

# Impact of micrometeorological conditions on the efficiency of artificial monolayers in reducing evaporation

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## Abstract

Monolayer products can potentially provide a cost effective solution for reducing evaporative loss from water storages. Commercial adoption has been low, due to the extreme variability of product performance. In this study, the efficiency of three monolayer compounds (stearyl alcohol, ethylene glycol monooleate and the commercial product WaterSavr) in reducing evaporation were tested at three controlled wind speeds inside a glasshouse in class-A evaporation pans. Water levels and micrometeorological conditions were monitored to document the impact of prevailing atmospheric conditions on monolayer performance. The evaporation reduction ranged from 13 to 71% depending on the product and micrometeorological conditions. The ethylene glycol monooleate was most effective reducing evaporation across all wind speeds.

Atmospheric conditions markedly affected monolayer products' performance. All monolayers were most effective when the wind was sufficient to drive evaporative loss but lacked the force to disrupt the condensed monolayer ( $1.5\text{ m s}^{-1}$ ). Continuous wind of  $3\text{ m s}^{-1}$  disrupted the condensed monolayer and substantially decreased the product performance. Without wind, the resistance to evaporation induced by monolayers had little additional effect. When atmospheric evaporation demand was very low, the evaporation suppression efficiency was minimized. High temperatures and high incoming radiation negatively affected the persistence of the condensed monolayer and decreased product performance. These results highlight the importance of analysing micrometeorological conditions when assessing product performance.

**Key words:** *evaporation suppression; water conservation; stearyl alcohol; WaterSavr; ethylene glycol monooleate.*

# 1 Introduction

Population growth and increase in living standards have led to a marked increase in water demand. To sustain food production over the next 50 years, improvements in water use efficiency are essential (de Fraiture and Wichelns 2010). Water lost from reservoirs through evaporation is unrecoverable and undesirable (Carter et al. 1999). In climates with high solar radiation and high vapour pressure deficit, evaporative loss may account for a high percentage of the total water stored in reservoirs (Martinez Alvarez et al. 2008; Mugabe et al. 2003). In many areas of Australia, up to 40% of the water stored in reservoirs can be lost through evaporation (Craig et al. 2005). The annual evaporation loss can exceed the total water consumed for domestic and industrial purposes (Gökbülak and Özhan 2006; Martinez-Granados et al. 2011). Reducing evaporative loss from water storages has the potential to significantly improve water use efficiency.

Physical structures such as floating covers (Daigo and Phaovattana 1999), suspended covers (Martinez-Alvarez et al. 2010), protective floats (Segal and Burstein 2010) or windbreaks (Hipsev and Sivapalan 2003) can be deployed to reduce evaporation. However, the capital outlay is considerable, and the efficacy of physical structures in reducing evaporative loss is restricted to small storages of less than about 10 ha (Craig et al. 2005). The application of chemical products to the water surface that create an artificial surface film one or several molecules thick has been investigated since the 1920's (Frenkiel 1965), with many laboratory trials confirming reductions in evaporative loss (Barnes 2008). Monolayer products could be a cost effective solution for evaporation mitigation, in particular for large storages where the installation of physical structures is not feasible. Commercial adoption is expected to increase with the adoption of systems that can automatically detect the presence of monolayer over the water surface (Coop et al. 2011) and Universal Design Frameworks (UDF) to optimise the use of monolayer materials for evaporation mitigation (Brink 2011).

The most commonly used monolayer molecules are the 16 and 18 carbon chain (C16, C18) length alkanes, cetyl alcohol and stearyl alcohol. These materials spontaneously spread when applied to water, to create a surface film that increases the evaporative resistance. Two evaporation suppression mechanisms have been postulated for monolayers: (i) increased surface resistance through the orderly packing of the molecules, and (ii) calming of the surface capillary waves, which reduces surface roughness. In practice, the evaporation reduction performance of a monolayer is affected by wind drag and volatilization (Fietz 1959), and interactions with dust particles, natural microlayers and aquatic microorganisms (Pittaway and van den Ancker 2010). Susceptibility to wind drag, volatilisation and microbial degradation can be reduced by increasing the chain length of the hydrophobic carbon tail of the monolayer molecule, and/or by substituting the hydrophilic head-group from a fatty alcohol to an ether and hydroxyl functional group (Barnes 2008; Pittaway and van den Ancker 2010). The performance of monolayers in reducing evaporative loss is highly variable, ranging from 0 to 43% according to a review by McJannet et al. (2008). Under field conditions, the vapour pressure deficit, solar radiation, water and air temperatures and water quality vary dynamically in time and with location, contributing to the observed variability in monolayer performance (Barnes 2008). To objectively document the performance of a monolayer, the following must be

1 considered (Hancock et al. 2009): (i) the prevailing atmospheric conditions, (ii)  
2 accuracy of water loss measurements (sensitivity of equipment, accounting for  
3 seepage losses), (iii) the quality of the water (interaction of the monolayer with  
4 biological processes). In addition, when comparing monolayer performance trials  
5 conducted in experimental tanks with those in big reservoirs, wave action needs to  
6 be accounted for.

7 In this study, the performance of three monolayer products applied to  
8 potable water contained in class-A standard evaporation pans was compared,  
9 under three controlled wind speeds inside a glasshouse in south-eastern  
10 Spain. Very accurate water level sensors were installed to provide continuous data  
11 on water loss, and solar and atmospheric radiation, air, surface and subsurface  
12 water temperatures and relative humidity were monitored for the duration of each  
13 experiment to document the impact of prevailing atmospheric conditions on  
14 monolayer performance. Potable water was used throughout the trials to limit the  
15 impact of water quality on monolayer performance, with tanks rigorously cleaned  
16 prior to the commencement of each trial. The selected monolayer products  
17 included two long-chain 18 carbon alkanes, stearyl alcohol ( $C_{18}H_{38}O$ , abbreviated  
18 to C18OH) and ethylene glycol monooleate ether ( $C_{20}H_{42}O_2$ , abbreviated to  
19 C18E1). The commercial product WaterSavr, formulated as a powdered mixture  
20 of C16OH ( $C_{16}H_{34}O$ , 5%) and C18OH (5%) in hydrated lime (calcium oxide,  
21 90%), was used as a performance benchmark, as this formulation has been widely  
22 used in field trials. Evaporation reductions of about 20% have been reported,  
23 ranging from 0% to 40% depending on prevailing environmental conditions  
24 (Knights 2005). C18OH has also been deployed in field trials for evaporation  
25 mitigation research (Frenkiel 1965). Therefore, it provides a point of reference for  
26 comparison with prior investigations. Numerous studies reporting the evaporation  
27 mitigation performance of C18OH have been published, a good summary of  
28 which can be found in McJannet et al. (2008). C18E1 has been reported to  
29 outperform C16OH and C18OH in reducing evaporative loss, under both still and  
30 windy conditions (Deo et al. 1960; Shukla and Kulkarni 1962). The molecule has  
31 the same carbon chain length as C18OH, but contains a larger ether and hydroxyl  
32 hydrophilic head group instead of an alcohol (McMurry 2004).

## 33 34 35 36 37 38 39 40 41 42 **2 Materials and methods**

### 43 44 **2.1 Experimental facilities and data collection**

45 The trial was carried out in a glass-covered, double continuous roof-vented  
46 greenhouse (north-south orientation), located at the Experimental Station of the  
47 University of Cartagena in south-eastern Spain (37°35'N, 0°59'W). The total floor  
48 area of the greenhouse was 197 m<sup>2</sup> (15.40 m x 12.80 m), the height to the eaves  
49 was 4m, and ridge height was 6 m.

50 Two standard class-A evaporation pans were used: Tank C refers to the  
51 control and Tank M to the monolayer treatment. Each tank was equipped with one  
52 water level sensor (Magnetostrictive Position Sensors C-series, Temposonics,  
53 accuracy:  $\pm 0.15$  mm), two water temperature probes (T-107, Campbell), one  
54 located on the base of the tank and another 5 mm below water surface (attached to  
55 a float) and one anemometer to measure wind speed placed 0.25 m above water  
56 surface (A100R, Vector Instruments) (Fig. 1).

1 The climatic conditions inside the greenhouse were continuously  
2 monitored: solar radiation (CMP 6 pyranometer, Kipp & Zonen), incoming long-  
3 wave radiation (CGR 3 pyrgeometer, Kipp & Zonen), temperature and relative  
4 humidity of air (HMP155 probe, Vaisala). All sensors were scanned at 10 s  
5 intervals, averaged hourly and recorded on a datalogger (CR1000, Campbell).

6 Four fans were positioned above the floor of the glasshouse, to control the  
7 wind speed blowing across both tanks. Three wind speeds, 0 m s<sup>-1</sup>, 1.5 m s<sup>-1</sup>, 3 m  
8 s<sup>-1</sup>, were maintained continuously in each trial. At the beginning of each product  
9 trial, the tanks were cleaned and topped up with potable water to a standard depth  
1 of 20 cm. No extra water was added over the duration of each wind speed trial  
11 (one week). The duration of each monolayer product trial was three weeks, with  
12 the three wind speed conditions applied in series.  
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## 15 **2.2 Monolayer formulation and application**

17 Application rates for C18 monolayers (C18OH and C18E1) were calculated at six  
18 times (6x) the monomolecular amount of material required per m<sup>2</sup> of water  
1 surface (force-area isotherm) to reach equilibrium surface pressure (Reiser 1969;  
20 Timblin et al. 1962). They were dissolved in ethanol at a rate of 20 mg ml<sup>-1</sup>, and  
21 applied to the water surface of Tank M using a micropipette (LM5000, HTL Lab  
22 Solutions) at 13.8 mg m<sup>-2</sup> and 16.2 mg m<sup>-2</sup> respectively. Note that in the field,  
23 application rates >1x are necessary in order to compensate for material losses  
24 (Frenkiel 1965; Reiser 1969; Crow and Mitchell 1975). The monolayer  
25 formulation should be dosed at a rate matching the rate at which it is lost from the  
26 water surface, which can be estimated by means of UFD (Brink 2011).  
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29 WaterSavr was applied as a powder to the water surface, at the manufacturers  
30 recommended application rate (100 mg m<sup>-2</sup>). Each experiment lasted one week,  
31 with the monolayer applied on day 1 and thereafter every second day. The  
32 products were applied at 9 am.  
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## 37 **2.3 Data analysis**

38 The performance of each monolayer in reducing evaporation under each  
39 prevailing wind speed was calculated as the daily evaporation Reduction Factor  
40 (RF, %) and as the water saved or Total Reduction in evaporation (TR, mm day<sup>-1</sup>),  
41 calculated as follows:  
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$$44 \quad TR = E_C - E \quad (1)$$

$$45 \quad RF = \frac{E_C - E_M}{E_C} 100 \quad (2)$$

46  
47 where  $E_C$  and  $E_M$  (mm day<sup>-1</sup>) are the depths of evaporated water on a daily  
48 basis from Tank C and Tank M, respectively.  
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50 As the product trials were conducted in series, changes in the atmospheric  
51 conditions over the duration of the experiment imposed different evaporative  
52 demands. Reduction factors were calculated to provide cross-experiment  
53 comparisons results by dividing the TR value (Eq. 1) by the evaporation of the  
54 untreated tank (Tank C), and expressing the result as a percentage (Eq. 2).  
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56 The impact of the monolayer in reducing latent heat loss was assessed by  
57 regressing the difference in averaged daily surface water temperature between  
58 Tank M and Tank C ( $\Delta T_s$ , water heating induced by the monolayer) against the  
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1 corresponding RF values. The impact of the monolayer on transport processes was  
2 assessed by plotting the averaged hourly difference in water temperature of Tank  
3 M between the surface (floating sensor, temperature measured at 5 mm depth,  $T_s$ )  
4 and subsurface (temperature measured at the base of the tank,  $T_w$ ) against the  
5 averaged hourly difference in the air temperature ( $T_a$ ) and  $T_w$  (Gladyshev 2002).  
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9 **Fig. 1** Experimental design and instrumentation: (a) Sensors in each tank and (b) general  
10 distribution. The tanks are standard class-A (diameter: 1.2 m and 0.25 m depth, over a 0.15 m  
11 wooden platform)  
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## 15 **3 Results and discussion**

### 16 **3.1 Efficiency of monolayers in reducing evaporative loss under** 17 **different wind speeds**

18 Wind speed had a major impact on the efficiency of all monolayers in reducing  
19 evaporation (Fig. 2). C18E1 provided the best performance (RFs of 40, 71 and  
20 58% for winds at 0, 1.5 and 3 m s<sup>-1</sup> respectively, Fig. 2b), substantially  
21 outperforming the other products for wind at 3 m s<sup>-1</sup>. WaterSavr provided similar  
22 RFs to C18E1 under calm and light wind (1.5 m s<sup>-1</sup>) conditions (41 and 68%  
23 respectively), but with wind at 3 m s<sup>-1</sup> the reduction in evaporative loss was  
24 significantly lower (RF = 20%). C18OH was least effective (RFs: 13, 58 and 32%  
25 for winds at 0, 1.5 and 3 m s<sup>-1</sup> respectively).  
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31 All three monolayer formulations performed best with the wind at 1.5 m s<sup>-1</sup>.  
32 Under light winds, the presence of a condensed monolayer increases the surface  
33 resistance and calms capillary waves, effectively retarding evaporation. Winds  
34 below 2.2 m s<sup>-1</sup> lack the power to disrupt a condensed monolayer (Fitzgerald and  
35 Vines 1963). In the absence of wind the water is expected to stratify and produce  
36 a thermally stable warm surface film (Katsaros 1980) in both tanks (control and  
37 treatment). Under these conditions, a thick vapour diffusion layer is also created  
38 just above the surface which limits evaporation from both tanks. Therefore, the  
39 transport resistance was already high in the untreated water surface and the  
40 presence of a monolayer had minimal additional effect. The reduction in  
41 evaporative loss recorded for all monolayers under calm conditions was  
42 significantly lower than at 1.5 m s<sup>-1</sup>. At 3 m s<sup>-1</sup> the wind disrupted the monolayer,  
43 reducing the RF for all three monolayers below the RF values recorded at 1.5 m s<sup>-1</sup>  
44 (Fig. 2b). The C18E1 monolayer performed best under windy conditions, which  
45 is consistent with published reports (Deo et al. 1962, Shukla and Kulkarni 1962).  
46 C18E1 spreads rapidly over the water surface to produce a high equilibrium  
47 surface pressure (48.9 mN m<sup>-1</sup> at 25°C), and is more resistant to volatilisation and  
48 wind than monolayer molecules with a fatty alcohol head-group. WaterSavr  
49 showed the poorest performance with wind at 3 m s<sup>-1</sup>, explained in part by the  
50 higher rate of volatilisation of the C16OH component of the formulation at higher  
51 wind speeds. The fractional loss of C16OH due to volatilisation is linearly related  
52 to wind speed (Mansfield 1958).  
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**Fig. 2** (a) Total Reduction of evaporation (water conserved, TR, Eq. 1) and (b) evaporation  
Reduction Factor (RF, Eq. 2) for continuous wind speeds of 0, 1.5 and 3 m s<sup>-1</sup>: The circles  
represent weekly means of daily values and the bars the range of variation

### 3.2 Impact of inter-trial climatic variability on monolayer performance

Controlling wind speed standardised one important driving force of evaporation, but the other drivers varied considerably over the duration of the trial (Fig. 3). During the first week, when C18OH was tested in the absence of wind, substantially warmer temperatures and higher levels of incoming radiation prevailed (Fig. 3a, b). Daily and hourly average maximum water surface temperature in Tank M were 29.9 °C and 35.7 °C respectively, higher than at any other time during the trial (daily and hourly average maximum water surface temperatures for WaterSavr and C18E1 were 22.7 °C and 28.2 °C and 21.1 °C and 27.0 °C respectively, for no wind trials). Higher water temperatures enhance volatilisation, with the shorter chain C16OH molecules more susceptible than the longer C18OH molecules (Brooks and Alexander 1960). Between water temperatures of 5-20 °C the fractional loss of monolayers increases gradually, whereas from 20-40 °C the fractional loss is more rapid. A greater rate of volatilisation of C18OH due to the higher water temperatures may in part explain the poorer performance of C18OH for calm conditions (Fig. 2).

Incoming radiation progressively declined over the duration of the trial (Fig. 3b). The evaporative demand (water-to-air vapour pressure deficit, Fig. 3c) was lowest during the final two weeks of the WaterSavr trial. The reduction in this evaporation driver was responsible for the low values of total conserved water recorded for WaterSavr (Fig. 2a). Standardising data for inter-trial microclimatic variation (RF factors, equation 2), elevates the performance of WaterSavr above that of C18OH with winds of 1.5 m s<sup>-1</sup> (Fig. 2b).

Within each week of the trial, there were also day-to-day variations in atmospheric evaporative demand. The wider range of variation in daily water-to-air VPD was observed when C18E1 was tested under calm conditions (Fig. 3c). The efficacy of C18E1 in reducing evaporative loss (RF factor) under calm conditions was linearly related to the water-to-air VPD (Fig. 4). RF dropped from 60%, at water-to-air VPD of 2.09 kPa, to 5% for 0.95 kPa.

**Fig. 3** Climate conditions inside the trial's glasshouse (a) Air Temperature, (b) Incoming short-wave Radiation and (c) water-to-air Vapour Pressure Deficit (evaporation driving force) of control tank. The circles represent the weekly means of daily values and the bars the range of variation

**Fig. 4** Regression between evaporation reduction factor (RF) and water-to-air Vapour Pressure Deficit of Tank M with C18E1 under calm conditions

### 3.3 Impact of monolayers on water temperature

The presence of a condensed monolayer on the water surface alters the heat transfer process between the surface and the surrounding atmosphere (Gladyshev 2002). The monolayer hinders the cooling of the surface by reducing latent heat lost through evaporation, effectively increasing the water temperature. Increases in daily water temperature varying from 3.0 to 4.4 °C in summer to only 1.0 °C in winter have been measured (Harbeck and Koberg 1959) and modelled (McJannet et al. 2008). Significant linear regressions for RF values and daily surface water temperature were obtained for all monolayer products when results for all three wind conditions were pooled ( $R^2$  values of 0.80, 0.89 and 0.73 for C18E1, C18OH and Watersavr respectively, Fig. 5). These relationships show the proportional

1 increase in  $\Delta T_s$ , (water heating induced by monolayer) as the monolayer reduces  
2 the latent heat loss.

3 The gradients of the linear regression for the three monolayer products  
4 differed, reflecting the change in meteorological conditions over the duration of  
5 the trial. The surface temperature of the water is influenced by latent heat loss, as  
6 well as the heat fluxes due to radiation and convection. The convective air-to-  
7 water heat flux is a function of the difference between the air and water  
8 temperature, and wind speed (Oke 1987). Wind speed was held constant in our  
9 experiments, but the other variables were not. Whilst the application of  
1 monolayers reduced latent heat loss, increasing the average daily temperature of  
11 the water surface, the averaged hourly difference between the temperature of the  
12 water surface and the surrounding air varied diurnally. Under warmer and higher  
13 radiation conditions the increase of temperature induced by the monolayer ( $\Delta T_s$ )  
14 was higher, which is in agreement with McJannet et al. (2008) who predicted  
15 higher  $\Delta T_s$  in the warm season. The gradient for C18OH was greatest (up to 4 °C,  
16 Fig. 5), reflecting the higher air temperatures and incoming radiation that occurred  
17 over the first three weeks of the trial (Fig. 2a). Air temperature and incoming  
18 radiation was consistently lowest over the last two weeks of the trial, when  
19 WaterSavr was being tested with wind at 1.5 and 3 m s<sup>-1</sup>, which is consistent with  
20 the smaller gradient for this product (Fig. 5). The increase of water temperature  
21 caused by monolayer presence may negate some of the potential effects of  
22 monolayer over longer time periods. Warmer water temperatures would enhance  
23 evaporation under the right conditions which include high radiation input and  
24 strong winds (McJannet et al. 2008). Besides, it is worth to mention here, that this  
25 increase of water temperature can have an impact in water quality.

26 The increase in the daily water temperature in the presence of monolayer  
27 was not cumulative. On diurnal basis, the air temperature remained above the  
28 water temperature during daylight hours when incoming radiation was greatest,  
29 but dropped below the temperature of the water overnight (Fig. 6). During the  
30 night, the surface heating associated with monolayer application was reduced,  
31 suggesting that proportionally more heat was lost from the monolayer-covered  
32 tank, or heat gain was greater in the control tank. Therefore, some of the gain  
33 during day can be offset by a greater nocturnal loss (i.e. greater loss through  
34 sensible heat flux and outgoing longwave).

35 **Fig. 5** Regression lines between evaporation reduction factor (RF) and the differences in daily  
36 water surface temperature between Tank M and C ( $\Delta T_s = T_{s,M} - T_{s,C}$ ) for each monolayer for all  
37 wind scenarios

38 **Fig. 6** Hourly variation of temperature of air ( $T_a$ ), water surface ( $T_s$ ) and subsurface ( $T_w$ ) of a  
39 representative day of Tank M with C18OH with continuous wind of 1.5 m s<sup>-1</sup>

### 40 **3.4 Effect of monolayers on the water surface film temperature**

41 The presence of a monolayer limits the heat flux between the surface film and the  
42 air, and influences the convective fluxes (Bower and Saylor 2011). Under a  
43 positive downward convective flux ( $T_a > T_s$ ), monolayers retard heat conduction  
44 from the warm surface to the colder subsurface, warming the surface film which  
45 increases the stability of the liquid thermal boundary layer (LTBL, Gladyshev  
46 2002). Temperature differences between the surface film and subsurface water ( $T_s$ )

–  $T_w$ ) were plotted against the difference between the air and subsurface water ( $T_a - T_w$ ) for the three wind scenarios (Fig. 7).

During daytime when  $T_a - T_w$  was positive (Fig. 6),  $T_s - T_w$  for the monolayer tank was greater than the control (Fig. 7), reflecting the increase in surface water temperature as the monolayer progressively reduced evaporation. The difference between the surface deviation temperature of the monolayer and control tanks was proportionally greater as  $T_a - T_w$  increased, and this was proportionality affected by wind speed. The difference between the surface deviation temperatures for the monolayer and the control tanks was greatest with a wind speed of  $1.5 \text{ m s}^{-1}$ . Increasing wind to  $3 \text{ m s}^{-1}$  substantially reduced  $T_s - T_w$  for both tanks across all values of  $T_a - T_w$ , indicating that wave turbulence had not only disrupted the monolayer, but had also increased forced convection and mixed the water profile (Katsaros 1980). For  $T_a - T_w > 0$  in absence of wind, the surface deviation temperature ( $T_s - T_w$ ) for tanks M and C increased as  $T_a - T_w$  increased, but the difference between tanks M and C was much less than when the wind was at  $1.5 \text{ m s}^{-1}$  (Fig. 7). These results suggest that the monolayer was still effective in reducing evaporative loss, but the reduction attributed to the monolayer was proportionally much less since the resistance to evaporative loss was greater. The thermal stability of a warm surface film increases the resistance to interfacial heat transfer, reducing the evaporation (Eames et al. 1997).

During the night when the air temperature was below the subsurface water temperature ( $T_a - T_w < 0$ , upward convective flux, Fig. 6), the presence of monolayer had almost no impact on  $T_s - T_w$ , under all wind conditions. In this study the range of values for  $T_s - T_w$  with  $T_a - T_w < 0$  was limited (0 to  $-9$ , compared with 0 to 25 for  $T_a - T_w > 0$ ), and the temperature of the water surface was generally warmer than the subsurface. In other studies the linear relationship between  $T_a - T_w$  and  $T_s - T_w$  continued when  $T_a - T_w < 0$  (Gladyshev 2002), as a cold film developed on the water surface ( $T_s - T_w < 0$ ). Under the prevailing conditions of our trial, the presence of a condensed monolayer had no substantive impact on  $T_a - T_w$  with  $T_s - T_w > 0$ . If the microclimatic conditions in the glasshouse were conducive to the formation of a cool surface film ( $T_a - T_w < 0$  with  $T_s - T_w$  also  $< 0$ ), the resistance of the LTBL would have been less (Wells et al. 2009), and the presence of a condensed monolayer may have exerted a greater impact on reducing evaporation.

**Fig. 7** Temperature difference between water surface and subsurface water vs. temperature difference between the air and the water surface ( $T_s - T_w$  vs.  $T_a - T_s$ ) for continuous wind of 0, 1.5 and  $3 \text{ m s}^{-1}$ . Hourly values for (●) Tank C and (□) Tank M with (a) C18OH (b) C18E1 (c) WaterSavr. The lines correspond to second-order polynomial regressions, black line for Tank C and grey line for Tank M.

## 4 Summary and Conclusions

The efficacy of three monolayers in reducing evaporation was tested under three controlled wind speeds inside a glasshouse, using class-A pans filled with potable water. Our results indicate that the impact of prevailing atmospheric conditions on monolayer performance may in part explain the high variability of results in field trials. Evaporation reduction factors varied from 13 to 71%, depending on the product and the prevailing micrometeorological conditions. The monolayer C18E1 was the most efficient in reducing evaporation and provided the greatest



1 resistance to wind disruption, which is consistent with previous reports (Shukla  
2 and Kulkarni 1962).

3 The greatest impact of all monolayers in reducing evaporation (RFs of 71,  
4 68 and 58% for C18E1, WaterSavr and C18OH, respectively) occurred when the  
5 wind speed was sufficient to drive evaporative loss but lacked the force to disrupt  
6 the condensed monolayer (wind speed at  $1.5 \text{ m s}^{-1}$ ). Provided the temperature of  
7 the air was above that of the water ( $T_a > T_w$ ), retardation of transport processes  
8 within the surface layer contribute to evaporation suppressant effect. In the  
9 absence of wind, the evaporation reduction efficacy of all monolayers was least.  
1 The presence of a condensed monolayer increased the resistance at the air-water  
11 interface, but the thick vapour diffusion layer that is created above the surface and  
12 the resistance imposed by a thermally stable warm surface film in the absence of  
13 wind was already high, with monolayer application having little additional effect.  
14 Increasing wind speed to  $3 \text{ m s}^{-1}$  substantially reduced the performance of the two  
15 fatty alcohol monolayer products (C18OH and WaterSavr), whereas the greater  
1 stability of the ether hydroxyl headgroup of C18E1 provided better wind  
17 resistance (Brooks and Alexander 1960). WaterSavr showed the poorest  
18 performance, which may be attributed to the higher rate of volatilisation of the  
19 C16OH component of the formulation. Winds of  $3 \text{ m s}^{-1}$  induced water  
20 turbulence, increasing forced convection and mixing the water profile.

21 High temperatures and incoming radiation negatively affected the  
22 persistence of the condensed monolayer and decreased product performance. As  
23 expected, the evaporation reduction factor was proportional to the average daily  
24 increase in water temperature induced by monolayer application, but this  
25 proportion also varied with meteorological conditions since surface temperature is  
26 also a result of the heat fluxes due to radiation and convection. For warmer and  
27 higher radiation conditions the increase in temperature induced by the monolayer  
28 was higher. The evaporation suppression efficiency was also observed to be  
29 correlated with on water-to-air VPD, and thus when atmospheric evaporation  
30 demand is very low, the imposition of a monolayer may have little effect on  
31 evaporation reduction.

32 The fact that the monolayer products tested, with C18OH and C18E1  
33 applied at 6x dose, have shown the best performance for rather low wind  
34 conditions ( $1.5 \text{ m s}^{-1}$ ) raise concerns about their potential efficacy in outdoors  
35 water storages where higher winds prevail. To properly assess whether these  
36 products can provide a cost effective solution for reducing evaporative loss from  
37 water storages or not, further detailed and accurate field trials (reservoir scale) are  
38 required. The optimal performance dose for different scenarios is one of the key  
39 missing information for such analysis. These scenarios should account for wind  
40 speed (and related wave action), radiation, water-to-air VPD, water temperature  
41 and water quality. Once the optimal doses were known for each situation as well  
42 as the associated evaporation reduction efficacy, the economic feasibility could be  
43 evaluated. Autonomous application systems should integrate a UDF to optimise  
44 monolayer application and maximize evaporation suppressing performance of  
45 monolayer products.

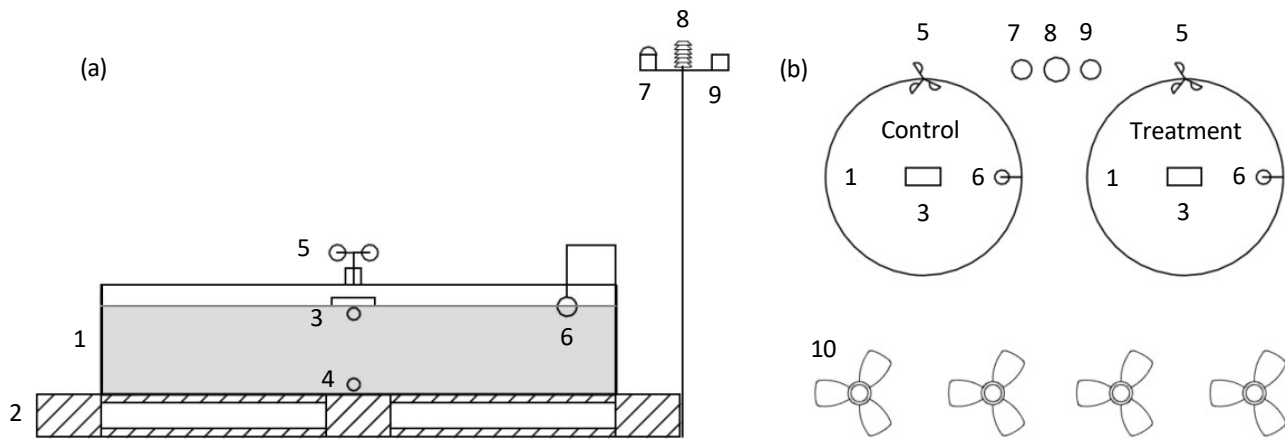
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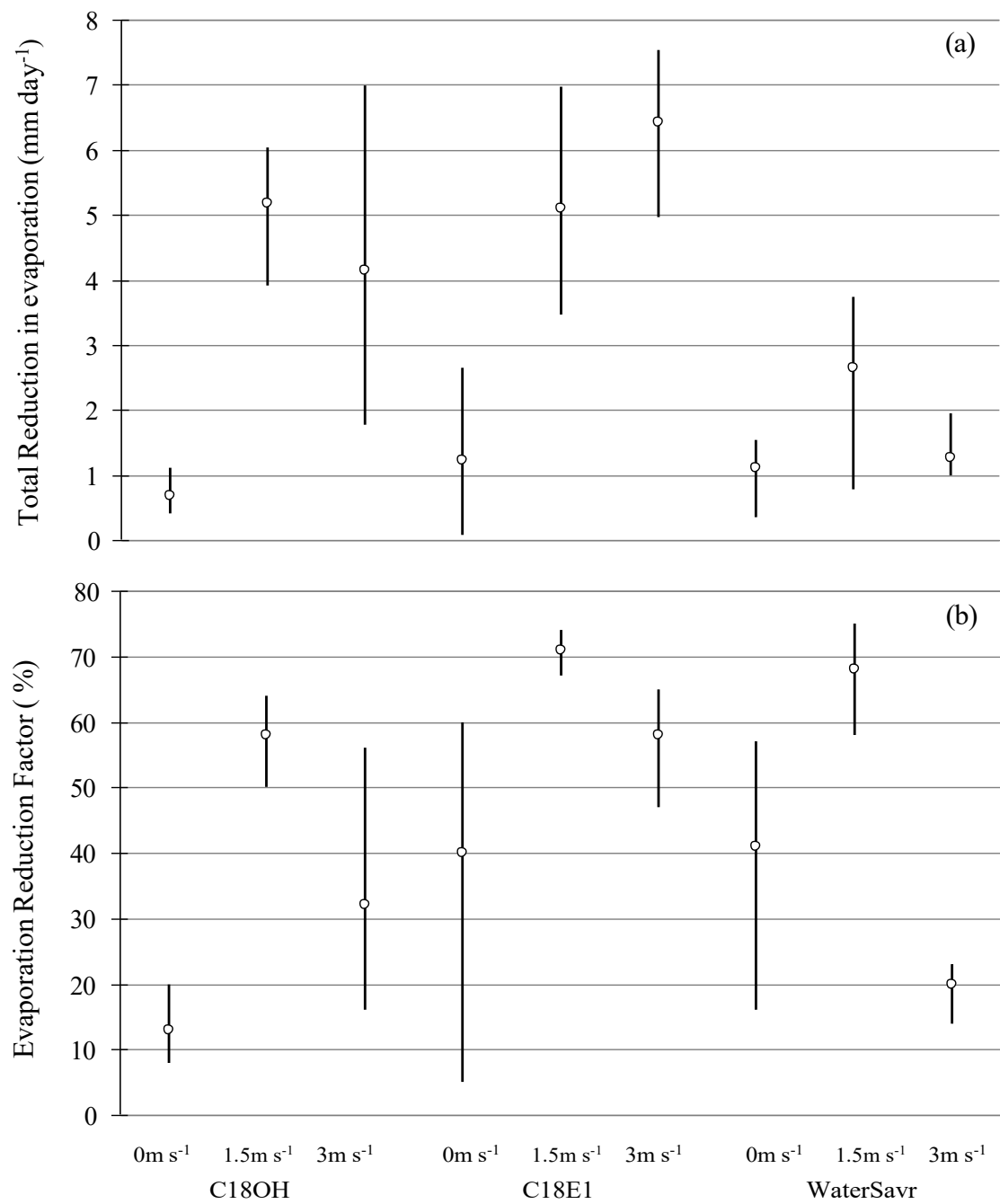
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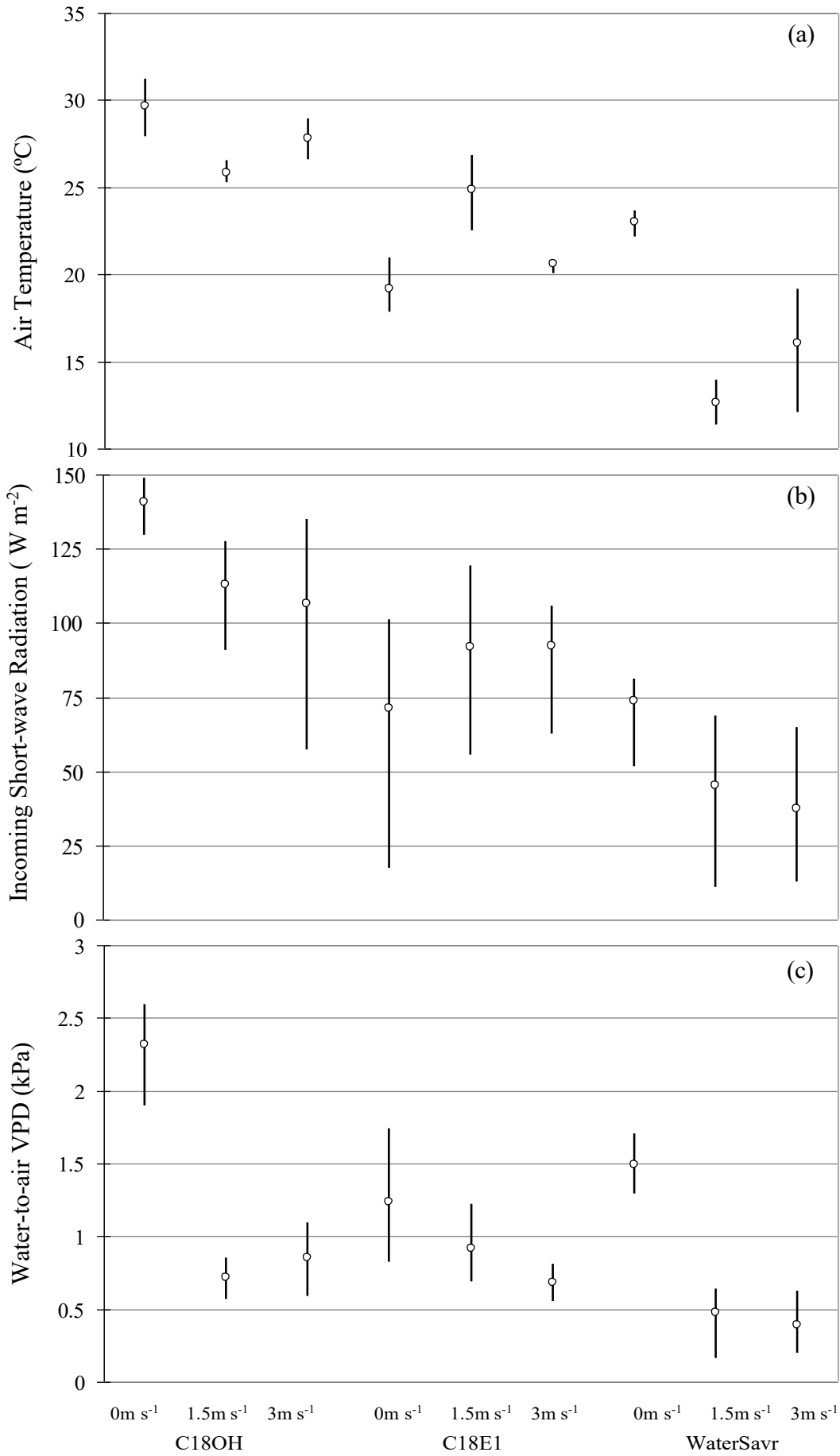


1: Standard class A tank, 2: Wooden platform, 3: Floating temperature sensor, 4: Temperature sensor on tank base, 5: Anemometer, 6: Water level sensor, 7: Pyranometer, 8: Temperature and relative humidity probe, 9: Pyrgeometer, 10: Fans.

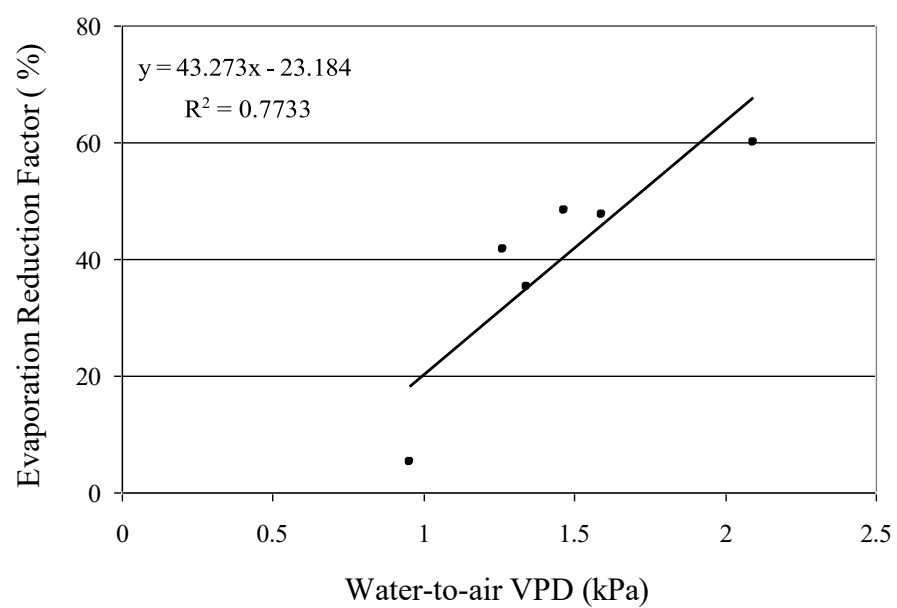
**Fig. 1** Experimental design and instrumentation: (a) Sensors in each tank and (b) general distribution. The tanks are standard class-A (diameter: 1.2m and 0.25m depth, over a 0.15m wooden platform)



**Fig. 2** (a) Total Reduction of evaporation (water conserved, TR, Eq. 1) and (b) evaporation Reduction Factor (RF, Eq. 2) for continuous wind speeds of 0, 1.5 and 3 m s<sup>-1</sup>: The circles represent weekly means of daily values and the bars the range of variation

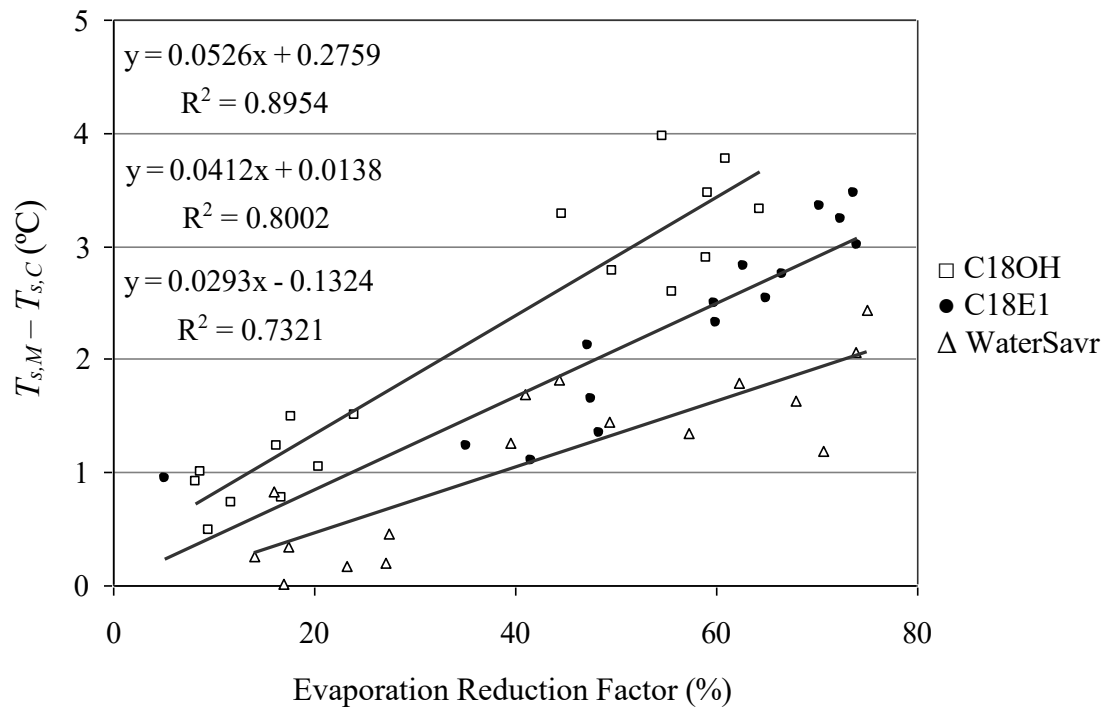


**Fig. 3** Climate conditions inside the trial's glasshouse (a) Air Temperature, (b) Incoming short-wave Radiation and (c) water-to-air Vapour Pressure Deficit (evaporation driving force) of control tank. The circles represent the weekly means of daily values and the bars the range of variation

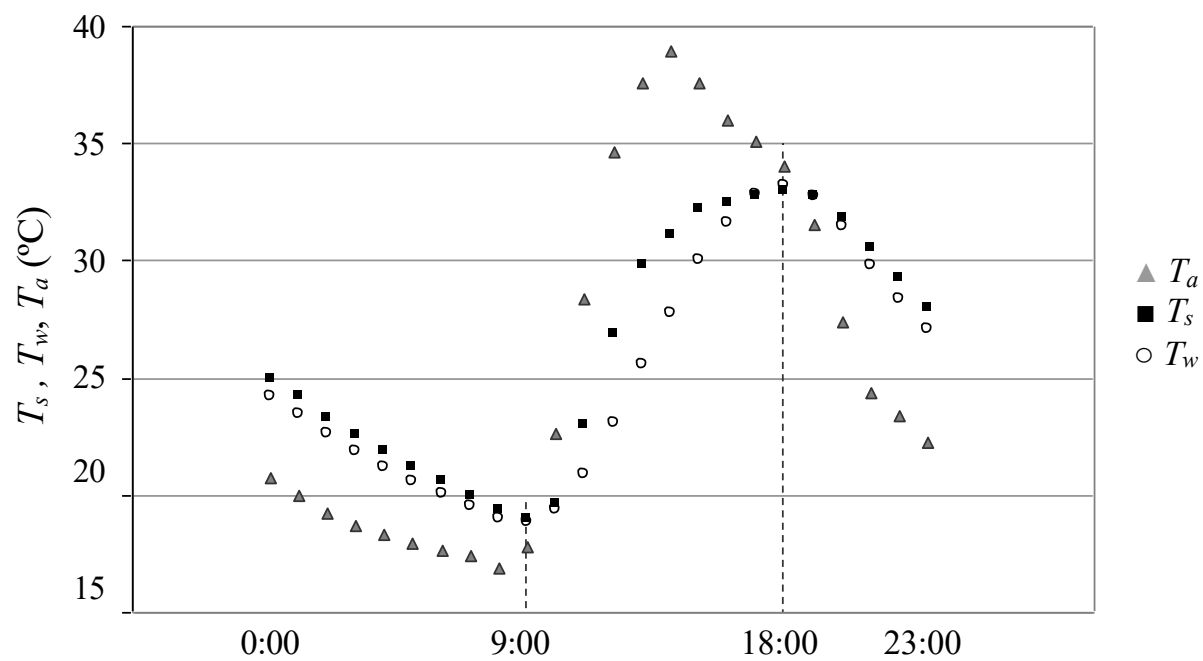


**Fig. 4** Regression between evaporation reduction factor (RF) and water-to-air Vapour Pressure Deficit of tank M with C18E1 under calm conditions





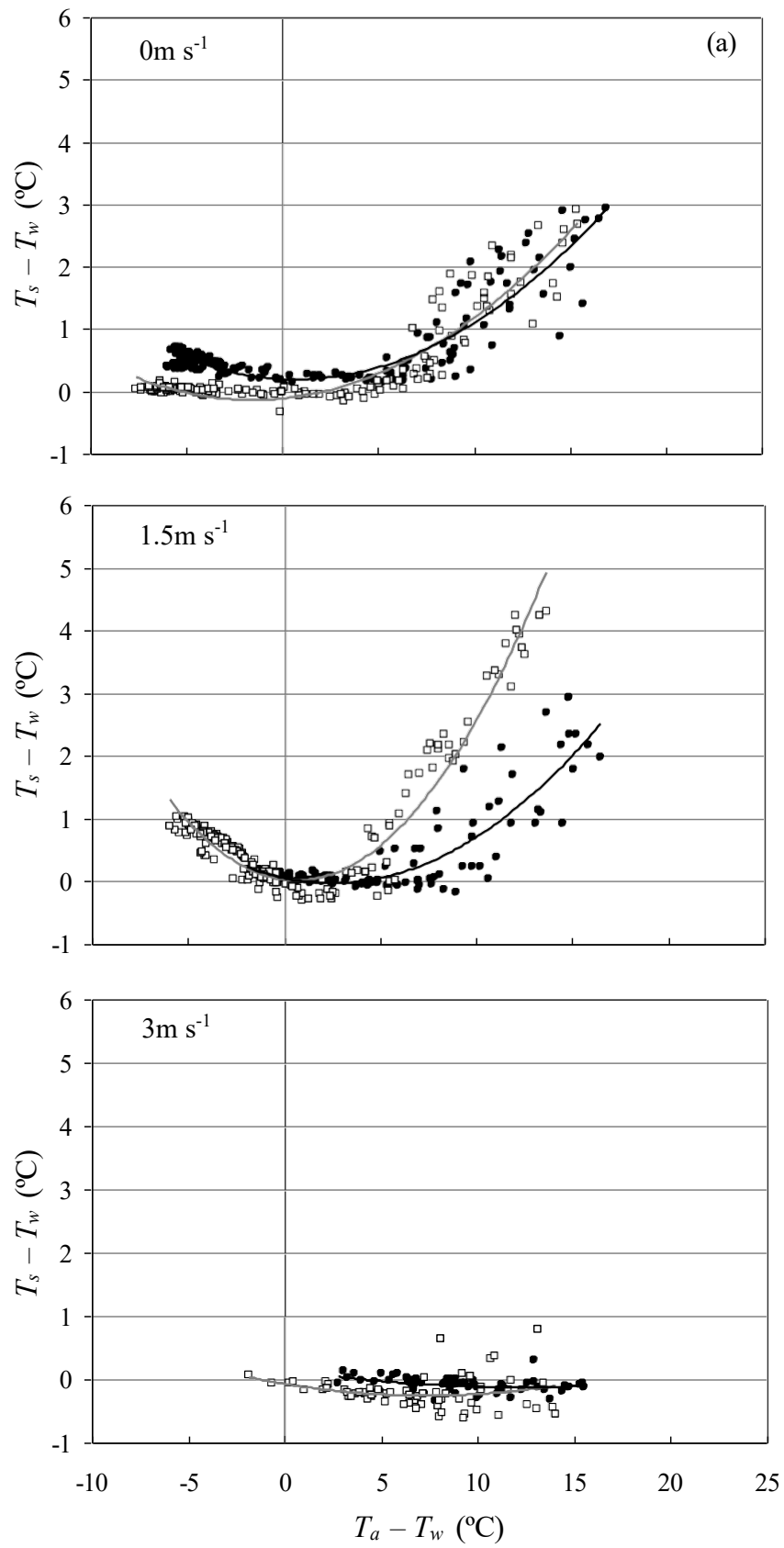
**Fig. 5** Regression lines between evaporation reduction factor (RF) and the differences in daily water surface temperature between tank M and C ( $\Delta T_s = T_{s,M} - T_{s,C}$ ) for each monolayer for all wind scenarios

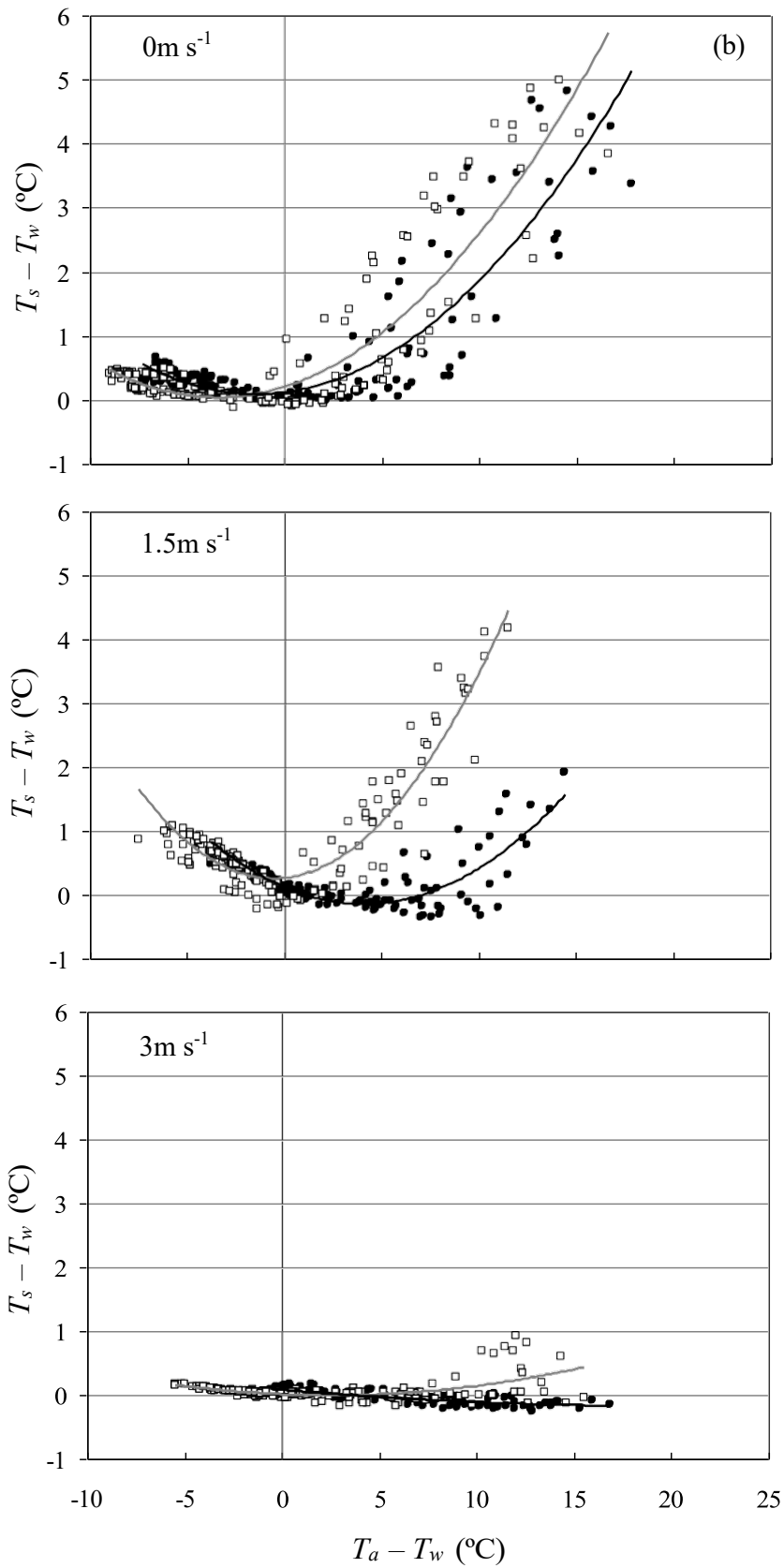


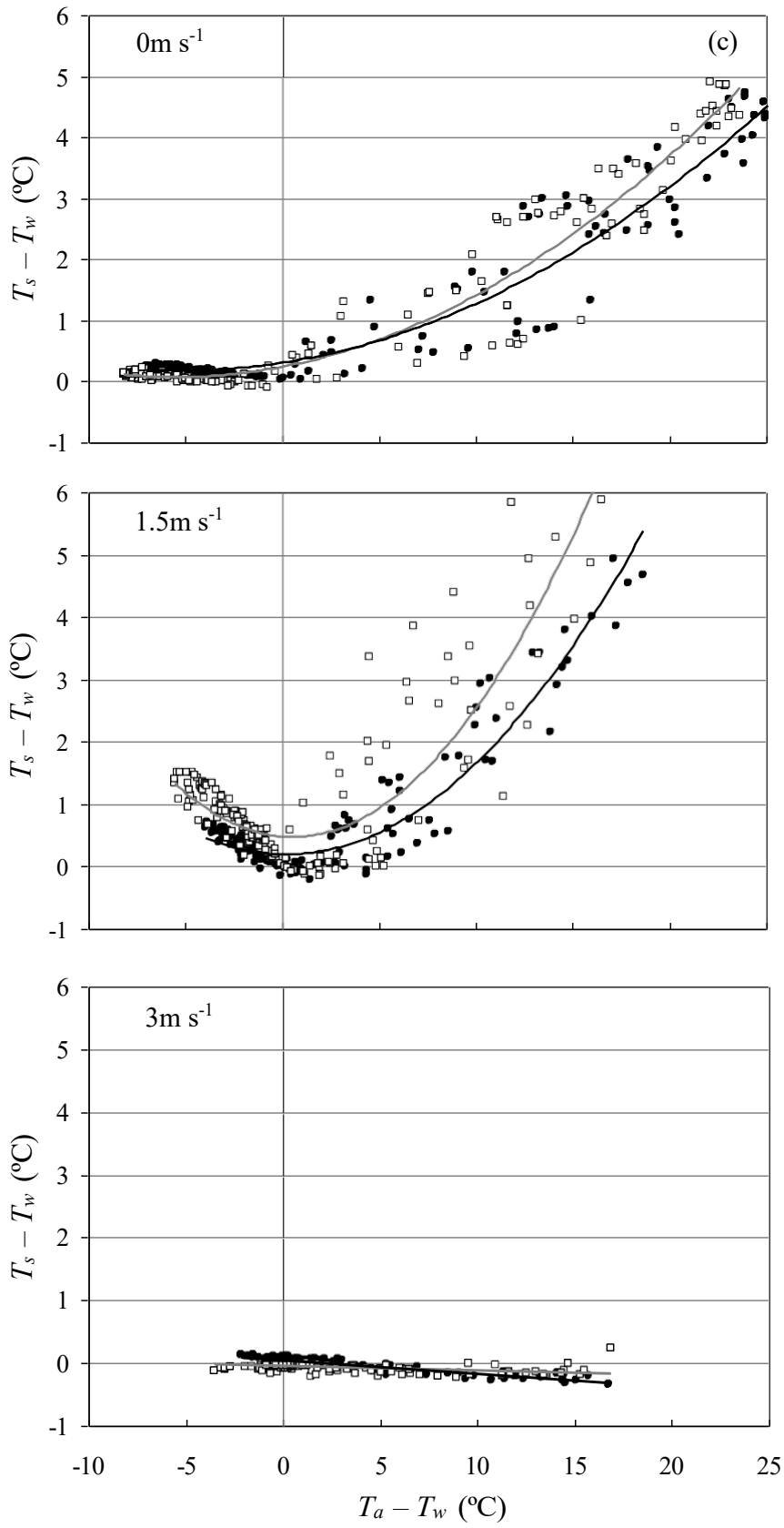
**Fig. 6** Hourly variation of temperature of air ( $T_a$ ), water surface ( $T_s$ ) and subsurface ( $T_w$ ) of a representative day of Tank M with C18OH with continuous wind of  $1.5\text{ m s}^{-1}$

Fig7

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**Fig. 7** Temperature difference between water surface and subsurface water *vs.* temperature difference between the air and the water surface ( $T_s - T_w$  *vs.*  $T_a - T_s$ ) for continuous wind of 0, 1.5 and 3m s<sup>-1</sup>. Hourly values for (●) tank C and (□) tank M with (a) C18OH (b) C18E1 (c) WaterSavr. The lines correspond to second-order polynomial regressions, black line for Tank C and grey line for Tank M.