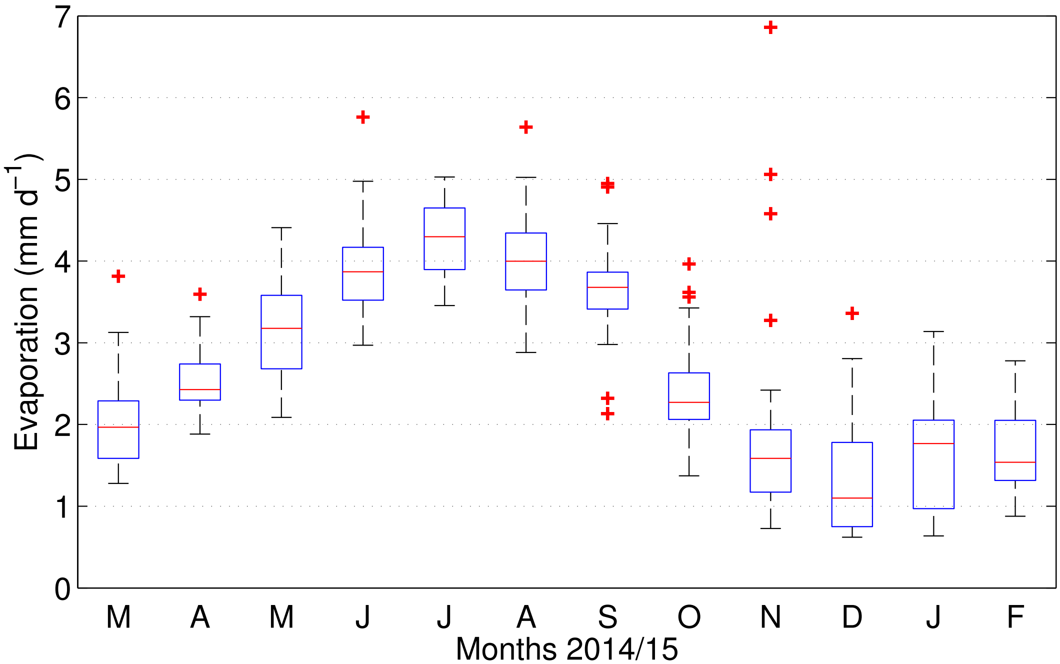

Figure 5. Boxplot of daily evaporation rates. Red lines indicate medians, the edges of the boxes are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually by red crosses.

5.1 mm d^{-1}, 6.9 mm d^{-1}, and 4.6 mm d^{-1} are measured, which is the absolute maximum of the whole measurement period. These extreme evaporation ~~values~~ rates are caused by a Red Sea Trough with a central axis and a dominant high to the east, which causes south-easterly winds above the valley. It can be observed that through the complex orography a pressure driven channelling occurs along the valley axis, resulting in a near-surface northerly wind with constantly high averaged wind speed ~~of over~~ exceeding 10 m s^{-1} (not shown). This leads to the advection of warm and very dry air over the lake, which, together with the high wind velocities, increases the evaporation dramatically. This case was also used to test the performance of the regression model as on these three consecutive days only 3 out of 72 evaporation values had to be calculated due to the fetch criteria. Applying the regression model to calculate evaporation on these 3 days completely yields good results for day one and three were the difference was only 4-5 % but it also shows the potential underestimation of extreme evaporation rates as the model underestimated the daily evaporation on the second day by 18 %

4.4 Indirect methods to estimate evaporation

~~For the calculation of evaporation several equations, based on different physical approaches, exist. Each approach connects evaporation to different meteorological parameters and is designed for different time intervals, ranging from sub-daily calculations to a time interval of at least 7 days.~~ With the comprehensive data set of the measurements, it is possible, for the first time, to evaluate four of the commonly used evaporation equations for their applicability for Dead Sea evaporation on different time scales (30 min, 1 d, 7 d, 14 d and 28 d) and perform a sensitivity analysis on simplifications and assumption used for the equations. The main goal is the identification of the best fitting equation, by using measurements purely made on land, as data from raft stations or buoys are often difficult to obtain (Giadrossich et al., 2015). The calculated evaporation ~~amounts~~ rates are compared to the eddy covariance measurements and evaluated in terms of their correlation coefficient, slope and offset of the regression line, mean difference and monthly differences between the estimates and the measurements. Additionally, the relative over- or underestimation of the annual evaporation is compared to the measured amount of 994 ± 88.2 mm.

The first equation is the aerodynamic approach after Brutsaert (1982) (Table 1)~~and is afterwards named V0~~. This equation uses wind speed and vapour pressure deficit as governing factors. In the default version (V0) the stability of the atmosphere is not considered. The aerodynamic approach is the only approach designed for sub-daily time intervals. The correlation coefficient for 30 min averages is 0.85 and it tends to overestimate evaporation ~~amounts~~rates. The slope of the regression line is 1.26 (Table 6) and the mean difference is 0.92 ± 0.54 mm d^{-1}. For time intervals of 1 d and longer, the aerodynamic approach yields better results. The correlation coefficients vary between 0.94 for 1 d intervals and 0.99 for 28 d intervals, mean differences are smaller, 0.02 ± 0.54 mm d^{-1} for the 1 d interval, and the slopes of the regression lines vary around 1.10 (Table 6, Fig. 6 a,V0). The mean differences are evenly distributed throughout the year, showing no seasonal bias, and the ~~total annual evaporation amount~~ annual evaporation is well represented (Fig. 7 a,V0). A sensitivity study was performed, considering the near surface stability (V1), using the stability factors after Cline (1997). However, the comparison with V0 shows that the inclusion of the stability has a negligible effect ~~on the daily evaporation amounts~~ (Table 6).

The BREB method is first used in the simplified version shown in Table 1, neglecting net advected heat fluxes, the ground heat flux, as well as the heat storage term. With this version (V0), only net radiation, surface water temperature, and air temperature have to be known. These variables are relatively easy to obtain and it would therefore be an easy approach to calculate evaporation. However, neglecting the heat storage term results in ~~an~~ a strong bias of the evaporation ~~amounts~~rates. The correlation coefficients range from only 0.67 for 1 d time intervals to 0.87 for 28 d intervals, the slope varies from 1.27 to 1.72, respectively, and the ~~larges~~ largest offset is -1.35 mm d^{-1} (Table 6). This indicates a strong overestimation of high evaporation ~~amounts~~ rates in spring and summer and an underestimation of small evaporation ~~amounts~~ rates mainly in winter (Fig. 6 b,V0), resulting in a clear seasonal bias. From April until September daily evaporation rates are overestimated by up to 3 mm d^{-1} and underestimated during the rest of the year (Fig. 7 b,V0). This seasonal bias was also observed in other studies, e.g. Winter et al. (1995); Rosenberry et al. (2007). Compared to the measured values, this results in ~~a~~ an overestimation of the annual evaporation ~~amount~~ by 22 %~~.~~, calculated from the 28 d averages. For the other time intervals the overestimation of the annual evaporation was comparable and is therefore not shown. The sensitivity study V2, ~~which~~ considers the heat storage of the lake using a hysteresis model~~, improved the results. Correlation coefficient~~ . Correlation coefficients are better and the mean differences are reduced (Table 6). ~~The~~ However, the slope and offset shows that the heat storage term is still not represented correctly. The slopes and the offsets indicate an overestimation of small evaporation rates and an underestimation of high evaporation rates (Fig. 6 b,V2). The intra-annual performance ~~also improved~~ improved slightly and evaporation estimates between November and April are quite good, however, evaporation rates are underestimated in summer and autumn by about 1 mm d^{-1} (Fig. 7 b,V2). This results in a underestimation of the ~~total evaporation amount~~ annual evaporation by about 11 %. ~~In~~

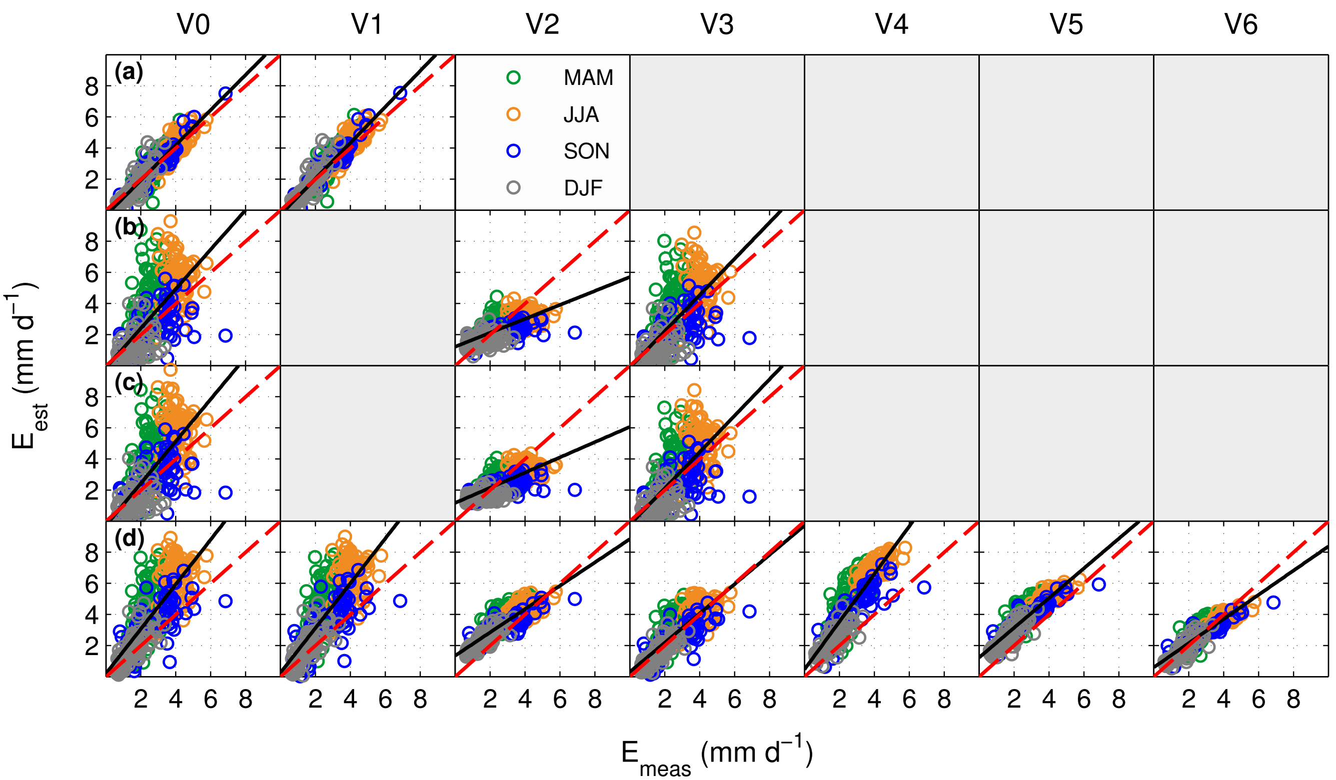

Figure 6. Correlation between estimated and measured daily evaporation ~~amounts~~ rates for (a) the aerodynamic approach, (b) the BREB method, (c) the Priestley-Taylor equation and (d) the Penman equation and their sensitivity studies (Table 2) calculated from 1 d averages. The colours indicate the meteorological seasons spring (MAM), summer (JJA), autumn (SON), and winter (DJF). The regression line is shown in black and the 1:1 line as dashed red line.

~~general, the slopes and the offsets indicate an overestimation of the small evaporation amounts and an underestimation of the high amounts (Fig. 6 b,V2).~~ Sensitivity study V3 also accounts for the heat storage term ~~, by using $\Delta Q = 0.08 \cdot Rn$~~by using $\Delta Q = 0.08 \cdot R_n$, derived from the deviation of ~~the~~ V0 from the measurements. This approach can only slightly improve the correlation coefficient, slope, offset, and mean difference in comparison to V0 (Table 6). Only the ~~total annual evaporation amount~~ annual evaporation improves compared to the default version and overestimates evaporation by only 13 % instead of 22 % (Fig. 7 b V3).

The Priestley-Taylor equation, as described in (Table 6), results in correlation coefficients between 0.69 for 1 d and 0.89 for ~~a~~ 28 d time ~~interval~~intervals. Like the BREB equation slopes are too high with values between 1.35 and 1.84 and offsets vary between -0.28 and -1.58 mm d^{-1} (Table 6). By neglecting the heat storage term small evaporation rates are underestimated and large ones overestimated (Fig. 6 c,V0), resulting in a strong seasonal bias and an overestimation of the ~~total evaporation amount~~ annual evaporation by 26 % (Fig. 7 c,V0). Sensitivity test V2 yields similar results as for the BREB equation (Table 6). With the hysteresis model the seasonal bias shifts to an underestimation of evaporation in summer and autumn and relatively good

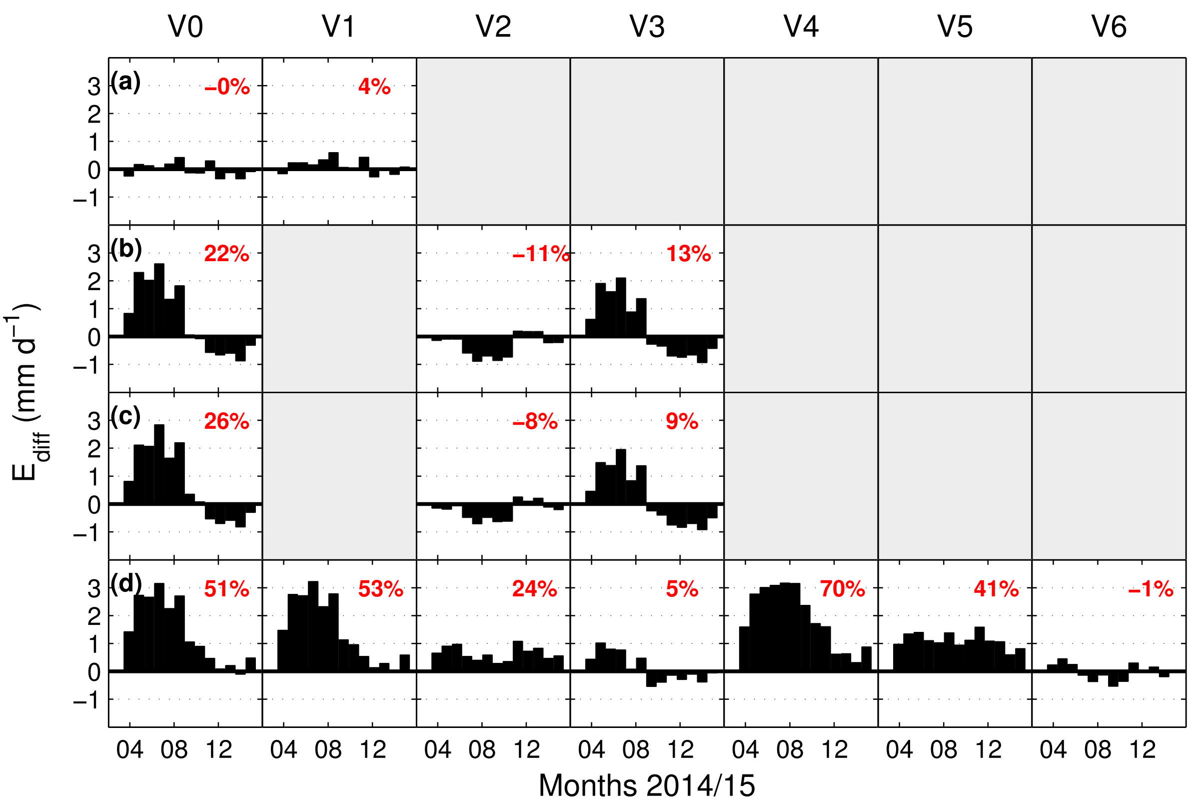

Figure 7. Differences between the estimated daily evaporation ~~amounts~~ rates calculated from the 28 d time averages and the measured daily evaporation ~~amounts~~ rates for (a) the aerodynamic approach, (b) the BREB method, (c) the Priestley-Taylor equation, (d) the Penman equation, and their sensitivity studies (Table 2). The red numbers show the total deviation of the accumulated calculated annual evaporation ~~estimate~~ (28 d averages) from the accumulated measured evaporation~~amount~~.

results for winter and spring, resulting in a total underestimation of the annual ~~amount~~ evaporation by 8 % (Fig. 7 c,V2). In V3 the heat storage is considered as a linear function of ~~Rn andthus~~ R_n and, thus, results in a new Priestley-Taylor coefficient of 1.09. With V3 the seasonal bias is reduced but still high evaporation rates are overestimated and low ones underestimated (Table 6). The ~~total annual amount~~ annual evaporation is overestimated by 9 % (Fig. 7 c,V3).

The last equation tested is the Penman equation. In its original form (Tab.6, V0) it results in correlation coefficients of 0.78 for time averages of 1 d to 0.91 for 28 d (Table 6). However, the slopes of the regression lines vary between 1.44 and 1.76, respectively, and indicate an overestimation. The mean differences also show a strong variability. Evaporation ~~values~~ rates are strongly overestimated from spring until autumn (Fig. 6 d,V0), exceeding the measured daily evaporation ~~amounts~~ rates by up to 100 % (compare Fig. 7 d,V0 to Fig. 5). The ~~total annual amount~~ annual evaporation is thus also overestimated by 51 % showing that the original Penman equation is not applicable for the investigation of intra-annual variations. The consideration of the heat storage using the hysteresis model (V2) yields considerable improvements ~~. The correlation coefficientis improved~~

~~to values~~ regarding the correlation coefficient. Its value varies between 0.87 and 0.97, and the mean difference and its standard deviation is reduced, meaning that the spread of the calculated values is smaller (Table 6). The slopes for V2 are all below unity and the offsets above 0.94 mm d^{-1}, meaning that small ~~values are highly~~ evaporation rates are overestimated (Fig. 6 d,V2). This is also apparent in the intra-annual deviation of the estimated ~~values~~ evaporation rates from the measured ~~amounts~~ones. Deviations are below or around 1 mm d^{-1} for all months, resulting in a total overestimation of the annual ~~amount~~ evaporation by 24 % (Fig. 7 d,V2).

The calculation of the heat storage term as a linear function of the net radiation results in $\cancel{\Delta Q = 0.46 \cdot Rn}$ $\Delta Q = 0.46 \cdot R_n$. Using this function for the heat storage term in V3, the results are strongly improved. The slopes of the regression lines are close to one, offsets are small and also the mean differences are smaller (Table 6). Correlation coefficients vary between 0.82 and 0.92 and the ~~overall annual evaporation amount is with 5~~annual evaporation is with 105 % within the range of the measurement uncertainties. However, the results show a seasonal bias with an overestimation in spring and summer and a underestimation in autumn and winter (Fig. 7 d,V3).

Another commonly used variation of the Penman equation is the removal of the surface water temperature from the calculation of the net radiation. This is tested in V4. However, in V4 the heat storage term is still missing an thus does not result in reliable evaporation ~~values~~ rates (Fig. 6 and 7 d,V4). The combination of the hysteresis model with the removal of the surface water temperature (V5) yields an improvement of the correlation coefficients, the slope of the regression lines and also the standard deviations, but the calculated ~~values~~ rates show an offset of over 0.93 mm d^{-1} (Table 6). This results in a constant overestimation of evaporation ~~values~~ rates throughout the year and results in ~~a total evaporation amount~~ an annual evaporation which is 41 % higher than the measured one (Fig. 7 d,V5). The last test for the Penman equation combines the removal of the surface water temperature with a derived linear function for the heat storage term from V4. With an heat storage term $\cancel{\Delta Q = 0.77 \cdot Rn}$ $\Delta Q = 0.77 \cdot R_n$ the discrepancy of the calculated from the measured ~~values can be minimized~~rates can be minimised. The regression line is still slightly tilted (Fig. 6 d ,V6), small evaporation ~~values~~ rates are overestimated, and large ones underestimated, but the mean difference is nearly zero and the standard deviation is in the range of 0.29 to 0.5 mm d^{-1} (Table 6). The ~~total evaporation amount~~ annual evaporation is well represented with this adjustments of the equation (Fig. 7 d ,V6).

5 Discussion and Conclusion

~~Results from former studies, which investigated Dead Sea evaporation by using indirect approaches, varied strongly. No~~ The eddy covariance method is used for the first high resolution, direct evaporation measurements ~~were performed at~~ of the Dead Sea~~so far to validate these results. Hence, there was a need for such direct evaporation measurements. The eddy covariance method is recognised internationally to be a very accurate method to directly measure evaporation (e.g. Rimmer et al., 2009) and was therefore chosen for this study~~. The first aim of this study was to present an applicable method to measure evaporation with a shoreline station. The measurement strategy ~~was~~ is based on the installation of the station on a headland, ~~which was~~ surrounded by water from 320°. ~~This~~ The advantage of this setup at the shoreline ~~was chosen to avoid influence on the measurements by~~ is the avoidance of raft motion and sea spray influencing the measurements, where the latter one leads to a

Table 6. Slope and offset of the regression lines between the evaporation estimates calculated with the different equations and the evaporation measurements and the corresponding correlation coefficient ~~*R*~~(R), for averaging periods of 30 min, 1, 7, 14, and 28 days. Mean difference (MD) and standard deviation (std) in mm d^{-1} are shown for 1 d and 28 d as no relevant differences for the other time intervals exist. V0 to V6 indicate the different sensitivity studies (see Table 2). The best fitting solutions are indicated with bold numbers.

		Slope					Offset					R					MD ± std	
		30 min	1 d	7 d	14 d	28 d	30 min	1 d	7 d	14 d	28 d	30 min	1 d	7 d	14 d	28 d	1 d	28 d
Aero-dynamic	**V0**	**1.26**	**1.13**	**1.08**	**1.10**	**1.12**	**-0.01**	**-0.33**	**-0.24**	**-0.29**	**-0.34**	**0.85**	**0.94**	**0.94**	**0.98**	**0.99**	**0.02±0.54**	**-0.02±0.24**
	V1	1.27	1.16	1.10	1.13	1.14	-0.01	-0.30	-0.17	-0.23	-0.26	0.85	0.94	0.94	0.98	0.99	0.13±0.54	0.11±0.24
BREB	V0	–	1.27	1.51	1.63	1.72	–	-0.13	-0.78	-1.11	-1.35		0.67	0.78	0.84	0.87	0.60±1.78	0.61±1.26
	V2	–	0.45	0.57	0.63	0.67	–	1.21	0.89	0.70	0.59	–	0.69	0.83	0.90	0.96	-0.30±0.89	-0.30±0.40
	V3	–	1.17	1.39	1.50	1.58	–	-0.12	-0.72	-1.02	-1.24	–	0.67	0.78	0.84	0.87	0.33±1.62	0.33±1.11
Priestley-Taylor	V0	–	1.35	1.61	1.74	1.84	–	-0.28	-0.98	-1.33	-1.58	–	0.69	0.80	0.86	0.89	0.69±1.81	0.70±1.30
	V2	–	0.49	0.62	0.70	0.74	–	1.17	0.81	0.59	0.47	–	0.73	0.87	0.93	0.98	-0.24±0.84	-0.23±0.32
	V3	–	1.17	1.39	1.51	1.59	–	-0.24	-0.85	-1.15	-1.37	–	0.69	0.80	0.86	0.89	0.23±1.53	-0.24±1.04
Penman	V0	–	1.44	1.58	1.69	1.76	–	0.19	-0.20	-0.49	-0.69	–	0.78	0.83	0.88	0.91	1.38±1.52	1.38±1.17
	V1	–	1.44	1.57	1.68	1.76	–	0.24	-0.12	-0.41	-0.61	–	0.78	0.83	0.88	0.91	1.44±1.52	1.45±1.16
	V2	–	0.75	0.80	0.85	0.89	–	1.34	1.21	1.04	0.94	–	0.87	0.89	0.94	0.97	0.65±0.61	0.64±0.25
	V3	**–**	**0.94**	**0.99**	**1.05**	**1.09**	**–**	**0.29**	**0.16**	**0.00**	**-0.11**	**–**	**0.82**	**0.84**	**0.90**	**0.92**	**0.13±0.82**	**0.13±0.51**
	V4	–	1.54	1.73	1.80	1.87	–	0.45	-0.09	-0.28	-0.48	–	0.89	0.91	0.94	0.96	1.92±1.16	1.91±1.07
	V5	–	0.96	1.01	1.04	1.06	–	1.22	1.10	1.00	0.93	–	0.92	0.93	0.96	0.97	1.10±0.51	1.10±0.27
	V6	**–**	**0.78**	**0.80**	**0.81**	**0.84**	**–**	**0.59**	**0.54**	**0.49**	**0.42**	**–**	**0.92**	**0.92**	**0.95**	**0.97**	**-0.02±0.50**	**-0.02±0.29**

serious soiling of the instrument and influences data quality strongly. ~~However,~~ The major drawback of land based eddy covariance measurements ~~have their limitations in measuring evaporation from the water surface,~~ is the limited data availability of measured lake evaporation as part of the flux footprint is located over land. ~~Therefore, a~~ In this study 19 % and in other works 15-25 % (e.g. Mammarella et al., 2015; Nordbo et al., 2011) of the data were rejected due to the fetch criteria. This was overcome by a novel approach. A multiple regression model was ~~applied to the data and the results show that evaporation from the Dead Sea water surface is driven by wind speed~~ trained with the onshore wind and vapour pressure deficit ~~. The model was tested using a MCCV, andit was confirmed that the model is reliable for calculating the Dead Sea evaporation and has a small model error of~~ data. With this model lake evaporation for offshore wind conditions was calculated and, thus, data availability was increased from 59.2 % to 76.8 %. The uncertainty introduced by this method is small with a prediction error of the calculated values of 4.8 % ~~. Additionally, a slight overestimation of model based evaporation might occur, as the~~ making it a very reliable method. However, there is still some uncertainty due to this method which cannot be accounted for directly. On the one hand, extreme values of wind velocity and water vapour pressure deficit ~~for offshore wind conditions is probably higher directly~~

~~at the shoreline in comparison to~~ were not used to calculate evaporation when they were outside the model boundaries. This leads most likely to an underestimation of the actual evaporation rate. On the other hand, wind velocity and vapour pressure deficit could decrease with increasing distance from the shoreline, which would lead to an overestimation of evaporation. However, the comparison with results from measurements in the middle of the ~~open water surface. Considering these uncertainties the model can be used to calculate evaporation values for offshore wind conditions, enabling, for the first time, the analysis of the full diurnal and intra-annual cycle of Dead Sea evaporation. The results show that the diurnal cycle of evaporation is mainly driven by the diurnal cycle of the wind systems and their related wind velocities. This leads to maximum evaporation rates after sunset, caused by~~ lake (Weiss et al., 1988; Hecht and Gertman, 2003) shows that even in the middle of the lake westerly winds with ~~high wind velocities . These westerly winds occur from spring until autumn. The results are consistent with findings for Lake Kinneret, where these westerly winds also occur in the evening (Assouline and Mahrer, 1993; Shilo et al., 2015). However, the daily evaporationrates are notably lower compared to the evaporation at Lake Kinneret through the much higher salinity of the Dead Sea water and thus the reduced saturation vapour pressure . The median daily evaporation ranges from 1.1~~hourly averaged velocities between 8 and 12 ~~mm~~m ~~d~~s^{-1} ~~in December to 4.3~~were observed. Wind lidar measurements confirmed, that the westerly winds regularly reach several km over the lake without loosing their strength (Metzger, 2017). In conclusion, offshore wind measurement seem representative for lake conditions and reasonable for the calculation of evaporation. A decrease of vapour pressure deficit has to be considered, but is most likely small for the following reasons. Firstly, the fetch of the station is limited with 600 ~~mm d^{-1} in July, but the absolute maximum of the measured daily evaporation rates was measured in November with 6.9 mm d^{-1}. This is extremely high compared to the median values in winter and highlights the stronger synoptic influence on the region during the wet season (Bitan, 1974, 1976). One of the typical synoptic systems during the wet season is the Red Sea Trough, which can cause high wind velocities and high vapour pressure deficits in the valley and thus leads to very high evaporation rates. This is particularly important as Alpert et al. (2004) found that the frequency of such Red Sea Trough systems nearly doubled since the 1960s from 50 to 100 days per year~~m, meaning that the distance the air mass passes over the water is short. Secondly, the westerly winds are connected with high turbulence and, thus, strong vertical mixing (Metzger, 2017). From these results we conclude that the approach is also applicable to other lakes, in case the measured onshore wind velocity and vapour pressure deficit values are representative for offshore conditions to appropriately train the model, and the fetch of the flux measurements is small enough that the meteorological measurements at the shoreline are representative for the fetch.

~~The total measured evaporationfor the period 1 March 2014 until 1 March 2015 was 994.5 ± 81.2~~The second aim was to evaluate the diurnal and intra-annual variability of Dead Sea evaporation. The annual Dead Sea evaporation was found to be 994±88.2 ~~mm, which agrees~~ mm for the measurement period. The uncertainty of 8.8 % results mostly from the gap filling procedure (81.2 mm) and not from the regression model. As gaps result from system malfunction or bad data quality, the uncertainty can be reduced by improving the system performance or by finding a better method to fill the gaps. The annual evaporation coincides well with previous findings such as ~~Stanhill (1994)~~ Stanhill (1994) with 1005 mm a^{-1} and is close to the results from Lensky et al. (2005) ($1100 - 1200$ mm a^{-1}), which both estimated the evaporation based on theoretical energy balance approaches. ~~However, it is~~ A certain degree of differences between the results is inevitable as the studies considered different data sets and different time periods, meaning different water salinities and different weather conditions. However, the measurements are far away from the ~~2~~2000 ~~m~~ mm from Salameh and El-Naser (1999), who estimated evaporation based on water balance calculations, which could indicate uncertainties in the assessment of the water balance components. ~~Eddy covariance measurements provide high resolution and accurate evaproation data but they are costly and need frequent maintenance. Therefore, it is difficult to maintain an operational system in remote areas. Hence, the third aim of this paper was to evaluate the applicability of commonly used indirect evaporation equations, which use standard meteorological measurements. The BREB, Priestley-Taylor, and Penman method, are difficult to apply for intra-annual calcuations. The main difficulty is the heat storage term. For these three methods the knowledge of the heat storage term is essential to achieve reliable results, as neglecting the heat storage results in a strong seasonal bias, with an overestimation of daily evaporation rates of up to~~ Therefore, the results could be implemented into hydrological models to study the uncertain water budget components and the development of the water budget in the future. Furthermore, the results show that the diurnal cycle of evaporation is in phase with the wind velocity, which corresponds to findings of other studies in the Jordan valley (e.g. Assouline, 1993; Assouline et al., 2008). As a result the strong westerly winds in the evening double evaporation compared to midday values. These findings are also important for other lakes, where strong and dry wind systems are observed, e.g. Bora, Tramontane, Mistral. Bouin et al. (2012) showed that the Tramontane in France trebles evaporation from a lagoon compared to non Tramontane conditions. In respect of ongoing climate change our results could motivate a regional study on the impact of climate change on the future evolution of thermally and orographically induced wind systems in the Mediterranean region. So far, there is little information, although it is important for the future development of the water bodies. As expected, Dead Sea evaporation is lower compared to other less/non-saline lakes. The ratio to Lake Kinneret, which is located only 100~~%. Using estimates of the heat storage term does not provide acceptable results for the BREB and~~ km north, is 0.68 in summer, but only 0.83 in winter. This difference is most likely caused by the different climatic conditions in winter. Lake Kinneret receives a considerable amount of rainfall due to more humid air masses as it is located within a Mediterranean climate zone (Goldreich, 2003), whereas the Dead Sea has arid climate, where, even in winter, very little rainfall occurs.

For the prospective affordable long-term assessment of evaporation, different equations to calculate evaporation were tested for their applicability for the ~~Priestley-Taylor method either. For the Penman equation an applicable solution is achieved when a linear function for the heat storage is empirically gained from the data set. We conclude that the BREB and Priestley-Taylor method can only be applied for the Dead Sea if heat storage is measured, which requires a raft station or ship measurements, or for long time periods, i. e. one year, where the heat storage term can be neglected. The Penman equation is applicable for the~~ Dead Sea~~, if the heat storage is considered using the described approaches. The aerodynamic approachyields the best results with respect to the diurnal and intra-annual calculation of evaporation. They were in best agreement with the measurements. It was also~~ . The best suitable, and also the only method applicable on sub-daily time scales, is the aerodynamic approach. It is shown that the consideration of the atmospheric stability in the calculations has an neglegible effect on the results. ~~This again coincides~~ These results coincide with results for Lake Kinneret (Shilo et al., 2015; Rimmer et al., 2009) and makes this method easily applicable for evaporation calculations ~~, as only wind velocity and vapour pressure deficit are required.~~

~~This study focuses on providing an applicable method to investigate the diurnal and intra-annual variability of evaporation from the Dead Sea water surface using an eddy covariance system located at the shoreline. Furthermore, it investigates the application of commonly used indirect methods to calculate evaporation with shoreline data . When using a station located at the shoreline , the use of a new model is proposed to calculate Dead Sea evaporation for offshore wind conditions on~~ applying data from a shoreline station. The other approaches are developed for longer time intervals and are not applicable for sub-daily ~~time scales. It was shown that a model consisting of a linear combination of wind speed and vapour pressure deficit results in a robust model for the calculation of evaporation. This approach can also be applied to other lakes~~calculations. The results also confirm the findings from various other studies (Rimmer et al., 2009; Giadrossich et al., 2015; Tanny et al., 2008; Rosenberry et al., 2007) that for the BREB, Priestley-Taylor and Penman method, the knowledge of the heat storage term is essential to achieve reliable results, as neglecting the heat storage results in a strong seasonal bias. Using estimates of the heat storage term does neither provide acceptable results for the BREB nor for the Priestley-Taylor method. For the Penman equation, an applicable solution is achieved when using the empirically gained function for the heat storage. Thus, we conclude that the BREB and Priestley-Tayler method are not applicable with data from a shoreline station, but the aerodynamic and the adapted Penman method can be used, making expensive raft measurements expendable. ~~From the evaluation of the indirect methods we conclude that for a reliable estimate of the Dead Sea evaporation the aerodynamic method is advisable and that the influence of the atmospheric stability is negligible. Like the new model, the aerodynamic method connects evaporation with its governing variables, which are wind velocity and vapour pressure deficit, and allows the calculation of sub-daily or multi-day evaporation amounts without a seasonal bias. The advantage thereby is clearly the use of~~ For future application it is advisable to use the Penman method only for longer time intervals as its prediction skill improves with increasing time interval and to use the aerodynamic method for short time intervals. The use of low-maintenance, cost-efficient measurements ~~, which can be installed on the shoreline,~~ to estimate evaporation ~~values on a sub-daily time scale. This~~ on short time scales is beneficial for economic purposes, such as the production of minerals from the saline water, as well as for further investigations of the water budget of the lake~~, and the resulting environmental changes on a longer time scale~~. For instance, pumping rates for mineral production can be adjusted according to the evaporation rates.

Appendix A: Calculation of surface water temperature

The surface water temperature T_s was not measured and could also not be retrieved from satellite data. Therefore, it was calculated following Monin-Obukhovs similarity approach:

$$T_{MO} = T_s = T(z_m) - \frac{\theta^*}{\kappa} \cdot \left(ln\frac{z_m}{z_0} - \Psi_H(\zeta_m, \zeta_0) \right). \tag{A1}$$

T_{MO} is the calculated surface water temperature at the height of the roughness length z_0, which is assumed as 0.001 m, z_m is the measurement height in m, $\zeta_m = z_m L_*^{-1}$ and $\zeta_0 = z_0 L_*^{-1}$ are independent dimensionless parameters using the Monin-Obukhov-Length L_*, and $\frac{\theta^*}{\kappa}$ is a scaling parameter defined as:

$$\frac{\theta^*}{\kappa} = -\frac{1}{\kappa u^*}\frac{H}{\rho_0 c_p}, \tag{A2}$$

with κ=0.4, which is the Kármán constant, sensible heat flux H in $\mathrm{W\,m^{-2}}$, specific heat capacity c_p=1004 $\mathrm{J\,K^{-1}\,kg^{-1}}$ and density of the air ρ_0 in $\mathrm{kg\,m^{-3}}$. Ψ_H is the integral over the empirical gained functions φ_H:

$$\Psi_H(\zeta_m, \zeta_0) = \int_{z_0}^{z_m} = \frac{1-\varphi_H}{z} dz \tag{A3}$$

In this work the φ functions from Dyer (1974) are used:

$$\varphi_H = 1 + 5\zeta \qquad \zeta > 0 \tag{A4}$$

$$\varphi_H = (1 - 16\zeta)^{-1/2} \qquad -1 < \zeta < 0. \tag{A5}$$

Appendix B: Measurement of the latent heat of vaporisation

The latent heat of vaporisation and the activity of water β for the highly saline water of the Dead Sea were measured using a water probe taken at the measurement site of the EBS at the end of 2014. First, the saturation vapour pressure of pure water E_w was measured with a capacitance manometer, which was calibrated by a linear regression to literature values from the Kilolabor ETH Zurich[1]. Afterwards, the saturation vapour pressure of the saline water, E_s, was measured as a function of water temperature with the calibrated manometer. Through this approach possible measurement uncertainties of the manometer could be minimized. The activity of water can then be calculated as:

$$\beta = \frac{E_s}{E_w}. \tag{B1}$$

The averaged activity for the Dea Sea water is $\beta = 0.65$.

The molar latent heat of vaporisation, ΔH_{vap} ($\mathrm{J\,mol^{-1}}$), can be derived by using the general form of the Clausius-Clapeyron

[1] https://cdm.unfccc.int/filestorage/U/4/B/U4BKYDK7NTLWWFQ1OTUFUCKJMTEE3Y/U4BKYDK7.pdf?t=Vm98bzQ0aGx1fDC3cDweIA5PuHui7yRAOy3k

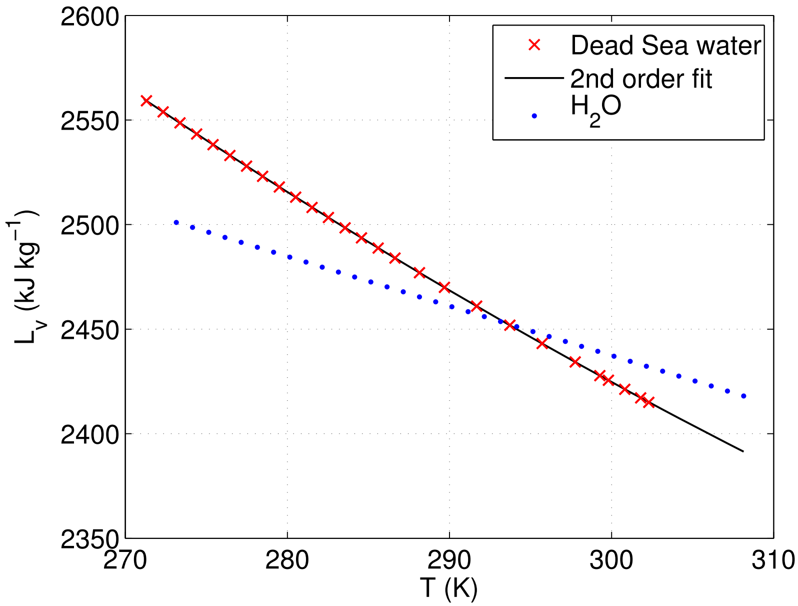

Figure A1. Dependency of the specific latent heat of vaporisation (L_v) on temperature. Measurements of L_v for the saline water of the Dead Sea, a second order polynomial fit and literature values for pure water (H_2O) are shown.

equation, assuming that the molar volume of the liquid can be neglected against the molar volume of the gas, and by using the ideal gas law:

$$\Delta H_{vap} = -R\,\frac{\mathrm{d}(\ln E_s)}{\mathrm{d}(\frac{1}{T_w})}. \tag{B2}$$

R=8.314 J mol^{-1} K^{-1} is the universal gas constant, the corrected saturation vapour pressure of the saline water is E_s in hPa, and water temperature is T_w in K. With the molar mass of water m_{H_2O}=0.018 kg mol^{-1}, the specific latent heat of vaporisation L_v can be calculated:

$$L_v = \frac{\Delta H_{vap}}{m_{H_2O} \cdot 1000}, \tag{B3}$$

in kJ kg^{-1}, and can then be fitted to the water temperature T_w (Fig. A1). The regression formula is:

$$L_v = 5150.6561 - 13.9530 \cdot T_w + 0.0162 \cdot T_w^2. \tag{B4}$$

Appendix C: Calculation of vapour pressure deficit

The vapour pressure deficit for the regression approach is calculated as follows: The vapour pressure deficit is defined as the difference between the saturation vapour pressure above the saline water, E_s, and the atmospheric vapour pressure in 2 m height, $e_{a,2\mathrm{m}}$:

$$\Delta e = E_s - e_{a,2\mathrm{m}}. \tag{C1}$$

The saturation vapour pressure of saline water is lower than that of freshwater, E_w, by a factor β, caused by the vapour pressure depression by dissolved salts (Raoult's law) (Atkins, 2014).

$$E_s = \beta \cdot E_w. \tag{C2}$$

The activity β depends on the composition of the dissolved salts and is determined to 0.65 for the Dead Sea water in this study (Appendix B). Saturation vapour pressure over water can be calculated using the Magnus equation after Bolton (1980):

$$E_w(T_{0mS}) = 6.112 \cdot exp\left(\frac{17.67\cdot(T_{0m}-273.15)}{T_{0m}-29.65}\frac{17.67\cdot(T_S-273.15)}{T_S-29.65}\right), \tag{C3}$$

with ~~water surface temperature T_{0m}~~ surface water temperature T_S in K. As ~~water surface~~ surface water temperature is not directly measured at the station, vapour pressure deficit is calculated using surface water temperature obtained by the Monin-Obukhov theory, T_{MO} in K:

$$T_{MO} = T(z_0) = T(z_m) - \frac{\theta^*}{\kappa}\cdot\left(ln\frac{z_m}{z_0} - \Psi_H(\zeta_m,\zeta_0)\right).$$

~~z_m is the measurement height in m, z_0 is the roughness length assumed as 0.001 m, $\zeta_m = z_m L_*^{-1}$ and $\zeta_0 = z_0 L_*^{-1}$ are independent dimensionless parameters using the Monin-Obukhov-Length L_*, and $\frac{\theta^*}{\kappa}$ is a scaling parameter defined as:~~

$$\frac{\theta^*}{\kappa} = -\frac{1}{\kappa u^*}\frac{H}{\rho_0 c_p},$$

~~with κ=0.4, which is the Kármán constant, sensible heat flux H in W m^{-2}, specific heat capacity c_p=1004 J K^{-1} kg^{-1} and density of the air ρ_0 in kg m^{-3}. Ψ_H is the integral over the empirical gained functions φ_H:~~

$$\Psi_H(\zeta_m,\zeta_0) = \int_{z_0}^{z_m} = \frac{1-\varphi_H}{z}dz$$

~~In this work the φ functions from Dyer (1974) are used:~~

$$\varphi_H \quad = 1+5\zeta \quad \zeta > 0$$
$$\varphi_H \quad = (1-16\zeta)^{-1/2} \quad -1 < \zeta < 0.$$

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