Response to Reviewers' Comments (manuscript # hess-2017-415):

"Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements"

Milad Aminzadeh, Peter Lehmann, and Dani Or

Dear Editor,

We greatly appreciate the constructive and many insightful comments made by the Editor and two reviewers. In the following we first address the points raised by the Editor:

As someone who is familiar with the challenges of evaporation reduction and also the complexities of lake mixing I believe the study has significant merit and in particular is in an area where there is currently limited literature. Bringing a theoretical energy balance/aerodynamic approach to the problem I think will make the study a useful contribution.

The reviewers have a somewhat mixed view of the status of the manuscript in its present form, and so I have spent a fair bit of time myself reviewing and assessing the paper. In short, Reviewer 2 was supportive of publication with some suggestions for improvements, whilst Reviewer 1 indicated the results were too speculative and requested the paper has more evidence the model fits with observations, plus other theoretical justifications. Following my own assessment, I agree fully with the comments by both, and also share the concerns of Reviewer 1. Further, based on the reply to Reviewer 1 comments I was not convinced how the manuscript would be improved to adequately address the concerns. Therefore, it is recommended that the manuscript be re-considered after major revisions.

For the re-submission, I would suggest the structure of the paper is reorganised and believe this may address some of the concerns.

Reply: We thank the Editor for the constructive and insightful comments. As the editor suggested, and to address some of the concerns of reviewer#1 regarding evidence that supports the modeling results, we have modified the organization of the manuscript to include the laboratory scale experiments within the main text. We emphasize the limitations of these laboratory results conducted in a shallow basin for validation of the reservoir scale model. Hence, the primary insights gained from the experiments were the systematic variations of external forcing (wind, radiation and combination) and their impact on energy partitioning, surface temperature and evaporation suppression of covered surfaces. These results improved our understanding of the top boundary conditions in the reservoir scale model results. In addition, we have changed the structure of the revised manuscript by separating "Results" and "Discussion" and hope that the Editor finds these changes useful.

- *The Lake Mead validation example appears out of context with the underlying motivation of the paper. The text refers many times to shallow reservoirs, and Figure 1 sets this context clearly. Yet Lake Mead is a very deep reservoir where the surface mixed layer is impacted by complex processes (and I note the simple diffusivity model appears to have an error in the thermocline depth by about 10 m during summer stratification). I find it hard to reconcile that validating the* *uncovered model on a reservoir of this size is also proof that the model is able to capture heat fluxes from a 3 m deep reservoir (covered or uncovered). Further, this un-covered model validation is presented as a result (Figure 4; Section 3.1), but this does not clearly align to an aim presented in the introduction, and seems better suited to an appendix - i.e. supporting material to help bench-mark the model prior to its application here. A second bench-mark simulation on a "shallow" reservoir would greatly help strengthen this argument - that your (uncovered) model is a reasonable tool for both shallow and deep reservoirs. Accessing public thermistor chain datasets through something like the GLEON network may provide a case-study?*

Reply: We thank the Editor for raising this point. Even if covered reservoir scale data were available we would have to perform a validation of the energy balance and temperature profile ingredients of the model as a reference state for comparison with the covered surface scenario. The use of the complete data set of Lake Mead provides a basis for this critical validation step (within the limits of a 1D model); we thus consider this element as an important ingredient of the study and not simply an appendix. The discussion of shallow reservoir behavior is an analysis of the model (without validation yet) for a range of boundary conditions to address the effects on heat storage and surface fluxes of reservoirs of different depths. Much is left to be studied about the effect of floating covers on water bodies and we slowly wade to this area using data from lab experiments in a shallow basin, and two ongoing field studies in deeper ponds under natural conditions (see images below). Even for the relatively well-studied behavior of uncovered water reservoirs, finding complete and definitive dataset for model testing was not a simple task (atmospheric forcing, temperature profile, surface fluxes, etc. …) and we felt fortunate to be able to use the Lake Mead data for model evaluation (even if many reservoirs of practical interest would likely to be shallower).

- *Following on from the comment above about the structure, the aims of the paper should more clearly align to the results and key discussion points. Currently, the connection is not always obvious - for example, there are two sections in the "Results and Discussions" that relate to ecology/gas fluxes (Section 3.3) and economics of covers (Section 3.4), yet neither of these sections present actual results, and also neither of these sections match the objectives listed in the introduction - usually sub-sections in the results/discussion should logically map to the objectives. Therefore, a revised submission should not use a combined results/discussion section, and better organise the sub-headings to separate results and discussion and to more obviously align with the objectives of the paper as they are argued in the introduction - i.e. every figure or sub-section should clearly align with one of the aims/objectives.*

  Reply: Following this constructive comment, we changed the structure so that “Results” and “Discussion” are now separated and thus aligned the manuscript to suitably address main research questions of the work. In addition, we also added the “Materials and methods” section to the revised manuscript to better orient readers.

- *The Lab Experiment presented in Figure A1 is poorly integrated into the paper, currently just mentioned as a "motivation" for the model context and approach. In the reply to Reviewer 1 another Lab based figure is presented (this one has black discs whereas the first figure has white* *discs). This is currently not clear - in the reply you state that you "incorporate insights" from your lab, and later state that the lab scale experiments "were in good agreement with model predictions for evaporation suppression and effects of cover color (as mentioned in page 15, line 3)" - however on Page 15 line 3 there is no specific comparison of the model with the lab data. I note it is stated it will be published a separate paper, however, that is not adequate for this paper. In the revision, the authors should better integrate the lab aspect of the study as a component of the paper (with a corresponding aim and result), or not mention it, or wait until the other paper is published. If it is included or referred to then the insights that link the lab and model should be clear rather than general statements that the agree. Related to my point above, I note that the validation of the Lake Mead is presented as a key result of this paper whereas the link with the lab results are an appendix - I would consider this should be the other way around given the aim of the paper is focused on covered systems.*

Reply: We have made changes in the structure of the revised manuscript by integrating the laboratory scale experiments into the main text and providing insights on processes at the covered surface of a reservoir (energy partition, evaporation suppression …) in support of model predictions. Considering the limitations of performing a quantitative comparison between “laboratory scale” measurements and “reservoir scale” modeling, we revised the manuscript to highlight the role of these different components of the study. The main role of the laboratory experiments is to provide direct evidence for cover efficiency and certain aspects of energy partitioning highlighting limitations to temperature profiles and associated feedbacks at the reservoir scale (i.e., heat storage, mixing and ground flux affecting water temperature and top boundary of the real reservoirs).

- *To address the lack of validation data for covered reservoirs, it may be worth refocusing the aims on exploring the potential sensitivities of the model to guide further experiments. For example, I found Appendix C to be an interesting result, yet it is only an appendix. More systematically demonstrating how the results vary in response to poorly known variables associated with the cover or lake will help make the model results more compelling, even in the absence of a full validation.*

Reply: We thank the Editor for this suggestion; hence such potential applications and merits of the modeling approach were highlighted in the revised manuscript.

- *The limitations of the model and needs for further research need to more comprehensively be discussed (in a discussion section). Currently there are aspects of this in the combined results/discussion. One issue raised by the reviewers, and is a big difference between Lake Mead and a small turbid reservoir, is the potential impact of non-neutral atmospheric boundary layer conditions - how would this impact the results? Others are raised in the discussion, and addressing them will enrich the paper*

Reply: We discussed limitations of the model in the “Discussion” section of the revised manuscript and provided suggestions for model improvements and further/future studies.

- *The summary needs to be re-written as a conclusion to more clearly align with the specific aims and highlight the most important findings and limitations/recommendations rather than repeat the study in general.*

  Reply: We thank the Editor for this important suggestion; the “Summary and conclusions” of the revised manuscript is now amended to better reflect major findings and limitations.

- *The paper needs to remove the speculative statements and more carefully word findings to match the specific results presented - for example, where it is stated the model was validated against the lab (page 15), or COMSOL simulations (page 13), this needs to be fully supported/justified rather than just asking us to trust and have faith that things are good. Statements such as "Floating elements efficiently suppress evaporative loss from water reservoirs and alter energy storage within the reservoir and oxygen exchange at the water-air interface" .... are not entirely supported by the current results and need to be much more carefully worded (there are no results related to oxygen exchange so how is this statement proven by this study?). To address the Reviewer 1 concerns, the paper must more clearly highlight that this study is assessing dynamics with a model that is yet to be validated on covered conditions.*

  Reply: Following the Editor’s comment, we removed speculative statements not directly supported by our results in the revised manuscript and thus partly discussed them in the “Discussion”. Moreover, we tried to better highlight our “primary” objective that was developing a physically based model for understanding energy dynamics and evaporation suppression of covered water reservoirs.

- *The paper needs a thorough review for grammar and expression, as many proof-reading errors occur throughout.*

  Reply: We have checked the manuscript thoroughly to remove errors and to improve the language.

In the following we address point-by-point concerns and add clarifications concerning issues raised by the reviewers.

Response to Reviewer # 1

- *First, at best, this investigation is speculative as there is no verification data presented to show whether or not is predictions are robust. At the simplest level, it would be anticipated that if a reservoir was covered in such a way as to prevent the penetration of electromagnetic radiation into its surface by elements of low thermal conductivity, the surface thermal forcing would be reduced. Therefore the outcomes shown in Figure 6 are not surprising. The authors have elected to use meteorological data that does not appear to have been gathered in the vicinity of a reservoir and apply it to a "hypothetical" reservoir. The key question is the degree to which the predictions are reliable and the authors have not addressed this question. As stated on page 11, the authors do have access to a model reservoir that is described in Appendix A. It is difficult to comprehend why they have not verified their model for a system where they were able to make measurements.*

Reply: We agree with the reviewer that certain aspects pertaining to covered "reservoir scale" predictions remain tentative and would require experimental confirmation (we acknowledged the lack of publically available data from covered reservoirs for model validation on page 12, line 19 of the original manuscript). To bridge the information gap, we have tested several key features of the model using data from uncovered reservoir in response to natural conditions (USGS Lake Mead data – see Figure 5 of the revised manuscript). This was done to establish a reference state for evaluating the potential role of floating covers on energy balance and heat storage of covered reservoirs. We also incorporated new insights from laboratory experiments using floating covers in a "small basin". These laboratory evaporation experiments used a 1.44 m^2 basin with 0.16 m depth (as depicted in Figure A below) and yielded valuable information regarding energy portioning and evaporation suppression under various forcing. The limitations are of course the limited depth and absence of vertical temperature profiles and mixing and behavior of covered reservoirs under natural atmospheric conditions. We consider the study as a step towards application of sound physical principles to the modeling of evaporation suppression, where model validation for uncovered reservoir using multi-season measured data has been performed and (limited) insights from laboratory experiments for covered and uncovered basins feed directly into the top boundary conditions for the model. We thus think that there are sufficient ingredients to make this investigation not so "speculative". We think that the study offers quantitative predictions for the effects of covers (most are intuitive except perhaps the "surprising" similarity of white and black covers in suppressing evaporation at equal efficiency despite different energy partitioning pathways).

Figure A: The water basin with 1.2×1.2 m^2 surface area and 0.16 m depth at the end of a wind tunnel built in our laboratory (STEP - ETH Zurich); uncovered basin (left) and covered with black discs (right). The experiments were conducted for a series of boundary conditions with black and white covers (not shown here).

- *Equation (4) is the conventional expression for stress transfer at an uncovered surface in the absence of wind wave growth. On page 11, line 13 we are told that* u^*_a *has been determined from bluff body theory. There is no discussion of the merits of combining these characterizations when their underlying assumptions are clearly at odds.*

Reply: Our main motivation is to address aerodynamic interactions of airflow with elements floating on water surfaces (for which very little is known unlike many studies on interactions with wavy or bluff body covered solid surfaces). The situation is even more complicated considering the simultaneous phase change where heat and mass are exchanged at the evaporating water surfaces thus potentially affecting aerodynamic interactions over these partially covered water surfaces.

More specifically, the eddy thermal diffusivity in the vertical temperature equation (Eq. 1) is based on a relatively simple and physically-based formulation of Henderson-Seller [1985] (Eq. 3) that expresses eddy diffusivity as a function of friction velocity at the water surface. Note that Eq. (4) emerges from equality of shear stresses at an interface. We invoked a well-established theory of drag partitioning over rough surfaces developed by Shao and Yang [2008] and Nepf [2012] that has been recently evaluated by Haghighi and Or [2015] to quantify the friction velocity (u_a^*) of air and define the friction velocity at the water surface (u_s^*) based on Eq. (4). Furthermore, we tested this representation by considering the boundary layer thickness (a function of u_a^* [Haghighi and Or, 2015]) obtained from direct measurements of mass loss from our water basin covered with floating discs (not presented in this study). Details of aerodynamic interactions between airflows and floating cover elements are key to evaluate evaporation suppression and thermal effects in covered reservoirs and deserve specially designed studies (beyond the scope of the present work). Additional details on the friction velocity and boundary layer thickness in Appendix A thus aim to address such concerns.

- *In Figure 2, the authors invoke a conventional approach to the numerical modelling surface mixing of reservoirs which encapsulates unstable convection due to surface cooling. However, such an approach is unreliable in terms of heat fluxes and the authors' own observations with their infrared camera should show. Certainly the longstanding work by Andy Jessup and his collaborators have revealed very different behavior of the surface skin (responsible for radiant heat from the surface) from that of the bulk.*

Reply: We thank the reviewer for raising this important point. Equation (1) is a general energy balance equation for describing vertical temperature profiles developing in a water body or in a solid slab (with $D_w = 0$). What differentiates the solutions for these two scenarios are the eddy diffusivity and vertical mixing in water body triggered by thermal/density instabilities (e.g., a cold layer of water due to evaporative cooling overlying warmer water below). Such mixing processes are triggered at small scales diurnally (due to evaporative cooling at the surface), or seasonally where subsurface heat accumulation raises to the surface and unifies the vertical temperature profile in a reservoir (either Monomictic or Dimictic reservoirs). We note that the simple vertical mixing approach of Dake and Harleman [1969] is designed to maintain the energy balance of the reservoir.

We agree with the reviewer that surface heat fluxes would be affected by the mixing scenario imposed (and probably the surface skin temperature). To minimize this effect, we imposed vertical mixing considering the "mean daily" temperature profile providing the initial condition at the beginning of next day. This step reduces transfer of heat towards the bottom of the water body. Consequently, the "instantaneous" values of surface temperature and surface heat fluxes are obtained directly from the temperature equation with the proper surface boundary conditions represented in Eq. (8) or (12), hence unaffected by surface thermal mixing as depicted in Figure 2.

This can be seen, for example, by comparing winter surface temperature of uncovered reservoir in Figures 6 and 7b of the revised manuscript. The good agreement between model predictions of vertical temperature profile in Lake Mead and measurements (Figure 5 of the revised manuscript) further confirms our modeling approach based on Dake and Harleman [1969] without affecting the calculation of surface temperature and thus surface heat fluxes represented in Table 2.

We note that the considerations of surface skin temperature is not unambiguously resolved by this treatment, yet, since the model ultimately aims to solve the full energy balance for the floating cover itself (with own radiative and thermal properties) the sensitivity to the exact water skin temperature for radiative transfer in covered reservoirs would be less important.

Response to Reviewer # 2

- *This is a well written and presented article. It provides a relatively simple but surprisingly comprehensive theoretical and physical basis of evaporation suppression from simple, shallow reservoirs from which more detailed work can emerge. It does this by comparing models of an uncovered reservoir to ones covered by white and black circular discs. A 1-D, column approach was used. I wondered why triangular covers were not considered as they have the potential of having no gaps between them (or much smaller ones than a disc).*

  Reply: We thank the reviewer for the efforts and for the many insightful comments. As mentioned in page 10, lines 10-16 of the original manuscript, the aerodynamic resistance for vapor flux from water gaps forming between cover elements is governed by the combined effects of gap size (a_g), boundary layer thickness (δ) and the lateral spacing between neighboring gaps. For very small gaps formed by polygonal covers, gap sizes could become smaller than the boundary layer thickness (the ratio of a_g/δ smaller than 1). This case may yield evaporation enhancement disproportional to size of the gap according to Eq. (13) [Schlunder, 1988; Shahraeeni et al., 2012]. In addition, for certain applications of multiuse reservoirs, water gaps formed between spherical or cylindrical covers allow light penetration and surface oxygen transfer; both play important roles in ecological aspects of the water body.

- *The paper could be well served by articulating right at the outset the methodology you use. This is how I perceive it (from reading p. 11): 1. Calculation of evaporation reduction due to discs; 2. Effect of heat balance of the discs on water column, the primary evaporation reduction element; 3. Effect of heat balance of the gaps between discs on water column, including conduction from disc to water; 4. Effect of the increase of gap water surface temperature due to 2 and 3.*

  Reply: We thank the reviewer for the suggestion. A summary of the main steps and methodology is provided in page 10, lines 5-9 of the revised manuscript.

- *Advection of (likely) colder water into the column was brought up in a discussion of managed input vs output for the reservoir but non-advective heat transfer was only considered for the bottom of the column. What about the four sides (can assume a simple soil temperature profile)?*

Reply: Clearly, for small reservoirs lateral heat exchange with the water body could be important in the energy balance. At this stage we seek to establish a simple 1D model for reservoirs where vertical temperature profile and surface heat fluxes dominate the response in the presence of floating elements, we thus neglect lateral heat transfers of the reservoir assuming that the side area of the reservoir is small relative to its surface area (as is likely in many shallow reservoirs). Following this comment, we explicitly mention this key simplifying assumption in page 8, lines 6-10 of the revised manuscript.

- *The diffusivity coefficient, D, did not appear to include any internal dynamics such as non-linear and/or breaking waves, which would likely increase it. The authors might consider such inclusion for completeness. Although, I must admit, internal motions in such a shallow reservoir would not be very large or complex. However, I am not aware of any observations of internal motions in shallow reservoirs and there are few for larger, deeper ones (with bottom topography forcing the wave motion). Managed releases would exacerbate wave activity.*

Reply: Some of the internal motions in deep reservoirs are attributed to the onset of thermal instabilities as included in the model representation (Eq. 10). Additionally, the effects of wind friction velocity are included explicitly in the (nonlinear) formulation of the eddy diffusivity in Eq. (3). Clearly, inflows-outflows, bottom topography, and breaking waves would enhance mixing and thus modify effective eddy diffusivity. However, keeping with the simple 1D formulation of Henderson-Seller [1985], we retain surface interactions of eddy diffusivity with wind (that is likely to be altered in the presence of the floating cover!). Following the reviewer's comment, we better highlighted these important aspects in the "Discussion" of the revised manuscript.

- *It appeared implicitly assumed that the water was not turbid, a rare condition in most reservoirs. A short discussion of the effect of turbidity on the columnar distribution of heat would enhance the work and provide an avenue for further theoretical work.*

Reply: We thank the reviewer for raising this point; we have considered parameterization of light penetration and various radiative effects in Eq. (2). However, we added a short discussion of this aspect in page 5, lines 3-5 of the revised manuscript.

- *While the amount of open water subject to heating is small in this study, for completeness at least a nod to the Clausius-Clapeyron relationship should be noted (and, I guess, dismissed). It had a major impact on the "failure" of monomolecular layer cover evaporation suppression in the famous Lake Hefner (Oklahoma, USA) Evaporation Reduction Experiment in 1967 (Bean and Florey, 1968, Water Resources Res., 4, 206- 208; also notes an evaporation reduction of about 60%) because the water warmed up when evaporation was reduced. Wind removed the layer, exposing the warm water, which then had higher evaporation due to the warmer water resulting in a net loss.*

Reply: We thank the reviewer for raising this important point. We include the Clausius-Clapeyron relationship in the representation of evaporative flux based on the "saturated vapor concentration" that is a function of surface temperature (e.g., see Eq. 8). The difference with the cases mentioned, is with the energy balance over the covers either via albedo reflection (white covers) or sensible heat exchange (black covers) with minimal net heat flux to the surface (laboratory experiments). We added a discussion of the potential nonlinear evaporation enhancement effects as a function of surface water temperature in page 6, lines 20-22.

- *An important metric, the mean depth, D = V/A, where V is the reservoir volume and A, its surface area was not discussed. An efficient reservoir would be one where V is large and A is small resulting in a large value of D; in other words a cylinder will evaporate less than a bowl of the same volume. In this case 3m < D < 10m was considered. This is very shallow, implying a rapid response of reservoir heat content to varying atmospheric forcing; in other words the surface temperature, the main driver of the evaporative process, responds rapidly to latent and sensible heat transfer as well as the mean temperature of the volume. There is little phase lag between the near surface heat balance and interior heat balance; both will closely follow the daily average air temperature and net radiation input.*

In a deeper reservoir, Lake Mead was used where D is 165, there is a considerable phase lag in the diurnal and seasonal variations of surface versus interior temperature. For instance, in summer daytime air temperature will likely exceed the water temperature; a stable situation resulting in reduced evaporation especially in windless conditions. The reverse is true at night, when water temperatures are likely warmer than air temperature. Since during summer mid-latitude daylight hours substantially exceed nighttime hours so the lower evaporation during the day will dominate. In Fall, surface temperature will decrease due to lower insolation amount and duration, but will this will likely be mitigated by heat transfer into the surface layer by relatively warmer water in the interior resulting in relatively warmer surface temperature than air temperature throughout the day resulting in potentially more evaporation in that season (and Winter) compared to summer. The results shown in this article do not support this heuristic argument. However, eddy correlation observations over a period of years over Lake Superior (Blanken, P. et al., 2011, J. Great Lakes Res., 37, 707-716) show this nicely.

Reply: The present model was developed with relatively shallow reservoirs used for seasonal storage in mind (i.e., depth<10 m). As pointed out by the reviewer, the response of such shallow reservoirs to atmospheric conditions is rapid and the time lag between surface and interior heat balances would be relatively short. A comparison with data from Lake Mead (a relatively deep reservoir), enabled testing of some key features of the model towards establishing a reference uncovered surface for evaluating effects of floating covers on the energy balance (the main objective of the present study). We agree with the reviewer that in the presence of phase lags and multiple mixing (e.g., dimictic reservoirs), the evaporative flux could be affected and even leading to enhanced evaporative losses during the winter. We point out however, that the monthly evaporation data from Lake Mead support the results of higher evaporative losses during summer even for such a deep reservoir (the Figure B below).

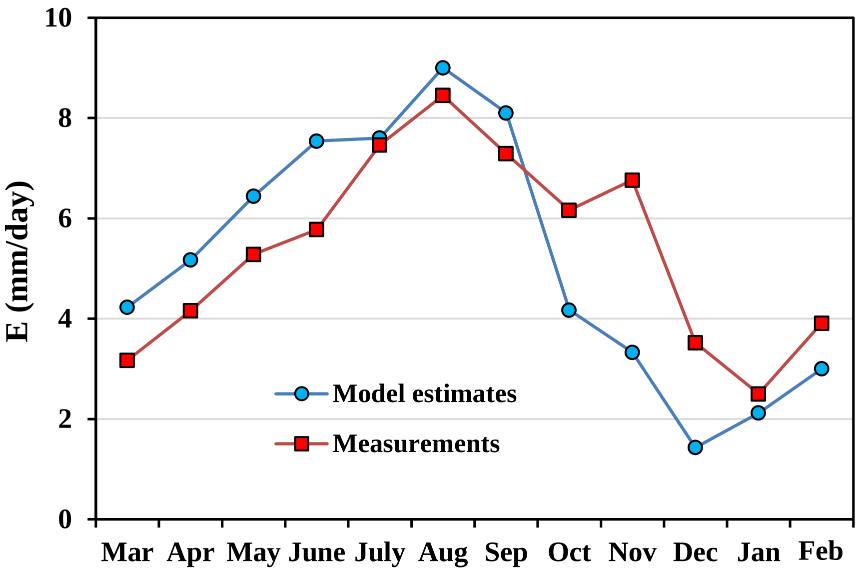

Figure B: Comparing model estimations of evaporative loss from Lake Mead with measurements demonstrating that evaporative losses during summer are dominant.

- *Last, I recall talking with a farmer who was the leader of a ditch company that managed a small reservoir as assumed here. He was very interested in estimating evaporation and, of course, suppressing it with some sort of cover as described here. I asked him if he had planted a wind break on the windward side. He was stunned and said he had not thought of it. So I said: "But you thought of it for your fields and that isn't open water. Furthermore, it would be a good use of otherwise "lost" leakage to ground water." So while I understand this windbreak approach and the consideration of internal boundary layers formed by changes in surface friction is not conducive to such a study as outlined here, I feel a theoretical approach to these aspects of real world reservoirs would be worthwhile in the search for low-impact geoengineering of simple reservoirs. This group obviously has the tools and expertise.*

  Reply: We thank the reviewer for sharing these insights; we also consider aspects of internal boundary layer and its impact on local heat and mass transfer processes key to the efficiency of the cover. We thus plan to further investigate such nuanced aspects in the next steps of this ongoing project to provide a comprehensive framework, including both physical and ecological aspects for design and management of (optimal) floating elements.

Minor comments

- *p. 2, l. 15: I believe the recent use of black balls in a Los Angeles reservoir was not aimed at evaporation reduction but the reduction of toxic algae blooms. I think Israeli engineers have used white ping-pong like balls to reduce evaporation in test reservoirs (don't have a reference).*

  Reply: The reviewer is right, the initial motivation was suppression of photochemical reactions and evaporation suppression from Los Angeles reservoir was a secondary goal. Nevertheless, the water saving aspect gained prominence with the lingering drought in California (as reflected in highly publicized media cover: https://www.engadget.com/2016/09/21/the-big-picture-shade-balls-los-angeles-reservoir/).

- *p. 7, eq. 6a: Please check for references for some of these empirical relationships. Some equations are referenced, some not.*

  Reply: As mentioned in page 6, line 9 of the original manuscript, Eq. (3) and subsequent equations used for quantification of eddy thermal diffusivity are provided by Henderson-Seller [1985]. Following the comment of the reviewer, we explicitly pointed it in the revised manuscript.

- *p. 7, eq. 6b: some readers will not recognize the Brundt-Viasala relationship, which carries some restrictive assumptions with it. Interestingly on a windless or low wind day, this might be more likely during the day and convective mixing, as noted in this work, which is more likely at night when surface temperature might be lower than temperatures below.*

  Reply: We thank the reviewer for the comment; the Brunt-Vaisala relation is part of the stability parameterization of the eddy thermal diffusivity by Henderson-Seller [1985] and plays an important role in the water mixing we consider in this work.

- *p. 7, l. 12-13: Do you have a reference for the assumption?*

  Reply: The assumption arises from the continuity of temperature profile at the interface of liquid and solid phases. We provided appropriate reference in page 6, line 10 of the revised manuscript.

- *p. 8, eq. 8: explain why you use C for vapor concentration instead of the more recognizable q, specific humidity.*

  Reply: The representation based on the vapor concentration arises from Fickian mass transfer across the air boundary layer (implying dominance of diffusive fluxes [Haghighi et al., 2012]). In any case, we do not expect this to affect the clarity of the analysis as vapor concentration and specific humidity are linked via air density (we added a comment for the readers more comfortable with q in page 7, line 1).

- *p. 8, l. 15, Fig. 2: is this the heavy dashed line in the Figure? It needs to be explained.*

  Reply: It is represented by the solid line denoted as T_m, we removed the heavy dashed line in the revised manuscript to avoid confusion of the readers.

- *p. 10, l. 13-14: jargon alert! "three-dimensional vapor shells" Show or explain further. Also what is meant by "lateral spacing"? Perhaps you can show these in Fig. 3b.*

  Reply: We thank the reviewer for alerting us of the use of such jargon. The point was that for small lateral spacing between neighboring water gaps in the cover (either for covers made up of small elements, or densely punctured plastic cover), the vapor concentration profile resulting over the surface is nearly 1D and layered (left image below); as spacing increases, the vapor profiles form individual 3D domes that act to enhance evaporative flux from individual gaps. This is schematically represented in the image below. We thus removed the expression in the revised manuscript to avoid confusion of readers.

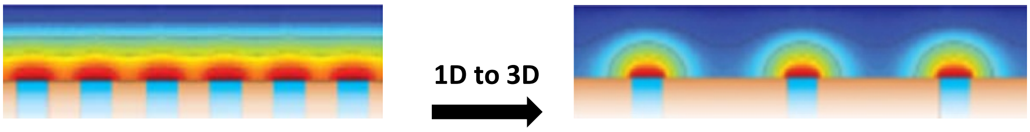

Figure C: Conceptual image of evolution of vapor shells above individual water gaps with increasing spacing between them.

- *p. 12, l. 12: Consider "Given the simplifying assumptions, the model overestimates: : :.".*

  Reply: Thanks, we amended the sentence.

- *P. 13, Fig. 5: Comment on the slow uptake of heat in Spring (cold water/warm air) vs rapid decrease in Fall (warm water/cold air) to add confidence in the model. You might find observational evidence to back up a heuristic argument: surface layer more stable in Spring, more convective in Fall.*

  Reply: We provided further discussions on the evolution of temperature profile in page 12, lines 18-23 of the revised manuscript.

- *p. 13, l. 18-19 "..demonstrate : : : a much colder reservoir." This is an impressive modeling result and should be tested by a field experiment. Is one being considered?*

  Reply: We are aware that model predictions require confirmation using reservoir scale experiments that are currently unavailable. We note that a colder water body under floating elements was observed in our preliminary lab scale measurements in a small basin ($1.2\times1.2\times0.16$ m^3), and are presently conducting two field scale measurements (in EAWAG (Switzerland) and Isfahan University of Technology (Iran); see images below) to provide the necessary data for model evaluation.

Figure D: Top: ongoing "field scale" experiments conducted in EAWAG near Zurich using 8 ponds each 14 m^2 and 1.5 m deep covered with white and black 0.2 m (EVA foam) floating covers including two uncovered control ponds; bottom: construction of two reservoirs (5×5×2 m^3) in Isfahan for field scale tests of the model in a dry and hot place with significant evaporative demand.

- *p. 17, Section 3.3, Ecological considerations: Reservoirs, even small, simple ones as assumed here, while not likely used for recreation, can be important to migratory birds and other wildlife as well as aquatic life in the reservoir (which often provide food for wildlife visiting the reservoir, extending the ecological boundary). Discs, as described here, will inhibit access for wildlife. That should at least be mentioned along with the impossibility of modeling it. Although, for any future work, you might consider entraining a wildlife expert who might.*

  Reply: We agree with the reviewer that ecological considerations of covered reservoirs are not limited to aquatic organisms only and additional biological agents such as birds and wildlife should be considered. Future development of the framework will consider other more nuanced ecological aspects such as optimizing surface coverage to provide required light and oxygen for aquatic life and accessibility to other organisms as pointed out. We thus mentioned this important point in page 18, lines 18-20.

- *p. 18, Section 3.4, Costs and water savings: A nice summary. Have an economist vet it, if you haven't. I especially liked the last sentence. You might mention water scarcity as a conflict enhancer as described recently by Tom Friedman, a well-known columnist for the New York Times. So efficient storage of water becomes political.*

  Reply: We thank the reviewer for raising this point and further discuss (the rapidly evolving) economics of water saving in the revised manuscript and in follow up studies.

- *p. 22, l. 10-18: You should mention an important effect of the discs I did not see in the paper but suggested in this discussion; the appearance of waves, breaking waves, and spray as wind increases (threshold _ 6 mps). This radically changes the situation in open, uncovered water and greatly increases the evaporation; modeling this effect is still elusive though a check of hurricane boundary layer modeling may provide some insights.*

  Reply: We discussed the impact of discs on surface waves and shear velocity and potential effects on the evaporative loss in the "Discussion" of the revised manuscript. However, note that such aspects deserve comprehensive studies that are beyond the objectives of this work.

- *P. 23, Eq. B3: Is this correct? Should it be $\lambda = D/H$ to be dimensionless as described later in the Appendix?*

  Reply: Please note that the dimension of $d.H$ is m^2 and the parameter N represents number of discs per unit "area" rendering λ a dimensionless parameter ($\lambda = N\, d\, H$).

- *p. 24, l. 13-15: 3 to 10 m is not enough depth variation. Note that Rn, H, and E are essentially constant and heat storage decreased by 27% for the 10 m depth. Can you show the "index" Ta – Tw for the two depths? I predict they will be nearly the same.*

Reply: Noting that the focus of the study is ultimately on evaporation suppression and behavior of shallow reservoirs often used for seasonal water storage in arid regions. The similarity in surface heat fluxes between "shallow" and "deep" scenarios considered here is associated with similar surface temperatures and the effect of depth is thus reflected in specific storage and bottom fluxes. Following the reviewers comment, the plot below depicts the difference between air temperature and mean vertical temperature of the reservoir. Although they look similar, the differences in summer and winter are of the order of 3°C.

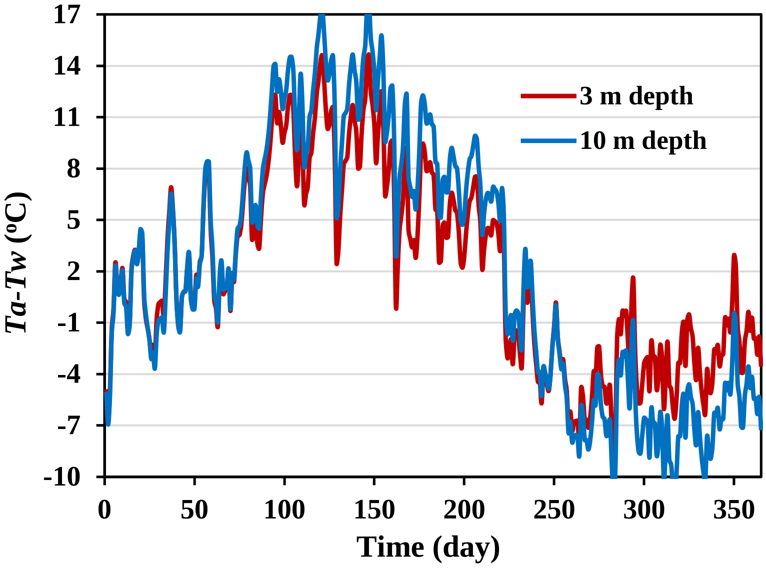

Figure E: Variation of T_a-T_w for shallow and deep reservoirs. The water temperature (T_w) represents the mean vertical temperature of each day.

- *Figure 1: I'd replace that with a Google Earth picture of the Front Range (eastward) of Colorado which is dotted with small reservoirs to show how ubiquitous they are. Using the area tool on the USGS National Map Viewer you could show that the combined area of these "small" reservoirs approximate that of major reservoirs in the Colorado River Basin system.*

Reply: We thank the reviewer for the suggestion; we are presently conducting a global survey of the characteristic of such on-farm reservoirs in different regions (completed surveying NE India, Italy and Australia). The survey would place the use of such storage in the context of other free water storage and highlight the potential evaporative losses (and potential usefulness of floating covers to suppress these losses). We opted to keep the images for simplicity (not much different than the images from the Front Range…).

- *Figure 2: Those two hatched areas do not look equal to me. Explain the dashed line.*

Reply: Considering Eq. (10), the hatched areas on the left and right hand sides of T_m are the same. As mentioned earlier, we removed the dashed line in the revised manuscript to avoid confusion of potential readers.

- *Figure 3: What is the red triangle on the far left side? You've labeled the down arrows to the far left and right, what is the label for the one between them? What does the expression below fc represent?*

Reply: The red triangle stands for the free water surface that is a standard sign in the literature. The arrow between the down arrows is q_c; we added it to the revised figure. The expression indicates attenuation of radiative flux in depth; we better explained it in the revised manuscript.

- *Figure 4: "assumed"? Be honest, wasn't it "tuned"? Were "η" and "β" observed?*

  Reply: To obtain the radiative properties and light attenuation coefficient in Lake Mead, we contacted Dr. Michael Moreo at USGS who is responsible for measurements at the lake; his reply was "*I do not have any subsurface radiation attenuation data. I will say the lake is very clear, and I suspect that radiation penetration is as deep as other very clear lakes*". We thereby estimated the values of η and β based on the literature data reported for clear water bodies.

- *Figure 7: I think 7c is a result of the shallowness of the reservoirs you are modeling. They are like an evaporation pan which has a similar trace with respect to season. Deeper reservoirs show a maximum in Fall/Winter and a minimum in Summer for good reasons. Dew forms on the surface of Lake Superior in summer!! I've witnessed explosive evaporation events associated with reservoir overturning in mid-winter with air temperature of -12C.*

  Reply: Please note that higher evaporative loss during winter is not general as observation in Lake Mead indicates higher evaporation during summer (please see Figure B above). Considering the reviewer's comment, we thus recall that the focus of the present work is on relatively shallow reservoirs whereby evolution of surface fluxes are expected to follow seasonal cycles with higher evaporative loss in summer.

We thank again the reviewers for many helpful comments and hope the Editor finds the clarifications satisfactory.

Sincerely,
Milad Aminzadeh, Peter Lehmann, and Dani Or

Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements

Milad Aminzadeh[1,2], Peter Lehmann[1], Dani Or[1]

[1]Department of Environmental Systems Science, ETH Zurich, Switzerland

[2] now at Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran

Correspondence to: Milad Aminzadeh (m.aminzadeh@cc.iut.ac.ir)

Abstract. The growing pressure on natural fresh water resources and projected climate variability would expand the need for water storage during rainy periods. Evaporative losses present a challenge to efficient water storage reservoirs, especially in arid regions with chronic water shortages. Among the various methods for suppressing evaporative losses, the use of self-assembling floating elements offers a simple and scalable solution especially for small reservoirs. The use of floating elements is not new, yet the science behind the design and the resulting performance including other effects on the water body remain empirical. We propose a systematic approach for modeling the energy balance and fluxes from covered water surfaces considering element geometry, radiative properties and local conditions. The water energy balance equation was linked to the energy balance of floating discs on the surface of reservoir to consider the effect of surface coverage and cover properties on radiative energy storage within the water body and surface heat fluxes. The modeling results demonstrated significant drop in evaporative losses from covered reservoirs where incoming radiative flux is primarily intercepted by the cover surface and released into the atmosphere in form of long wave radiation and sensible heat fluxes yielding much higher Bowen ratio over covered relative to uncovered water reservoirs. The model findings were consistent with laboratory scale observations using an uncovered and covered small basin. The theoretical approach provides a scientific basis for an important water resource protection strategy and a predictive framework for design purposes.

1 Introduction

The competition over dwindling fresh water resources is expected to intensify with projected increase in human population and expansion of irrigated land (Assouline et al., 2015), and with changes in precipitation and drought patterns (Dai et al., 2011). Present global storage capacity for reservoirs > 0.1 km^3 is about 6200 km^3, with estimated total storage volume of 8070 km^3 when smaller reservoirs are considered, resulting in total evaporating surface area exceeding 300000 km^2 (Lehner et al., 2011). The reliance on water storage in reservoirs (Figure 1) is likely to increase to mitigate seasonal shortages due to projected precipitation variability, and to meet water needs for increased population and food production. By some estimates up to half of stored water in small reservoirs is lost to evaporation (Craig, 2005; Rost et al., 2008) thereby exacerbating the water scarcity problem. Interest in methods for suppressing evaporation has led to upsurge in the use of self-assembling floating covers over water reservoirs (e.g., Los Angeles reservoir in Sylmar, California); yet the selection, performance and implementation of such measures remain largely empirical. Recent studies (Assouline et al., 2011; Ruskowitz et al., 2014) have shown that evaporation suppression is a highly nonlinear process that depends on the properties of the covers (size, shape, radiative and thermal properties).

This study aims to provide a scientific basis for using self-assembling floating covers to suppress evaporative losses from reservoirs. The available strategies include deepening the water reservoirs (to reduce evaporative surface per stored volume), covering the surface, underground storage, or introducing wind breakers to reduce exchange with wind. Among these different measures for evaporation suppression, the use of self-assembling floating elements appears most promising for small-scale reservoirs due to its simplicity, cost-effectiveness and scalability (Craig, 2005; Assouline et al., 2011; Gallego-Elvira et al., 2012; Chaudhari and Chaudhari, 2015). Floating covers spontaneously rearrange in response to changes in water level or external conditions, e.g., wind (in contrast with chemical films that may break up due to the wave action, UV radiation, or biological activity).

Laboratory studies of evaporation from partially covered water surfaces (Assouline et al., 2010; Assouline et al., 2011) suggest a nonlinear relationship between the covered area fraction and evaporative losses (see Figure 1 in Assouline et al. (2011)). These nonlinearities are attributed to vapor diffusion from water gaps across air viscous boundary layer (Schlünder, 1988; Shahraeeni et al., 2012; Haghighi et al., 2013) and potential feedback on the gap temperature (Aminzadeh and Or, 2013). The combined effects of gap size, spacing and thickness of the air boundary layer (Shahraeeni et al., 2012) support laboratory experimental results of Assouline et al. (2011) that have shown higher evaporation rates from small water gaps (per unit gap area) relative to evaporation rates from larger gaps (with similar uncovered surface fraction). These nonlinear relationships and additional energetic constraints must be considered in design and deployment of evaporation suppression floating covers.

The quantification of energy partitioning over partially covered water surfaces remains largely empirical with limited predictive capabilities beyond calibrated scenarios (Cooley, 1970; Assouline et al., 2011; Yao et al., 2010; Gallego-Elvira et al., 2011). Incoming radiative energy is intercepted primarily by the floating covers in which energy is mediated by cover geometry, radiative properties (albedo and emissivity), heat conduction and heat capacity of the material. The absorbed heat may be transferred to the water body in contact with floating covers, or return to the atmosphere as emitted long wave radiation and sensible heat flux. Interactions of floating elements with air flow regimes over the surface (turbulent or laminar) may generate complex aerodynamic patterns that affect sensible heat flux from surface elements.

The thermal coupling between floating cover elements and the water body has seldom been considered systematically by investigating surface energy balances for water and covers (Cooley, 1970). A few studies have considered this aspect via changes in heat storage of the water body as deduced from measurements (Gallego-Elvira et al., 2012). As the covered area fraction increases, the increase in intercepted radiative energy over the floating elements and their potential warming up may increase (lateral) heat fluxes towards water gaps thereby contributing to enhanced vapor flux from the uncovered water surface fraction (Aminzadeh and Or, 2017). Additionally, the decrease in the radiative energy penetrating into the water body affects the heat storage and aspects of biological activity within the reservoir. Hence, consideration of the energy balance over water surfaces covered by floating elements is a critical ingredient for any design and management of evaporation suppression from water reservoirs that will be analyzed in this study.

The objectives of this study are to: (1) mechanistically model energy storage and surface fluxes of uncovered and partially covered water reservoirs; (2) consider the effect of cover properties on surface heat fluxes and radiative energy storage in a reservoir; and (3) predict evaporation suppression efficiency of floating covers.

In the following, the theoretical considerations of energy balance for uncovered and partially covered reservoirs are presented. We then investigate evaporation suppression efficiency of floating discs and their effects on surface heat fluxes and radiative energy storage.

2 Modeling framework

2.1 Energy balance and evaporation from uncovered water reservoirs

Before considering evaporation suppression from covered reservoirs, we first quantify fluxes from the uncovered reservoir as the reference state. The quantification of the temperature profile within the water body is the key to define surface heat fluxes and thus radiative energy storage into the reservoir. For simplicity, we employed a one-dimensional energy balance equation with subsurface radiation absorption and diffusive heat transfer including molecular and eddy thermal diffusivity to describe the vertical temperature profile in a reservoir according to (Dake and Harleman, 1969; Vercauteren et al., 2011):

$$\frac{\partial T_w}{\partial t} = \frac{\partial}{\partial z}\left(\left(\alpha_{T,w} + D_w\right)\frac{\partial T_w}{\partial z}\right) + \frac{Q(z,t)}{\rho_w c_w} \tag{1}$$

where T_w is water temperature at depth z, $\alpha_{T,w}$ is molecular thermal diffusion, D_w is eddy thermal diffusivity, ρ_w and c_w are density and specific heat of water, respectively. The heat source Q accounts for the absorption of radiative flux within the water body and is a function of depth (light attenuation) and time (diurnal/seasonal variation of incoming radiation) (Dake and Harleman, 1969):

$$Q(z,t) = \eta(1-\beta)(1-\alpha_w)R_s(t)\,\mathrm{e}^{-\eta z} \tag{2}$$

where β is the absorption coefficient of incoming solar radiation (R_s) at the water surface, α_w is water surface albedo and η is the light attenuation coefficient that is affected by the total suspended solids, dissolved organic matter and chlorophyll (Lee and Rast, 1997). For example, η increases with increasing water turbidity. Alternatively, the heat source term can be quantified based on the dependence of light attenuation on wavelength (Rabl and Nielsen, 1975; Vercauteren et al., 2011). Among different formulations for eddy thermal diffusivity that governs heat transfer within the water body (McCormick and Scavia, 1981; Malacic, 1991; Vlasov and Kelley, 2014), we opt for the analytical representation based on Henderson-Seller (1985) which describes D_w as a function of depth, density and friction velocity at the surface (that is a function of wind speed over the reservoir):

$$D_w = \frac{k u_s^* z}{P_0} \exp(-k^* z)[1+37R_i^2]^{-1} \tag{3}$$

where k is von Karman's constant, P_0 is the neutral value of turbulent Prandtl number, u_s^* is the friction velocity at the water surface that is characterized based on friction velocity of the air flow at the surface (u_a^*):

$$u_s^* = \sqrt{\frac{\rho_a}{\rho_w}}\, u_a^* \tag{4}$$

with air density ρ_a. The parameter k^* is a function of latitude (ϕ) and wind speed (U) (Henderson-Seller, 1985):

$$k^* = 6.6\sqrt{\sin\phi}\, U^{-1.84} \tag{5}$$

and R_i is the Richardson number defined as (Henderson-Seller, 1985):

$$R_i = \frac{-1+\left(1+40N^2k^2z^2/(u_s^{*2}\exp(-2k^*z))\right)^{1/2}}{20} \tag{6a}$$

with buoyancy frequency N:

$$N^2 = \frac{-g}{\rho_w}\left(\frac{\partial \rho_w}{\partial z}\right) \tag{6b}$$

The bottom boundary condition in deep reservoirs is often considered as a constant temperature or zero heat flux. In shallow reservoirs, one must consider the energy balance at the reservoir bottom and heat exchange with soil profile beneath. Hence, in a shallow reservoir with depth D, the energy balance at the bottom and related heat flux are expressed as:

$$\rho_w c_w (\alpha_{T,w} + D_w)\frac{\partial T_w}{\partial z}\Big|_{z=D} = (1-\beta)(1-\alpha_w)R_{s,D}(t) + \frac{k_s}{Z}(T_{sZ} - T_D) \tag{7}$$

where k_s is the effective thermal conductivity of the soil layer beneath the reservoir, $R_{s,D}$ is the shortwave radiation intercepted at the bottom of reservoir, T_D is the bottom temperature of the reservoir (assumed similar to the water temperature at $z = D$ (Incropera and DeWitt, 2001)), and T_{sZ} is a linearized soil temperature at thermal decay depth Z (Shahraeeni and Or, 2011; Aminzadeh and Or, 2014). The water surface energy exchange expressed in terms of radiative, sensible and latent heat fluxes governs the surface boundary condition for Eq. (1):

$$\rho_w c_w \alpha_{T,w}\frac{\partial T_w}{\partial z}\Big|_{z=0} = \beta(1-\alpha_w)R_s(t) + \sigma(\varepsilon_a T_a^4 - \varepsilon_w T_{ws}^4) + h_a(T_a - T_{ws}) - \frac{D_a L}{\delta}(C_s(T_{ws}) - C_a) \tag{8}$$

where α_w is water surface albedo, σ is the Stefan-Boltzmann constant, ε_a and ε_w are atmospheric and water surface emissivity, respectively, T_{ws} is water surface temperature, T_a is the air temperature, h_a is the sensible heat flux coefficient (see below), D_a is the vapor diffusion coefficient in air, L is the latent heat of vaporization, δ is the thickness of air boundary layer that is a function of wind speed (Haghighi and Or, 2013), C_s is saturated vapor concentration at the water surface and C_a is the vapor concentration in air mass above the boundary layer. The dependency of saturated vapor concentration on the water surface temperature (Eq. 8) through the Clausius-Clapeyron relation highlights the potential nonlinear evaporation enhancement with surface warming (Aminzadeh and Or, 2014). Note that evaporative flux (driven by vapor concentration gradient) could alternatively be represented in terms of specific humidity. The sensible heat flux coefficient h_a is quantified as (Gaikovich, 2000; Aminzadeh and Or, 2014; Haghighi and Or, 2015a):

$$h_a = \frac{k_a}{\delta} \qquad (9)$$

in which k_a is the air thermal conductivity.

Often, an unstable temperature profile develops in the water column where a cold water layer may form above a warmer layer due to subsurface radiation absorption; such conditions trigger convective mixing in natural reservoirs. Typically, mixing processes in the water body may require complex and higher dimensional modeling of flows; however, for simplicity, we opted for the 1D mixing approach of Dake and Harleman (1969) that results in a uniform temperature within a mixed layer of water while conserving energy (see Figure 2):

$$\int_0^{h_m} (T_w - T_m)\, dz = 0 \qquad (10)$$

where T_m and h_m are temperature and vertical thickness of the surface mixed layer, respectively. The solution of Eq. (1) results in vertical temperature profile, an important ingredient for quantifying surface heat fluxes including evaporative loss from the reservoir (and for updating the mixed layer temperature).

The inflows and outflows of water in a reservoir may alter the heat storage of the water body, especially in multiuse reservoirs (e.g., water release for electrical energy production in dams). The net advected heat into the reservoir is characterized by the volume-weighted heat content of water inflows and outflows (Moreo and Swancar, 2013):

$$Q_V = \sum_i \rho_w c_w V_i (T_i - \overline{T}) - \sum_e \rho_w c_w V_e (T_e - \overline{T}) \qquad (11)$$

where Q_V is the rate of change in heat content due to the changes in water budget of the reservoir; V_i and T_i, and V_e and T_e are the rates and mean temperatures of inflows and outflows, respectively, and $\bar{T}$ is the mean temperature of the reservoir. The parameter Q_V can be considered in terms of a heat source/sink (e.g., similar to the radiation absorption) to investigate the effect of heat advection due to water exchanges on the energy balance and thus temperature profile in a reservoir.

We have neglected lateral conductive heat transfer in the reservoir assuming that the side area of the reservoir is small relative to its surface area (reflecting conditions in many shallow reservoirs where surface fluxes and subsurface radiation absorption dominate). This simplifying assumption enables focus on a simple 1D model for quantification of vertical temperature profile and thus surface heat fluxes from uncovered and covered shallow water bodies.

2.2 The energy balance of partially covered reservoirs

The use of floating cover elements aimed to suppress evaporative losses also modifies interactions of the reservoir surface with overlying air flow and thus wind-driven subsurface mixing patterns. The interception of radiative flux by the cover surface decreases radiation penetration into the water body shifting the energy partitioning to the cover surface. To simplify the analyses, we consider the energy balance of a reservoir covered by floating Styrofoam discs (similar to the laboratory experiments described in section 3.3). A covered reservoir surface (Figure 3a and b) is represented by a unit cell comprised of a floating disc surrounded by water gaps whereby the ratio of cover area to the total unit cell area defines the surface coverage (Figure 3c). We thus modify the surface boundary condition of the reservoir while retaining a simple 1D formulation and considering energy exchanges with the airflow and floating elements:

$$\rho_w c_w \alpha_{T,w} \frac{\partial T_w}{\partial z}\bigg|_{z=0} = f_w\left(\beta(1-\alpha_w)R_s(t)+\sigma(\varepsilon_a T_a^4-\varepsilon_w T_{ws}^4)+h_a(T_a-T_{ws})-\varphi\frac{D_a L}{\delta_e}(C_s(T_{ws})-C_a)\right)+f_c\, q_c \qquad (12)$$

where f_w and f_c are the areal fractions of free and covered surface, respectively ($f_w = 1 - f_c$), and δ_e represents an effective air boundary layer thickness over the partially covered reservoir. The parameter

φ accounts for the aerodynamic enhancement of vapor flux from relatively small water gaps in comparison with the thickness of viscous sublayer (Assouline et al., 2011). Hence, the reduction of vapor diffusion resistance from individual gaps (governed by the combined effect of gap size a_g, boundary layer thickness and lateral spacing) would enhance vapor diffusion and result in values of $\varphi \geq 1$ that is defined as (Schlünder, 1988; Haghighi et al. 2013):

$$\varphi = \frac{1}{f_w + \frac{a_g}{\delta_e}\sqrt{\frac{f_w}{\pi}}\left(\sqrt{\frac{\pi}{4f_w}} - 1\right)} \tag{13}$$

Note that in this expression it was assumed that a_g has a circular shape. This expression becomes effective for gap sizes much smaller than the boundary layer thickness.

Due to the strong lateral mixing induced by air flow at the reservoir surface (relative to the scale of water gaps), we assume a uniform horizontal temperature at the water surface that is defined based on the heat exchanges with air and conductive flux between floating elements and water surface (q_c) via Eq. (12). Hence, the energy balance equation of the floating disc in the unit cell is used to quantify temperature distribution of the cover and thus the conductive heat exchange with water:

$$\frac{1}{\alpha_{T,c}}\frac{\partial T_c}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_c}{\partial r}\right) + \frac{\partial^2 T_c}{\partial h^2} \tag{14}$$

in which T_c is cover temperature at radial coordinate r and thickness h, and $\alpha_{T,c}$ is molecular thermal diffusivity of cover material. The boundary condition at the surface and periphery of disc in contact with air flow is governed by radiative and sensible heat fluxes. For the bottom of the disc in contact with water surface we assume that the temperature equals to water temperature. Simultaneous solution of Eqs. (1) and (14) with associated boundary condition (Eq. 12) enables quantification of temperature profiles in water body and floating elements that are linked via conductive heat flux (q_c).

The air flow friction velocity (u_a^*) and the effective thickness of viscous sublayer over the partially covered reservoir (δ_e) are determined using the analyses of Haghighi and Or (2015b) for evaporating porous surfaces covered with bluff body obstacles obtained based on the theory of drag partitioning over rough surfaces (Shao and Yang, 2008; Nepf, 2012) (see appendix A for details).

In summary, the effect of floating elements on the energy balance of the reservoir and thus surface fluxes is seen by considering: 1) the energy balance of the water column which now receives less radiative energy in the presence of covers, 2) the energy balance of the cover and its thermal exchanges with water column, and 3) the heat and mass exchanges at the surface of unit cell (comprised of floating cover and water gap) with overlying air flow.

3 Materials and methods

3.1 Model evaluation for the uncovered reservoir

The energy balance equations were solved numerically using the finite difference method (forward time-central space scheme). The modeling results of vertical temperature profile and surface heat fluxes for the uncovered water reservoir are assessed using water temperature and surface flux data from Lake Mead, USA (Moreo and Swancar, 2013). We have used hourly meteorological data (air temperature and humidity, wind speed, and solar radiation) measured at Lake Mead (March 2010 to February 2011) to model the evolution of vertical temperature profile and thus quantify surface fluxes including radiative, evaporative and sensible heat fluxes.

3.2 Modeling the energy balance of a partially covered reservoir

In the absence of “reservoir scale” data for model validation of a covered reservoir (e.g., data from the Ivanhoe Los Angeles reservoir are not publically available) we opted for synthetic test of the model using FLUXNET data from Majadas (Spain), a dry region with significant atmospheric evaporative demand for the water year from March 1, 2004 to March 1, 2005. We then employed the model and considered potential effects of floating disc-shaped elements (diameter of 0.2 m and thickness of 0.02

m) on heat fluxes and water temperature profiles within a hypothetical reservoir with a depth of 10 m using half-hourly meteorological data.

3.3 Laboratory experiments of evaporation suppression using floating discs

As mentioned above, not much is known on evaporation suppression and energy balance of partially covered reservoirs; we thus designed a series of experimental studies of evaporation suppression from a small water basin covered with floating discs at laboratory scale (Figure 4). The main purpose of the study was to systematically vary external forcing (wind, radiation and combination) towards gaining new insights into energy partitioning at the surface of covered water bodies and improve our understanding of the reservoir scale modeling results. A square-shaped water reservoir of 1.44 m^2 area and depth 0.16 m (mounted on a balance to measure mass loss) was covered with Styrofoam discs of 0.2 m diameter and 0.02 m thickness. The black or white colored discs covered 91% of the water surface. Wind velocities controlled with a wind tunnel and radiation by four light sources were used to create different evaporative forcing. Evaporation suppression was determined by measuring the mass of the water reservoir. Water temperature profile within the reservoir was measured with eight thermocouples. Air temperature, relative humidity and wind velocity were also monitored above the covers. An infrared camera (FLIR SC6000, USA) recorded the surface temperature of the covered reservoir with a spatial resolution of 0.8 mm. We conducted a series of experiments in which external boundary conditions (forcing) such as constant wind (2.3 m/s) without radiation, radiation (400 W/m^2) without wind, and combination of radiation and wind were maintained for two days to permit equilibration and convergence to steady state conditions. A similar series of conditions were applied to reservoir covered with white or black floating discs and to the same basin uncovered.

4 Results

4.1 Energy budget and evaporation from uncovered water reservoirs – model application

The theoretical model for quantification of water temperature profile within the water body and surface fluxes was evaluated using vertical water temperature and surface energy balance components obtained from measurements at Lake Mead (Moreo and Swancar, 2013). Figure 5 compares our model estimations of mean monthly temperature profiles with water temperature measured at different depths (Moreo and Swancar, 2013). The assumed thermal and radiative properties of the lake (and covers) are listed in Table 1. The measured and simulated fluxes are summarized in Table 2 showing good agreement between modeled and measured annual net radiation (R_n) and evaporation (LE) fluxes. Given the simplifying assumptions, the model overestimates the reported sensible heat flux (H) that was estimated by Moreo and Swancar (2013) based on the Bowen ratio method with associated energy closure considerations (Foken, 2008; Kalma et al., 2008).

These results for temperature profile and energy fluxes of uncovered water reservoir primarily provide a "reference state" for investigating effects of partial coverage on heat storage and energy balance of reservoirs.

4.2 Evaporation and energy budget of partially covered water reservoirs

Covering a water reservoir with floating elements affects absorption of radiative energy at the surface and consequently the water body heat storage and temperature profile. Considering the lack of field scale data from a partially covered reservoir, we implemented the model for a hypothetical reservoir using meteorological data obtained in Majadas, Spain.

Figure 6 shows model predictions for the evolution of mean daily temperature profile of uncovered and covered reservoir using white and black Styrofoam discs in a (hypothetical) reservoir with depth of 10 m. The stable temperature profile and slow heat uptake during spring results in a gradual temperature increase especially in uncovered reservoir. As expected, the highest water temperature of uncovered reservoir occurs during summer with a warm layer of water at top of the reservoir whose temperature decreases monotonically to the bottom. On the other hand, the onset of convective thermal mixings in fall and low radiative flux rapidly yield an almost uniform temperature profile in winter and beginning of spring. The reservoir was then assumed to be covered by Styrofoam discs with diameter of 0.2 m and thickness of 0.02 m providing a surface coverage of 0.91 (maximum packing of discs). Due to the geometry of floating elements and their density on the surface (cover areal fraction), the effective thickness of air boundary layer over the covered surface was calculated similar to the thickness of boundary layer over uncovered water reservoir (appendix A).

The mean daily temperature profiles of the reservoir covered with white and black discs depicted in Figures 6 clearly demonstrate that covering the surface with floating elements yields a much colder reservoir. Surprisingly, despite large difference in surface albedo of black and white discs (see Table 1) and thus different cover surface temperatures (Figure 7), the resulting water temperature profile did not vary much between reservoirs covered with these two types of floating discs.

In the following, we investigate the effect of surface coverage and cover properties on the evolution of surface heat fluxes.

4.2.1 Energy partitioning and surface fluxes from partially covered reservoirs

The evolution of surface heat fluxes over the uncovered and partially covered reservoir is shown in Figure 8. The reflection of incoming shortwave radiation by the covers resulted in a decrease in net radiative flux of the covered reservoir. The impact of surface albedo on net radiative flux is evident with changing the cover color, yielding lower net radiation over the reservoir covered with white discs relative to the reservoir that is covered with black discs.

The effect of floating discs on evaporation from the reservoir is illustrated in Figure 8c. It shows that discs significantly suppress evaporative flux relative to uncovered water reservoir especially during summer. The substantial decrease in evaporative flux from covered reservoir with concurrent increase in sensible heat flux (due to the high cover temperature) results in a higher Bowen ratio over the covered reservoir relative to water surfaces (Priestley and Taylor, 1972). Interestingly, the color of the floating discs did not affect evaporation suppression from the covered reservoir; hence, the higher sensible heat flux from the black discs yields higher Bowen ratio relative to the white discs scenario. A summary of mean annual surface heat fluxes for uncovered and covered reservoir is presented in Table 3.

The ratio of heat storage in the water body relative to the net radiation over the surface of the uncovered and partially covered reservoir is shown in Figure 9. To compute the heat storage we have chosen the initial (assumed uniform) temperature profile at the beginning of the water year (March 1) as a reference. Such a reference state is motivated by measurements in Lake Mead (Figure 5). The heat storage is then calculated by integrating changes in the temperature profile relative to the reference (and water heat capacity). At beginning of the year, the ratio of heat storage to net radiation is sensitive to temperature variations close to the surface showing large fluctuations. After an equilibration period, Figure 9 shows a maximum value of the ratio in the summer for the uncovered water reservoir before decreasing in the fall, following the annual variation of radiative flux. For the partially covered reservoir, the ratio remains nearly constant with only a slight increase during the summer. Moreover, the lower net radiative flux of the reservoir covered with white discs (Figure 8) results in higher values of the ratio of heat storage to the net radiation while subsurface heat storage does not change significantly with changing color of floating discs.

We have also investigated the effect of reservoir depth on energy storage and surface heat fluxes and a summary of results is provided in appendix B.

4.2.2 Evaporation suppression efficiency of floating covers

Self-assembling floating discs effectively cover the reservoir and decrease water surface exposure to the atmosphere. We plotted the ratios of evaporative fluxes from covered water reservoirs relative to uncovered water surface (E_c / E) to quantify evaporation suppression efficiency of the floating discs (i.e., $\varepsilon = 1 - E_c / E$). The results in Figure 10 demonstrate that application of discs yields more than 80% drop in evaporative loss from the reservoir ($E_c / E < 0.2$) with highest efficiency during summer. This result was obtained based on the 1D modeling of vapor flux ($\varphi = 1$) from relatively big water gaps between neighboring discs (diameter of 0.2 m) representing the upper bound of evaporation suppression efficiency. However, under certain conditions where the boundary layer thickness (often in the order of a few millimeters (Haghighi and Or, 2013)) is comparable with gap size (a_g / δ_e in Eq. 13), enhancement of vapor flux from individual gaps may decrease the suppression efficiency ($\varphi > 1$).

4.3 Laboratory evaporation suppression experiments

We conducted laboratory experiments focusing on the surface-cover-air interface under different forcing to capture energy partitioning dynamics under steady state conditions and mimicked diurnal cycles and thus provide a basis for the modeling assumptions and interpretations. Surprisingly, independent of the forcing (wind and radiation) and color of the discs the evaporation rate of the covered reservoir was about 20% of the uncovered surface (Figure 11a). The corresponding evaporation suppression efficiency of 80% is less than the cover fraction of 91%. This reduced efficiency is attributed partially to the increased surface temperature of the water between the discs compared to uncovered water reservoir as shown in Figure 11b.

These experiments provide direct evidence for cover interactions and efficiency and highlight important aspects of energy partitioning but do not consider the full suite of issues related to real reservoirs. We thus invoke these “laboratory scale” findings in the context of energy partitioning, surface temperature and evaporation suppression as guidance for the surface modeling and to some extent, interpretation of the associated results obtained from the reservoir scale approach in section 4.2. The laboratory results clearly demonstrated that the main effect of floating covers on evaporation suppression and energy partitioning was concentrated at the surface and thus supported the focus on the top boundary condition for the full reservoir scale model reported in this study. These experiments do not reflect influences of temperature profiles and mixing represented in the reservoir scale model in which heat storage, mixing and ground flux affect water temperature and, in turn, the top boundary of the reservoir.

5 Discussion

5.1 The energy balance of covered reservoirs

The physically based model highlights the substantial impacts of floating elements on the energy budget and surface fluxes of a reservoir and the great potential for suppressing evaporative losses. Our modeling results demonstrated that covering the surface with modular floating elements yields a colder reservoir relative to the uncovered scenario due to the interception of incoming radiative flux by the cover surface shifting the energy partitioning to the reservoir surface. Despite significant difference in surface albedo of black and white discs, the water temperature profile of the covered reservoir was similar. We attribute this to the strong insulating properties of the Styrofoam that energetically decouples the top of cover with different temperature and flux conversions from the water surface.

Considering the low thermal diffusivity of Styrofoam discs that yields negligible heat conduction to the water body, the intercepted radiative flux on the cover surfaces (especially the black) results in considerable increase of cover temperature (Figure 7a). In contrast with our expectation that the radiative properties of the floating covers would greatly affect the water surface temperature, the thermally insulated covers leaked only small amounts of heat to the water (Figure 7b) and only mildly influenced the evaporative flux from covered reservoir (Figure 8c). Most of the energy absorbed by the cover was then exchanged with the atmosphere as sensible and radiative heat fluxes. These results have been confirmed in laboratory experiments for the basin covered with white or black discs where the evaporative fluxes from the covered surface were 20% of the uncovered regardless of the cover color and forcing (see Figure 11a).

5.2 Evaporation suppression in covered reservoirs

The reduction of evaporating area on the surface of covered reservoirs primarily suppresses evaporative loss from the water body. Considering the 1D modeling of vapor flux in the present study, the decrease in evaporative loss is expected to be equal to the covered area fraction. However, the evaporation ratio larger than the uncovered areal fraction (0.09) in Figure 10 is attributed to the higher water surface temperature in gaps between floating elements relative to the uncovered water surface as illustrated in Figure 7b. An interesting feedback mechanism may play a role in evaporation suppressing efficiency where high evaporative fluxes from uncovered water reservoirs may result in more surface temperature depression and thus lower saturated vapor concentration relative to the vapor concentration at the surface of water gaps over partially covered reservoirs. In addition, conductive heat fluxes from cover elements to the water surface could potentially contribute in increase of water surface temperature depending on thermal properties of the cover material. The higher gap temperature relative to the uncovered water obtained from the modeling was also observed in laboratory experiments (Figure 11b) supporting the nonlinearity of evaporation suppression from partially covered reservoirs.

Although we assumed that air temperature and humidity (obtained from FLUXNET measurements for the numerical experiment) are the same over uncovered and partially covered reservoir, it is important to note that the higher sensible heat flux over covered reservoir could locally increase air temperature in contact with water gaps that, in turn, enhances evaporative loss from covered reservoir and decreases evaporation suppression efficiency.

In addition to the physical considerations of the energy balance and evaporation suppression in covered reservoirs, further investigations including the ecological aspects and cost efficiency discussed below are needed to provide a comprehensive assessment for application of floating covers.

5.3 Ecological considerations

Reservoirs may serve multiple functions including the support of various ecosystems, hence, the introduction of opaque floating covers to supress evaporation may alter water temperature, light penetration and gas exchange all affecting the ecology and life in the reservoir. The full consideration of ecological targets is beyond the scope of this study, clearly, certain parameters could be included in the cover design and management to limit adverse impacts on the ecology of the water body (in some cases, a cover may supress toxic algal blooms in a reservoir). For example, here we consider effects of floating covers on gas exchange across the air-water interface as a function of uncovered fraction (f_w). The oxygen transfer at the surface of reservoir (F_{s,O_2}) is expressed as (Stefan et al., 1995; Schladow et al., 2002):

$$F_{s,O_2} = f_w \, k_{s,O_2} (C_{e,O_2} - C_{w,O_2}) \tag{15}$$

where k_{s,O_2} is the oxygen transfer coefficient, and C_{e,O_2} and C_{w,O_2} are equilibrium oxygen concentration and oxygen concentration in the surface layer, respectively. The dissolved oxygen in the water body is consumed by aerobic organisms (e.g., fish and aquatic microorganisms) and affects various chemical reactions in a reservoir (Stefan et al., 1995). The mechanical sheltering impact of surface covers that dampens wind-driven mixing at the surface may affect air-water oxygen exchange and transport in water column yielding a stratified oxygen profile in the reservoir. Although the interception of radiative flux by the cover surface decreases subsurface radiation absorption and results in a colder reservoir that may enhance oxygen solubility in water (Wilkinson et al., 2015), the reduction of radiation absorption limits convective mixing driven by unstable temperature profiles and intensifies a stratified oxygen distribution. Moreover, the photosynthesis by aquatic plants and microorganisms in darker and colder reservoirs covered with floating elements decreases which then affects the oxygen budget according to the oxygen transfer equation (Stefan et al., 1995):

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial z}\left(\left(\alpha_{O_2}+D_w\right)\frac{\partial C}{\partial z}\right)+P_{O_2}-R_{O_2} \tag{16}$$

where C is oxygen concentration at time t and depth z, α_{O_2} is molecular oxygen diffusion, and P_{O_2} and R_{O_2} are oxygen production by photosynthesis and consumption due to biological activities within the water body, respectively. In summary, exchange rates and oxygen production and concentration in a reservoir are strongly dependent on water temperature, radiative flux, transport processes and nutrients that are likely to be influenced by surface coverage. Note that ecological considerations of covered reservoirs are not limited to aquatic organisms and additional aspects including accessibility of birds and wildlife should also be investigated. Such ecological objectives become part of the reservoir cover design and evaporation suppression must be balanced by ecological and also economic constraints as discussed next.

5.4 Costs and water saving

The significant reduction in evaporative loss from the reservoir could be gauged by direct economic impact in terms of cost of alternate source of water where available. The economic efficiency of evaporation suppression depends on the costs of construction (P_c [\$/m^2]), annual maintenance of covers (P_m [\$/m^{2}year]), alternate water cost (w [\$/m^3]), annual evaporation from the uncovered reservoir surface (E [m/year]), and evaporation suppression efficiency of floating covers (ε) (Cooley, 1983; Assouline et al., 2011). Assuming a life span of Y years for the floating elements, the economic efficiency per unit area of reservoir (ζ [\$/m^2]) is estimated as:

$$\zeta = Y(\varepsilon w E - P_m) - P_c \tag{17}$$

We thus calculate ζ for the hypothetical reservoir presented in section 3.2 with annual evaporative losses for uncovered surface E=1.6 m/year (see Table 3), and estimated cover efficiency ε=0.8. Considering water price w=1 \$/m^3 (e.g., seawater reverse osmosis costs are in the range of 0.5 to 3 \$/m^3 (Gilau and Small, 2008; Guler et al., 2015)) floating cover cost P_c=5 \$/m^2 (based on commercially available HDPE floating balls) and cover maintenance cost P_m=0.1 \$/m^{2}year, the economic efficiency of such floating elements for a period of 5 years is ~1 \$/m^2. Hence, for a reservoir with 100×100 m^2 surface area, water costs saving equivalent to \$10000 is feasible in 5 years operation (along with 64000 m^3 of water protected from evaporation).

Tacit in this standard estimate is availability of an alternate water source (e.g., desalinated water); whereas in many regions in the world with poor infrastructure and acute water shortages, the value of evaporation suppression may transcend such estimates and the real measure could be expressed in terms of livestock supported by the additional water or avoidance of crop failure. Water scarcity and droughts may exacerbate water scarcity problems and transboundary (or regional) conflicts over shared water resources. Some of these political challenges could be alleviated by promotion of efficient local storage using cost effective evaporation loss mitigation measures (such as floating covers).

5.5 Improvement of the modeling approach

Many aspects of the hydrodynamics and turbulent conditions associated with atmospheric stability over the evaporating reservoir surface were not explicitly addressed in the present study. In a recent study of soil surface evaporation, Haghighi and Or (2015c) have linked effects of different stability conditions in the Monin-Obukhov similarity (MOST) atmospheric turbulent profiles with the surface boundary layer approach used in this study. The study offered corrections for adjusting the viscous sublayer and thus the effects of atmospheric stability conditions on heat and vapor exchange with surfaces. Elements of the analyses of Haghighi and Or (2015c) could be incorporated into the modeling of surface-atmosphere exchanges over partially covered water reservoirs. Such an analysis would be warranted once we resolve important aspects of the effects of floating elements on features of the viscous sublayer over the partially covered surface. At present, the effects of floating element shapes and cover density on surface shear stresses (in the air and in the water body), impacts of inflows-outflows, bottom topography and breaking waves have not been implemented and are expected to affect surface condition and subsurface turbulent mixing and thus modify effective eddy diffusivity. The availability of data from covered ponds and larger reservoirs would provide the impetus to systematically address these important ingredients and improve the predictive framework for application of modular covers in controlling evaporative losses from water bodies.

As commented above, the simple 1D energy and mass flux model has tacitly neglected lateral conductive fluxes between the water body and sides of the reservoir which was deemed a reasonable approximation for shallow reservoirs and where floating elements dominate surface fluxes. Energy balance errors incurred due to lateral heat fluxes in small reservoirs (e.g., agricultural ponds) warrant special studies (motivated by measurements) to improve energy closure and provide reliable estimates of surface fluxes and evaporation suppression efficiency.

6 Summary and conclusions

Evaporative loss from local water storages in dry regions accounts for up to 50% of the stored water used to guarantee municipal, industrial and agricultural water supply in dry seasons (Shilo et al., 2015). Self-assembling floating elements offer an efficient and cost-effective measure for suppressing evaporative loss from water reservoirs. Despite the wide application of floating elements, modeling evaporation and energy balance of covered reservoirs is often addressed empirically or limited to simple scenarios where salient features of cover properties and energy exchange between reservoir and floating elements are ignored.

We employed the water energy balance equation with an implicit convective mixing approach to quantify surface fluxes and vertical temperature profile in a water reservoir. Simultaneous solution of energy balance equations in water body and floating elements linked via heat exchanges between cover and water surface, enabled quantifications of surface heat fluxes and energy storage within the water body. Modeling results for a hypothetical reservoir covered with white and black Styrofoam discs demonstrated that interception of radiative flux by floating covers significantly decreases subsurface radiative energy absorption in covered reservoirs yielding colder water temperatures relative to uncovered water reservoirs. The lower water temperature and less radiative energy storage of the covered reservoir may thus affect the oxygen content of the water body and, in turn, aquatic life. The intercepted radiative flux on the surface of floating elements that primarily increases cover temperature is released in form of sensible heat flux and long wave radiation into the atmosphere depending on the cover thermal and radiative properties. The increased sensible heat flux could raise local air temperature over water gaps and contribute in the enhancement of evaporative losses from individual gaps. Such nuanced aspects of energy partitioning over covered surfaces not investigated in the present study may decrease suppression efficiency of floating elements.

The modeling results (supported by laboratory experiments in a shallow basin) suggest that evaporation from covered reservoir was reduced by about 80% relative to uncovered water surfaces. Interestingly, the model shows that floating covers with low thermal conductivity are energetically decoupled from the water surface. Consequently, changes in cover color (affecting albedo) did not significantly modify the evaporative flux (a result that was also observed in laboratory experiments). The primary effect of floating cover color was thus reflected in increasing the cover temperature and sensible and longwave radiative fluxes for the black cover, or increased reflectance of shortwave radiation for the white covers (and lower cover temperatures). The reduction in evaporative fluxes and the higher sensible heat flux over partially covered reservoir may result in a significantly higher Bowen ratio over the covered relative to uncovered water surfaces (Priestley and Taylor, 1972).

Floating elements efficiently suppress evaporative loss from water reservoirs and alter energy storage within the reservoir and oxygen exchange at the water-air interface. Notwithstanding theoretical considerations of evaporation and energy balance of covered reservoirs in the present study which primarily aimed to provide a physically based framework for design purposes, certain ecological aspects including light and oxygen transmission associated with multiuse reservoirs need to be addressed systematically. The model provides a useful tool for investigating effects of partial coverage and reservoir depth on surface fluxes and specific energy storage in the water body, and thus may provide design and management guidelines for different objectives, ranging from evaporation suppression to other ecological goals. The study highlights the need for field scale experimental studies of evaporation and energy fluxes from partially covered reservoirs (different covers and climatic conditions) towards generalization of the results and development of new insights, and for critical evaluation of key assumptions.

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Appendix A: Effective boundary layer thickness over covered reservoirs

We use the analysis of Haghighi and Or (2015b) based on the theory of drag partitioning over rough surfaces (Shao and Yang, 2008; Nepf, 2012) to obtain the effective thickness of viscous sublayer over the covered reservoir:

$$\delta_e = g(\alpha)\frac{v}{u_a^*} \tag{A1}$$

where $g(\alpha)$ describes the effect of eddy characteristics (=21 for a practical range), v is the kinematic viscosity of air, and u_a^* is the air flow friction velocity:

$$u_a^* = U\sqrt{f_r\lambda(1-f_c)C_{rg} + \left(f_s(1-f_c)+f_g f_c\right)C_{sg}} \tag{A2}$$

where U is air flow velocity, and λ is the frontal area index that is a function of disc diameter (d) and height (H):

$$\lambda = N\ d\ H \tag{A3}$$

with N as the number of discs per unit area; $C_{rg} = \gamma C_{sg}$ and C_{sg} are drag coefficients of discs and uncovered surface, respectively with λ =0:

$$C_{sg} = \left(k/\ln\left(z_U/z_{0s}\right)\right)^2 \tag{A4}$$

where z_U and z_{0s} are reference height for measurement of wind velocity and roughness length of uncovered surface, respectively. The parameters f_r, f_s, and f_g are defined as:

$$f_r = \exp\left(-\frac{a_r\lambda}{(1-f_c)^m}\right) \tag{A5}$$

$$f_s = \exp\left(-\frac{a_s\lambda}{(1-f_c)^m}\right) \tag{A6}$$

$$f_g = 1+\left(\frac{C_{sgc}}{C_{sg}}-1\right)f_c \tag{A7}$$

with a_s =5, a_r =3, and m=0.1. The drag coefficient on the surface of disc C_{sgc} is expressed as:

$$C_{sgc} = \left(k/\ln\left(\frac{z_U-H}{z_{0s}}\right)\right)^2 \tag{A8}$$

By increasing λ from zero (uncovered surface) to $\lambda \approx 0.2$, the interaction of overlying air flow with floating elements results in formation of smaller scale eddies which then decrease the effective thickness of viscous sublayer. Increasing λ more than 0.2 reduces air flow penetration into the gaps which thus traps air between floating elements and forms relatively thick boundary layer in the order of element's height. Figure A1 depicts the effect of cover geometry (diameter and height) on the effective thickness of boundary layer.

Appendix B: The effect of reservoir depth on energy balance

We investigated the effect of reservoir depth on the energy balance and surface heat fluxes considering shallow (3 m) and deep (10 m) hypothetical reservoirs for the conditions in Majadas, Spain (March 2004 to March 2005). The bottom boundary condition was assumed to follow a linear heat flux to the underlining soil (Shahraeeni and Or, 2011). Although (as expected) the specific energy storage (storage per volume of reservoir) was higher in the shallow reservoir, the surface temperature and heat fluxes were similar for the shallow and deep reservoirs (Table B1). Considering similar aerodynamic conditions at the surface, the similarity in surface fluxes of shallow and deep reservoirs indicate that surface temperatures were similar (e.g., uncovered water surface temperature depicted in Figure B1). These results highlight the dominance of atmospheric forcing in adjusting surface temperature and thus surface heat fluxes whereas the effect of reservoir depth is reflected in the specific energy storage and heat flux at the bottom (especially in uncovered reservoirs), *G*, which is governed by the bottom temperature of the reservoir (Figure B1).

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Table 1: The physical properties of water and the Styrofoam discs (white and black surfaces) used for modeling.

	Specific heat (J/kg K)	Emissivity	Albedo	Thermal conductivity (W/m K)	Molecular thermal diffusivity (m^2/s)
Water	4200	0.95	0.05	0.6	1.43×10^{-7}
Discs	1130	0.85	white: 0.6 black: 0.1	0.03	3.9×10^{-8}

Table 2: Comparison of modeled and measured annual surface energy balance components for (uncovered) Lake Mead (2010-2011).

	R_n (W/m^2)	LE (W/m^2)	E (mm/day)	H (W/m^2)
Measurements (Bowen ratio EB)	147	170	5.95	-18
Model estimates	187	148	5.2	-36

Table 3: Modeled annual surface heat fluxes of uncovered and covered hypothetical reservoir using FLUXNET data from Majadas, Spain (March 2004 to March 2005).

	R_n (W/m^2)	LE (W/m^2)	E (mm/day)	E (mm/year)	H (W/m^2)
Uncovered	147.9	127.3	4.48	1635	-65.1
Covered with black discs	122.1	14.5	0.51	187	94.9
Covered with white discs	54.8	12.9	0.45	167	30.7

Table B1: The effect of reservoir depth on heat fluxes and specific storage of uncovered and covered reservoirs.

		Rn (W/m^2)	H (W/m^2)	G (W/m^2)	E (mm/day)	Storage: June-Sep (MJ/m^3)
3 m depth	Uncovered	148.7	-67	29.2	4.43	**25**
	Covered with black discs	122.9	92.7	2.2	0.44	2.1
	Covered with white discs	55.4	28.5	1.8	0.39	1.6
10 m depth	Uncovered	148.1	-65.6	20.4	4.46	**18.4**
	Covered with black discs	122.5	93.8	2.2	0.47	1.9
	Covered with white discs	55.1	29.5	2.1	0.41	1.3

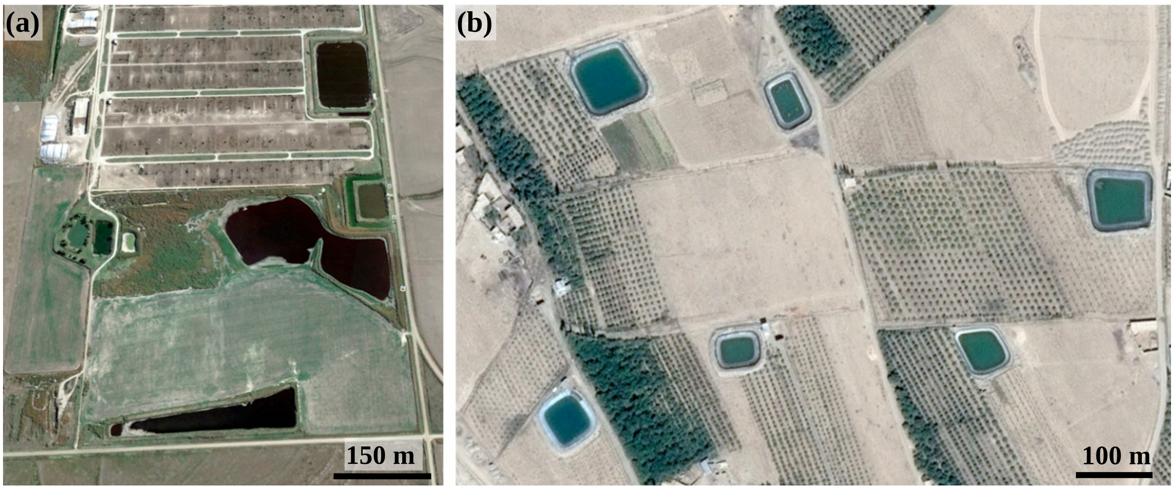

Figure 1: The growing number of small reservoirs for local supply during dry periods highlights the need for evaporation suppression measures to conserve water (satellite images from (a) Hanston, Kansas, US, and (b) Shahrood, Iran; reproduced from Google Earth (2017)).

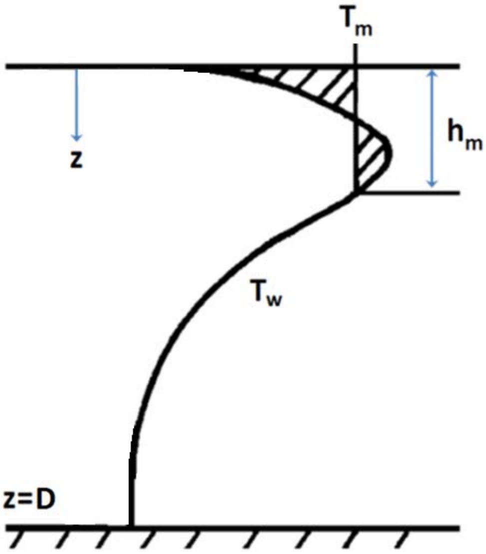

Figure 2: Convective mixing at the surface of water reservoir of depth *D* due to the unstable temperature profile associated with subsurface radiation absorption (adapted from Dake and Harleman (1969)). Based on Eq. (10), the hatched areas on the left and right hand side of T_m are equal representing transfer of subsurface heat accumulation to the surface.

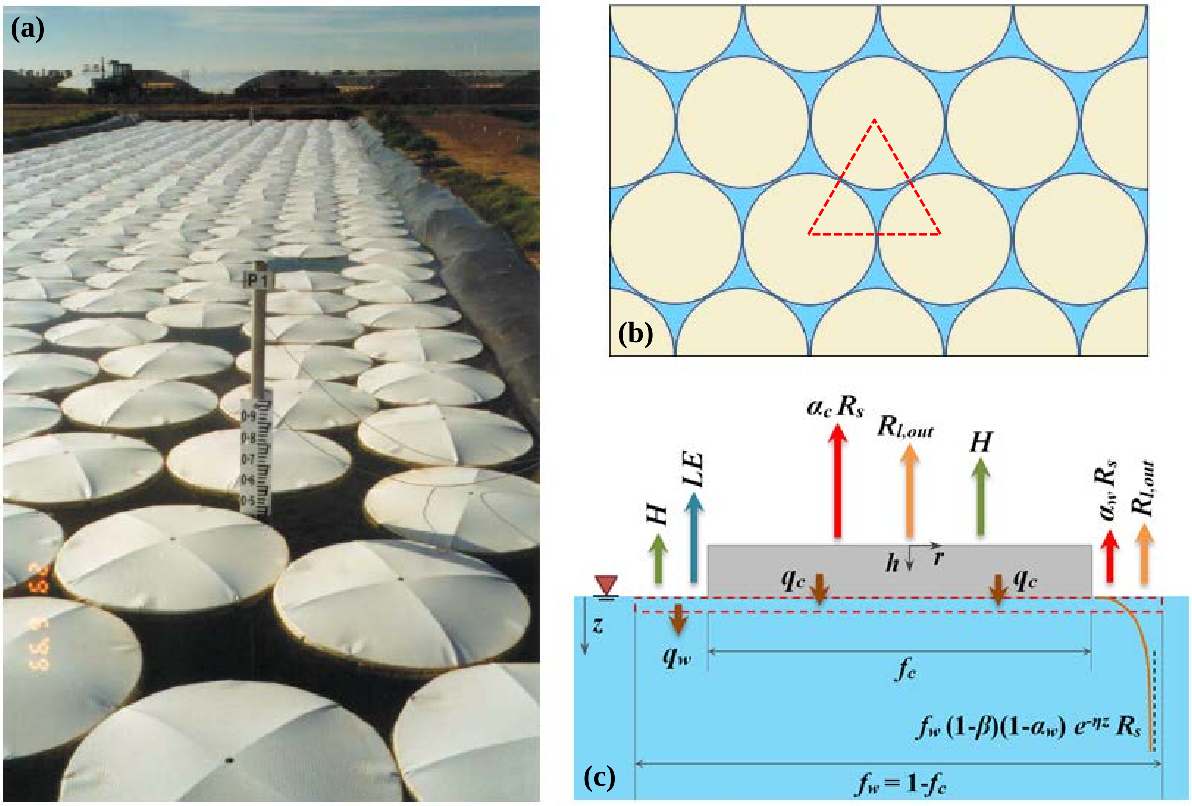

Figure 3: (a) Application of floating discs in evaporation suppression from water reservoirs (adapted from Assouline et al. (2011)); (b) top view of reservoir surface covered with discs; due the geometrical constraints, dense packing of discs provides a surface coverage of 0.91 (inferred from the depicted triangle with side lengths equal to disc diameter); (c) schematic representation of subsurface radiation attenuation (the curve with associated expression) and surface heat fluxes in a representative unit cell including a floating element and free water surrounding it with areal fractions of f_c and f_w, respectively (Eq. 12). See section 2 for definition of the various parameters.

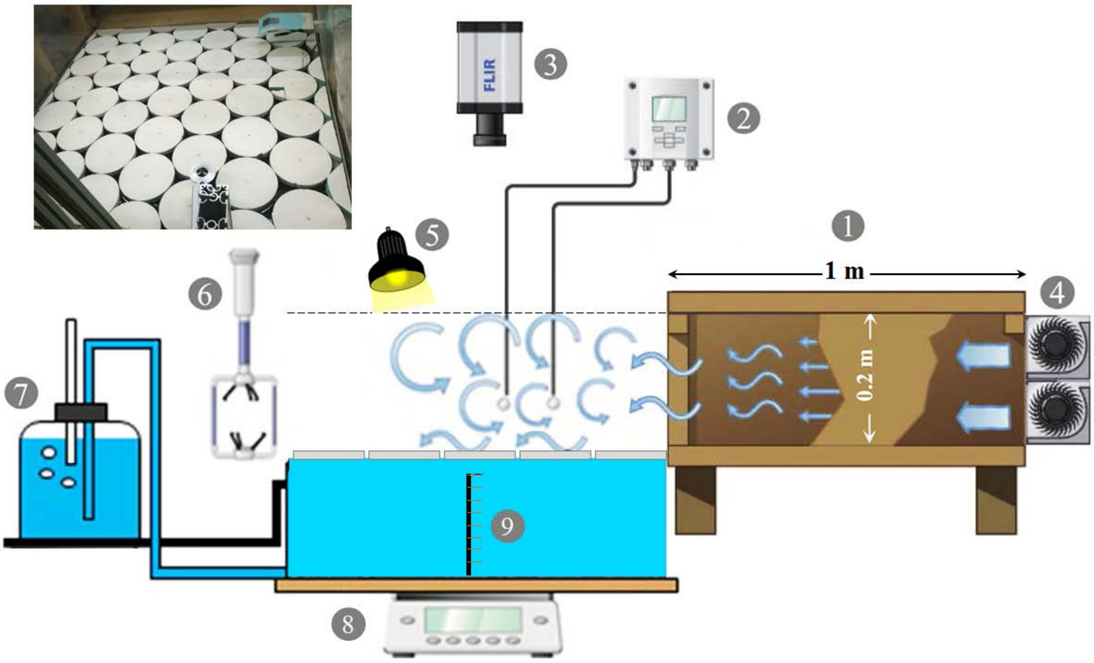

Figure 4: Experimental setup for evaporation suppression measurements from a small water basin covered with floating discs: (1) wind tunnel, (2) air temperature and humidity sensors (Vaisala HUMICAP, HMT337, Finland), (3) IR camera (FLIR SC6000, USA), (4) tunable fans generating wind flow, (5) xenon lamps for shortwave radiation, (6) high-frequency 3D sonic anemometer (WindMaster, Gill Instruments Ltd., The Netherlands), (7) Mariotte bottle to adjust water level, (8) balance to determine mass loss and evaporation rates, (9) temperature sensors in water body.

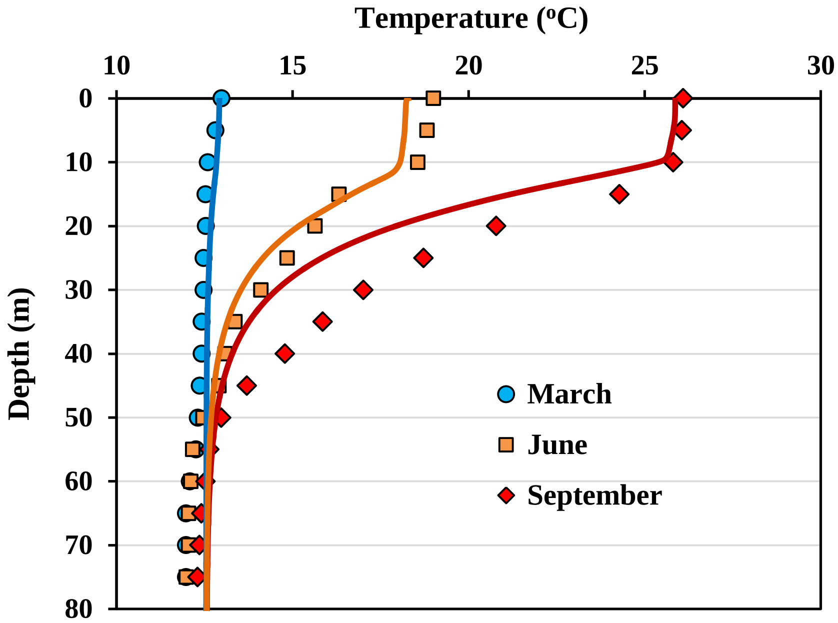

Figure 5: Model predictions (lines) and measurements (symbols) (Moreo and Swancar, 2013) of mean monthly vertical temperature profiles in Lake Mead; modeling results were obtained using meteorological data measured at Lake Mead assuming radiation absorption at surface (β) and attenuation coefficient (η) of 0.3 and 0.1, respectively.

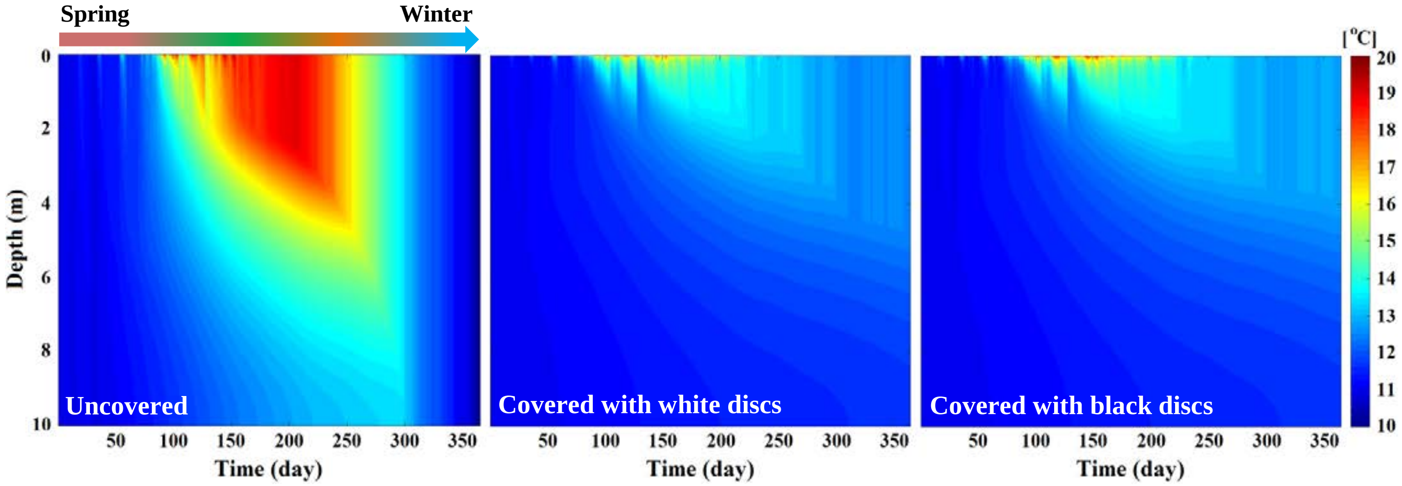

Figure 6: Modeling the effect of surface coverage on mean daily temperature in a hypothetical reservoir with 10 m depth using meteorological data from FLUXNET in Majadas, Spain (March 2004 to March 2005); the reservoir was covered using white and black Styrofoam discs (diameter: 0.2 m and height: 0.02 m) that provide 0.91 coverage of the reservoir surface. A uniform vertical temperature at 11 °C was assumed as the initial condition, and the bottom boundary condition was set to zero heat flux.

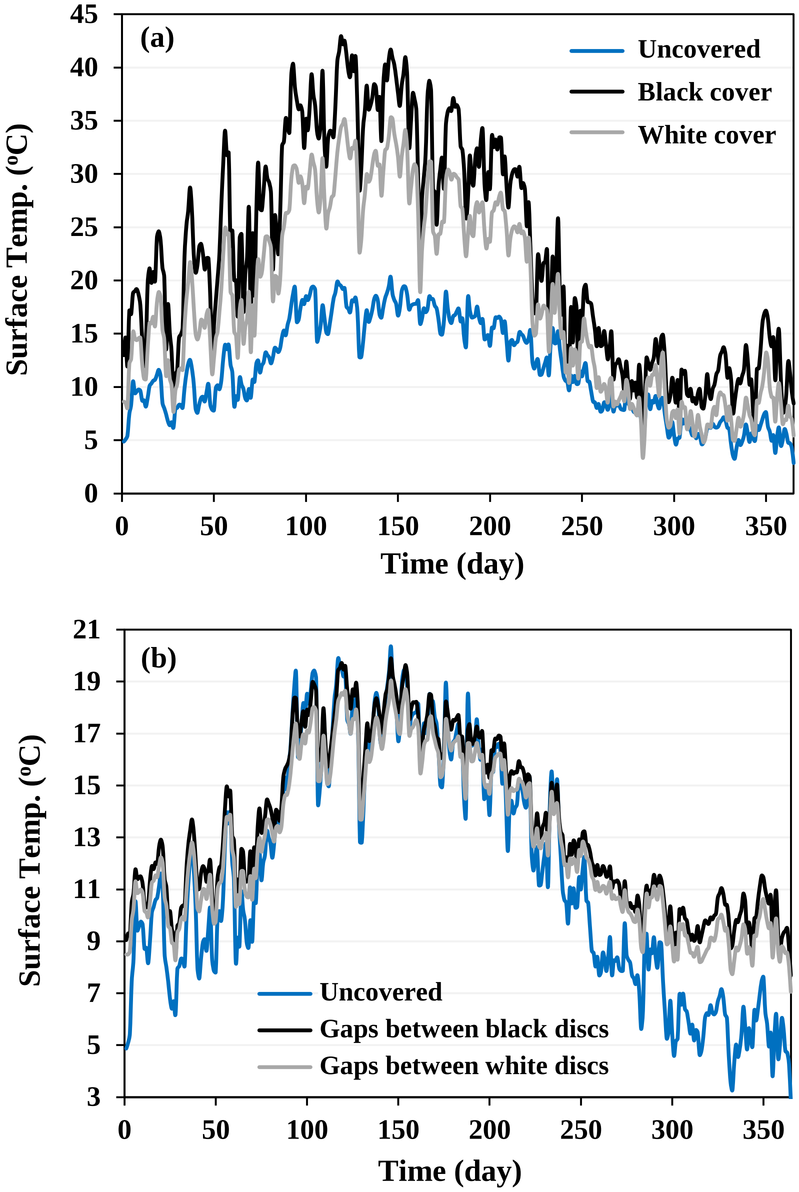

Figure 7: (a) The evolution of temperature on the top surface of floating discs and on the surface of uncovered reservoir; (b) comparing surface water temperature of the uncovered reservoir and of water gaps between floating elements. The plots show simulation results for a hypothetical reservoir in Majadas (Spain).

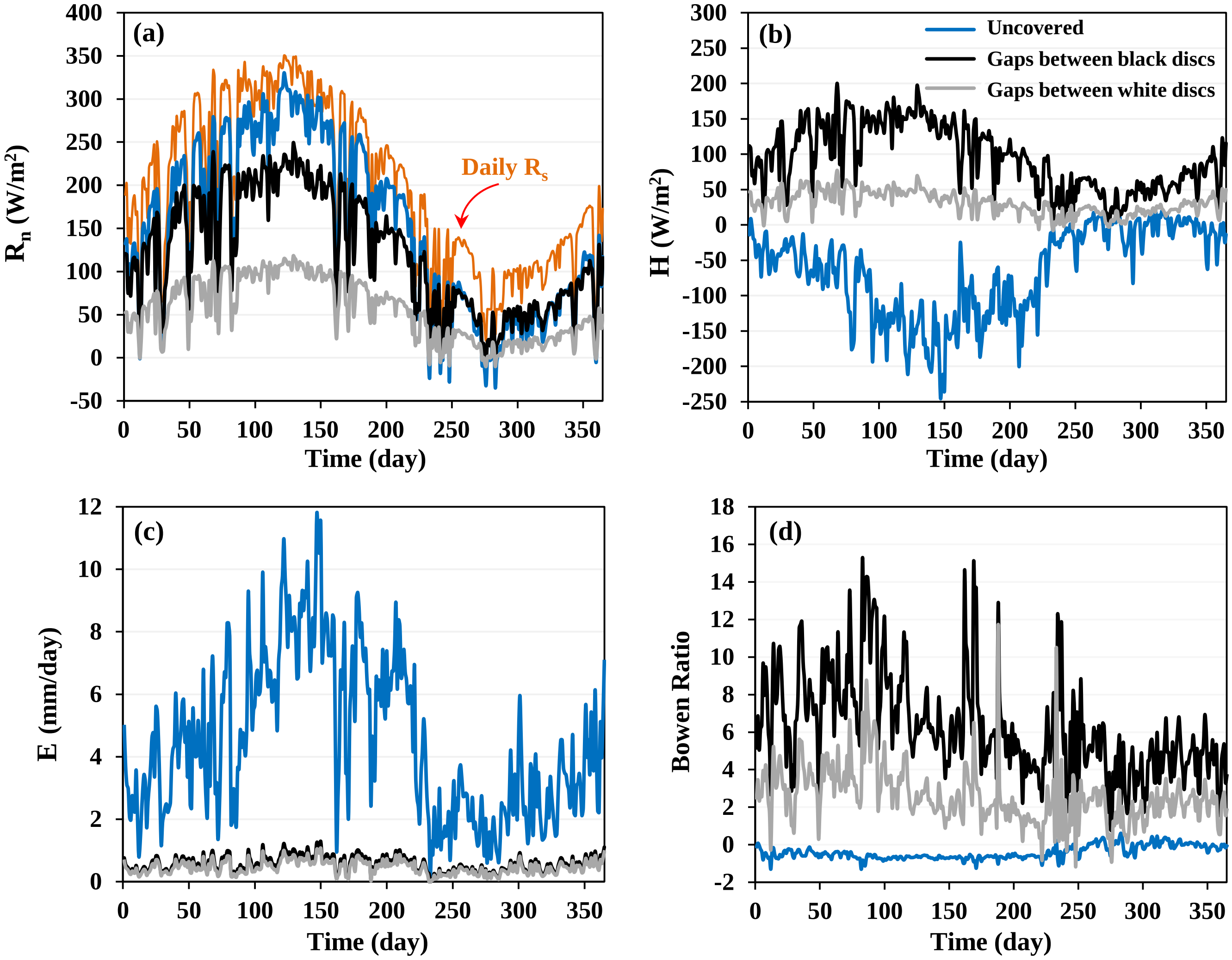

Figure 8: Model estimates for the evolution of net radiation (a), sensible heat flux (b), evaporation rate (c), and Bowen ratio (d) for uncovered and partially covered reservoir with black and white Styrofoam discs for the FLUXNET data from Majadas, Spain (March 2004 to March 2005). Mean daily incoming solar radiation is marked in (a).

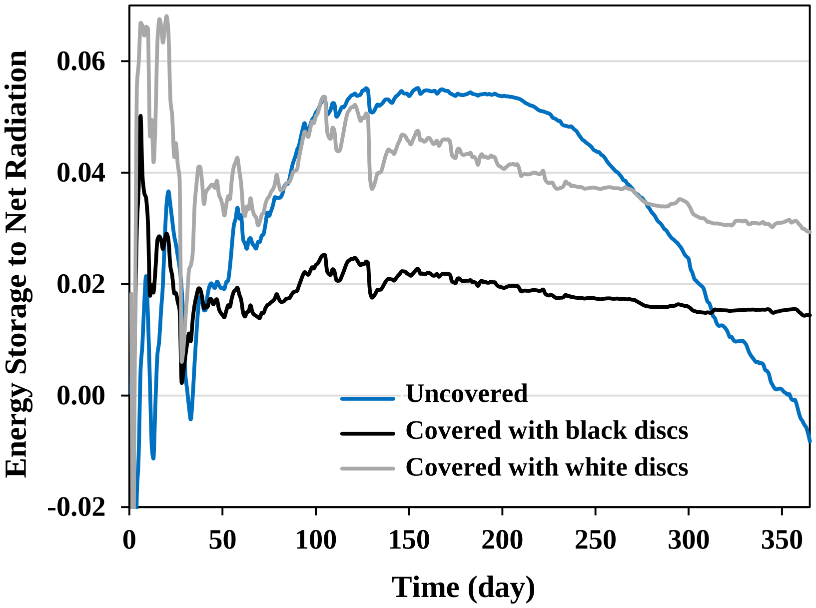

Figure 9: Model estimates of changes in the ratio of energy storage in the water body to the net radiative flux at the surface of uncovered and partially covered hypothetical 10 m deep reservoir (Majadas, Spain). The heat storage is calculated relative to reference state at the beginning of the water year. Following an equilibration period, the ratio follows the annual variations in the radiative flux for the uncovered reservoir, whereas for the partially covered surface, the ratio remains nearly constant.

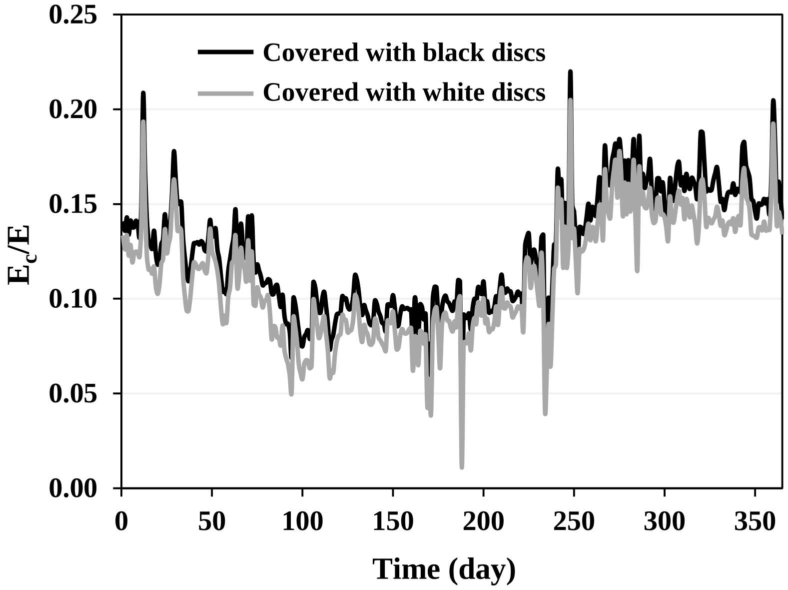

Figure 10: The ratio of evaporation from covered (E_c) to uncovered water reservoir (E) representing evaporation suppression efficiency of floating elements (for the meteorological conditions in Majadas, Spain from March 2004 to March 2005).

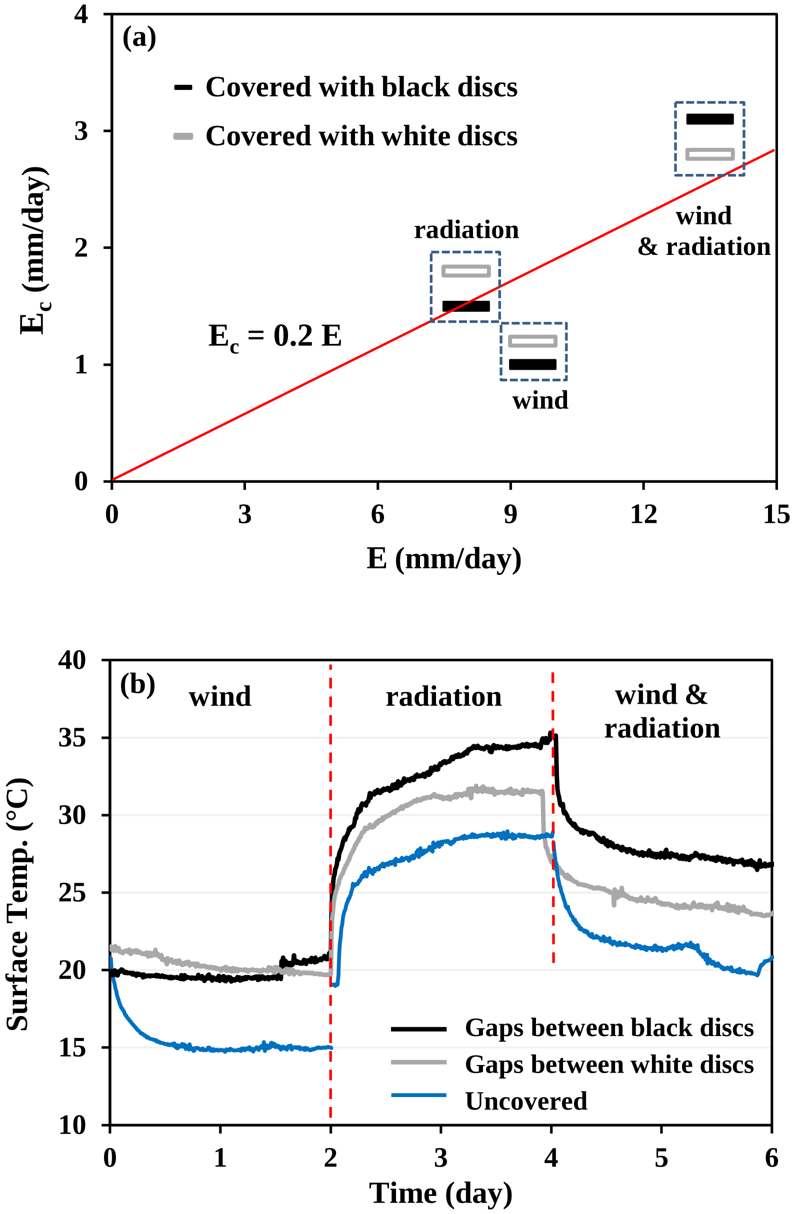

Figure 11: Laboratory results for a small water basin covered with floating discs of 0.2 m diameter. (a) The ratio between evaporation from covered and uncovered reservoir is about 0.2, corresponding to suppression efficiency of about 80%. (b) Surface temperature of uncovered water reservoir and gaps between white and black discs obtained from IR measurements.

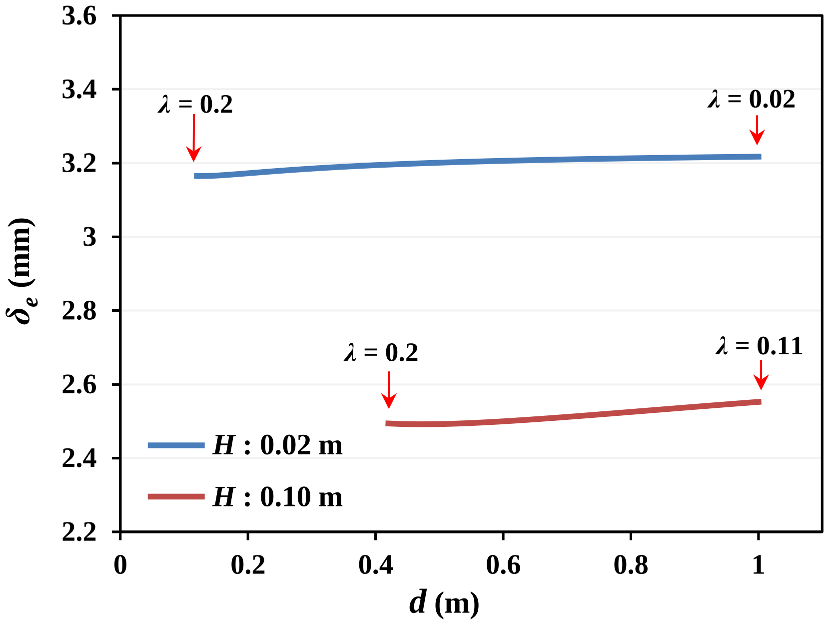

Figure A1: Variation of effective boundary layer thickness with disc diameter (*d*) for different disc heights (*H*) at wind speed of 1 m/s and surface coverage of 0.91 (dense packing). The increase of λ more than 0.2 forms relatively thick boundary layer in the order of disc height. For *U*=1 m/s, the boundary layer thickness over uncovered surface is calculated as 3.2 mm based on Haghighi and Or (2013).

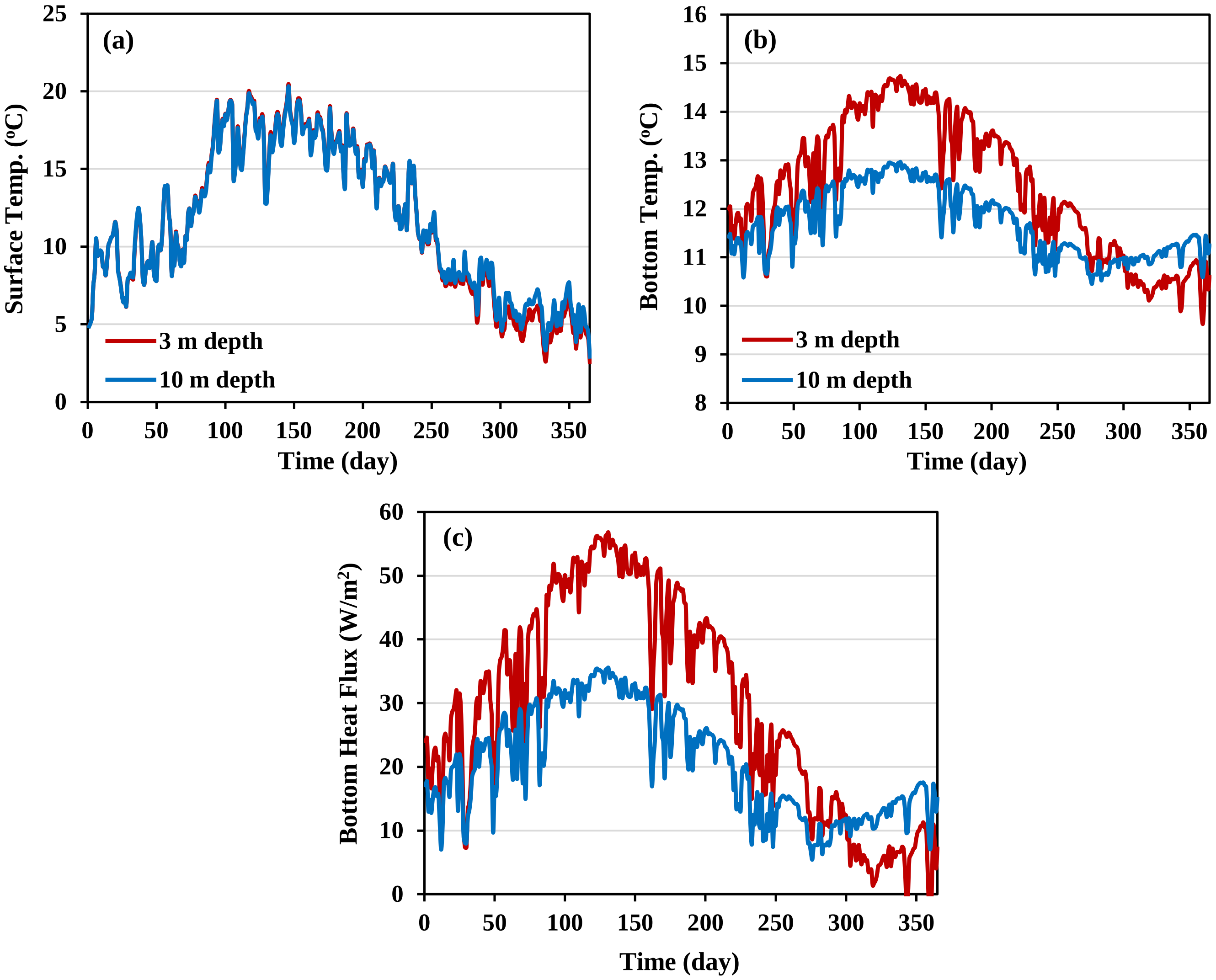

Figure B1: The effect of reservoir depth on surface (a) and bottom (b) temperature of the uncovered reservoir considering bottom heat flux towards the underlining soil layer (c); T_{sZ} was assumed at 10 ^{o}C.