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The Alpha, Beta, Gamma of Evaporation From Saline Water Bodies

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Evaporation from a saline water body is less than that from a freshwater body because of two factors: a decrease in saturation vapor pressure and a partially compensating increase in water surface temperature. These factors are quantified by analyzing field data for eight evaporation pans containing solutions with different salinities and ionic compositions (extending the analysis of Salhotra et al. (1985)). A large saline lake (Dead Sea) is also analyzed using a one-dimensional numerical model with coupled heat, salt, water, and mechanical energy balances. Further, the use of experiments involving evaporation pans, to study the effect of salinity on lake evaporation, is discussed in light of the fact that the two water bodies have different wind speed functions and hence different temperature feedback effects. Finally, data on the direct measurement of the saturation vapor pressure from mixtures of Mediterranean and Dead Sea waters are presented and compared with results from the analyses of the evaporation pan data.

INTRODUCTION

In an earlier paper [*Salhotra et al.*, 1985] we presented an accurate method (which we designated as the β approach) to account for the effect of salinity on evaporation. This approach is based on first computing the effect of salinity on the saturation vapor pressure of the saline solution and then incorporating this information in a Dalton type formula to estimate evaporation. It was shown that this approach is superior to the often used approach based on a simple empirical ratio of saltwater to freshwater evaporation (designated as the α approach). Field data from eight evaporation pans containing brines of different salinity and ionic composition (obtained by mixing Mediterranean Sea and Dead Sea water in different proportions) were analyzed in detail to support the above conclusions.

This paper includes further analysis of the pan data and presents additional insights and clarifications on the effect of salinity and temperature on evaporation, extending the work of *Harbeck* [1955] and *Calder and Neal* [1984]. First, the negative temperature feedback effect of salinity on evaporation is quantified for the evaporation pans as well as a large saline water body. The latter is illustrated by incorporating the β approach into a one-dimensional numerical model of the Dead Sea. This model consists of a coupled thermal energy, salt, water, and mechanical energy budget that simultaneously computes water temperature, salinity, and evaporation. Second, the use of pans to analyze the effect of salinity (or other perturbations such as the addition of dye or waste heat) on evaporation from large water bodies is discussed in light of the fact that the two water bodies have different wind speed functions and hence different temperature feedback effects. Third, laboratory data on the direct measurement of saturation vapor pressure for the Dead Sea brines are presented and compared with results obtained using empirical equations based on ionic composition of the solution and the evaporation pan data. These empirical equations are discussed in detail by *Salhotra et al.* [1985].

COMPUTATION OF EVAPORATION FROM A SALINE WATER BODY

The rate of evaporation per unit area of a saline water surface, E_{sal}, may be expressed as

$$E_{sal} = f(W)\{e'_{sat}(T_s, S_i) - \psi e_{sat}(T_a)\} \tag{1}$$

where $e_{sat}'(T_s, S_i)$ is the saturation vapor pressure above the saline water surface at temperature T_s and total salinity and ionic composition S_i, $e_{sat}(T_a)$ is the saturation vapor pressure of fresh water at the air temperature T_a, ψ is the relative humidity (expressed as a fraction), and $f(W)$ is an empirical function of wind speed W. Equation (1) can also be expressed as

$$E_{sal} = f(W)\{\beta(S_i)e_{sat}(T_s) - \psi e_{sat}(T_a)\} \tag{2}$$

where $\beta(S_i)$ is the activity of water in the saline solution and is the ratio of the saturation vapor pressures of saline solution and freshwater both measured at the same temperature, i.e.,

$$\beta(S_i) = \frac{e_{sat}'(T_s, S_i)}{e_{sat}(T_s)} \tag{3}$$

In using (2) to compute evaporation, $\beta(S_i)$ can be estimated by one of three methods: (1) analysis of field data from evaporation pans containing saline water, (2) computations using empirical equations based on the total salinity and ionic composition of the solution, and (3) direct laboratory measurements of the saturation vapor pressure of the saline solution. In principle, the third method is the most accurate and could be used to check the results obtained from the first two methods, both of which were discussed in detail by *Salhotra et al.* [1985]. Since the publication of that paper, data on the direct measurement of saturation vapor pressure of mixtures of Mediterranean and Dead Sea water have been obtained. Comparison of this data with results obtained from analyzing evaporation pan data is discussed in this paper.

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TABLE 1. Mean Values of the Salinity Effect ($\overline{\gamma'}$), Temperature Feedback Effect ($\overline{F'}$), and the Composite Effect ($\overline{\alpha'}$) for the Eight Pans

	Pan 12	Pan 13	Pan 14	Pan 15	Pan 16	Pan 17	Pan 18	Pan 19
Relative composition, %								
Mediterranean Sea	100	100	100	41	25.5	10.3	0	0
Dead Sea	0	0	0	59	74.5	89.7	100	100
S, % by weight (range)	4.8–6.0	18.5–21.5	22.1–24.5	18.8–20.9	22.0–24.2	23.2–27.2	18.6–21.0	26.0–27.8
$\overline{T_s}$, °C (mean)	19.3	20.5	21.1	20.9	21.6	22.3	21.0	22.5
$\overline{\alpha_j'}$	1.0	0.87	0.79	0.82	0.74	0.82	0.84	0.63
$\overline{F_j'}$	1.0	1.23	1.36	1.31	1.44	1.59	1.33	1.65
$(\overline{\gamma_j})' = \overline{\alpha_j'}/\overline{F_j}$	1.0	0.71	0.58	0.63	0.51	0.52	0.63	0.38
$\overline{\gamma_j'} = \overline{(\alpha_j'/F_j')}$	1.0	0.73	0.62	0.65	0.55	0.46	0.66	0.42

TEMPERATURE FEEDBACK EFFECT OF EVAPORATION

Application of the thermal energy budget to a freshwater body and a saline water body exposed to identical meteorological forcings would result in an inverse relationship between the water surface temperature and the rate of evaporation. The lower vapor pressure over saline water permits less energy to escape as latent heat, thus causing an increase in temperature within the saline water body in relation to that of the freshwater body. This increase in temperature also enhances the rate of evaporation from the saline water body, partially compensating for the reduction in evaporation due to salinity. This negative feedback effect on evaporation can be quantified by using empirical ratios (α and γ) to express evaporation from a saline water body, i.e.,

$$E_{\text{sal}} = \alpha f(W)\{e_{\text{sat}}(T_f) - \psi e_{\text{sat}}(T_a)\} \tag{4}$$

$$E_{\text{sal}} = \gamma f(W)\{e_{\text{sat}}(T_s) - \psi e_{\text{sat}}(T_a)\} \tag{5}$$

where T_f is the surface temperature of the freshwater body exposed to the same meteorological forcings as the saline water body. In (4), α accounts for both the salinity and the negative temperature feedback effects on evaporation and is the ratio of saltwater to freshwater evaporation from two otherwise identical water bodies, i.e.,

$$\alpha = E_{\text{sal}}/E_f \tag{6}$$

In (5), γ accounts for only the salinity effect; the temperature feedback effect is directly accounted for by computing the saturation vapor pressure of the saline water body at its surface temperature T_s. Note that evaporation pan experiments such as those conducted by *Bonython* [1956, 1965] and *Turk* [1970] typically yield the value of α (equation (6)), whereas γ is a derived quantity. (Also note that γ has a different meaning than that used by *Salhotra et al.* [1985].)

By equating (4) and (5) to (2),

$$\alpha = \frac{\beta(S_i)e_{\text{sat}}(T_s) - \psi e_{\text{sat}}(T_a)}{e_{\text{sat}}(T_f) - \psi e_{\text{sat}}(T_a)} \tag{7}$$

$$\gamma = \frac{\beta(S_i)e_{\text{sat}}(T_s) - \psi e_{\text{sat}}(T_a)}{e_{\text{sat}}(T_s) - \psi e_{\text{sat}}(T_a)} \tag{8}$$

respectively. Comparing (7) and (8), since $T_s > T_f$ and hence $e_{\text{sat}}(T_s) > e_{\text{sat}}(T_f)$, γ is less than α. This is due to the temperature feedback effect and can be highlighted further by dividing (7) by (8) so that

$$\alpha = \gamma F \tag{9}$$

where F is the feedback effect expressed as

$$F = \frac{e_{\text{sat}}(T_s) - \psi e_{\text{sat}}(T_a)}{e_{\text{sat}}(T_f) - \psi e_{\text{sat}}(T_a)} \tag{10}$$

In (9) the left-hand side (α) is the ratio of saline water to freshwater evaporation that is composed of a salinity effect ($\gamma < 1$) and a temperature feedback effect ($F > 1$). The latter depends on water surface temperatures (T_s and T_f) and meteorological parameters (T_a and ψ) which may exhibit large temporal variations; hence similar variability may be expected in α.

FEEDBACK EFFECT FOR EVAPORATION PANS

The salinity, temperature feedback, and the composite effect for evaporation pans are demonstrated by computing γ, F, and α for the eight Dead Sea evaporation pans analyzed in our earlier paper [*Salhotra et al.*, 1985]. Recall that the experimental setup consisted of eight identical cylindrical evaporation pans located at Sedom at the southern end of the Dead Sea. The pans were sunk in the ground and were 3 m in diameter, about 1 m deep, and filled to a depth of about 0.95 m with mixtures of Mediterranean and Dead Sea waters in

TABLE 2. Monthly Meteorology, Equilibrium Temperatures, and α Values for a Pan and Lake

	Meteorology			Equilibrium Temperature				Alpha	
Month	Ta, °C	W, m/s	ψ, %	SL	FL	SP	FP	L	P
January	13.1	2.9	55	14.3	12.7	13.6	11.8	0.66	0.65
February	14.6	2.8	48	16.8	15.0	15.6	13.8	0.74	0.73
March	17.5	3.1	69	21.9	19.7	20.7	18.5	0.69	0.65
April	23.4	3.3	55	26.5	24.0	25.0	22.5	0.77	0.75
May	27.5	3.4	45	29.5	26.8	27.8	25.1	0.82	0.81
June	31.0	3.3	40	32.8	29.9	30.8	27.9	0.85	0.84
July	32.3	3.4	44	34.1	31.1	32.3	29.2	0.84	0.83
August	32.1	3.2	48	34.5	31.5	32.7	29.7	0.83	0.81
September	28.7	3.1	49	31.0	28.2	29.4	26.6	0.81	0.79
October	25.8	2.7	55	28.6	26.1	27.3	24.7	0.77	0.75
November	21.5	2.8	58	23.0	20.8	22.1	19.8	0.69	0.67
December	15.3	3.6	73	17.2	15.3	16.7	14.7	0.45	0.40
Mean	23.6	3.1	53	25.8	23.4	24.5	22.0	0.74	0.72
Using mean annual meteorology	23.6	3.1	53	26.4	24.0	25.0	22.5	0.78	0.77

Ta, air temperature; W, wind speed; ψ, relative humidity; F, fresh; S, saline; P, pan; and L, lake.

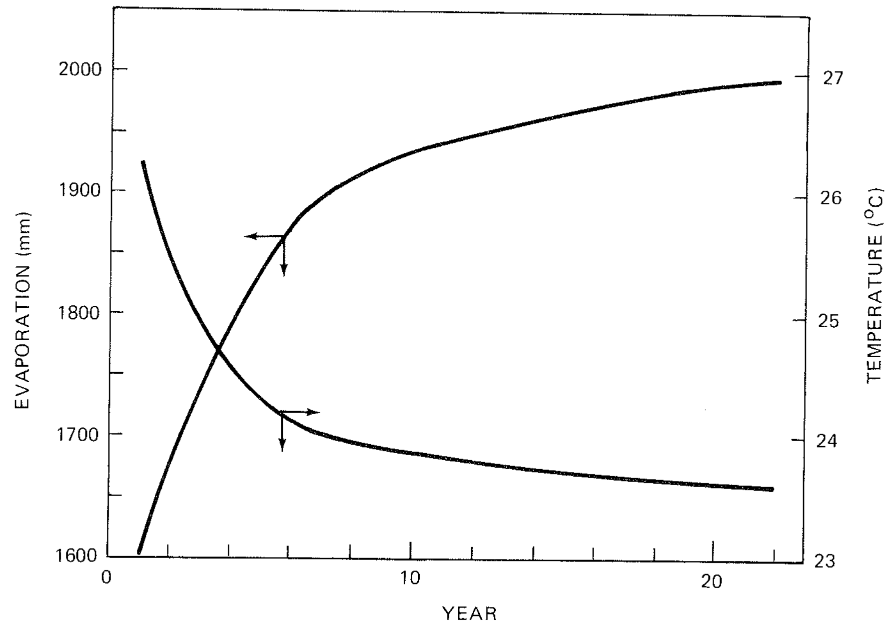

Fig. 1. Annual evaporation and mean surface temperature with the hydropower project in operation.

different proportions and salinities, as shown in Table 1. Each pan was provided with thermometers to measure the temperature at the water surface and at various depths within the pans. Air temperature and relative humidity were also measured at the site. At intervals ranging from 3 days to several weeks, fresh makeup water was added to each pan to compensate for the evaporative water loss and to maintain a constant chemical composition. Maximum makeup water added at any time was 5 mm.

Since none of the Dead Sea pans contained fresh water, values of T_f in (7) and (10) are not known, and hence neither α nor F can be directly computed. For water with low salinity, α is approximately equal to γ. This assumption was used in the computation of α for pan 12 in our earlier paper. For the purpose of the following analysis, this assumption is not necessary, and instead, α', F', and γ' are computed in relation to pan 12, which has water with the lowest salinity.

Thus for a given cycle and pan j,

$$\alpha_j' = \frac{E_j}{E_{12}} \tag{11}$$

$$F_j' = \frac{e_{\text{sat}}(T_j) - \psi e_{\text{sat}}(T_a)}{e_{\text{sat}}(T_{12}) - \psi e_{\text{sat}}(T_a)} \tag{12}$$

$$\gamma_j' = \frac{\alpha_j'}{F_j'} \tag{13}$$

In (11) through (13) the primes denote the fact that the results are normalized with respect to water in pan 12 with mean salinity of about 5.4% rather than with a freshwater pan.

Table 1 shows the mean values of the salinity effect ($\overline{\gamma'}$ values), the temperature feedback effect ($\overline{F'}$ values), and the composite effect ($\overline{\alpha'}$ values) for each of the eight pans in relation to those of pan 12 for the entire duration of the field experiment (November 1982 to August 1983). Thus for pan 19, containing "pure" Dead Sea water, the mean salinity effect alone reduces evaporation to about 42% of the evaporation from pan 12, which contains slightly concentrated Mediterranean seawater. However, the temperature effect increases in relation to evaporation by about 65%, so that the composite effect is an observed reduction in evaporation to about 63% of pan 12. As expected, the salinity and the temperature feedback effects for the eight pans are perfectly correlated; effects are maximum for pan 19 with the highest salinity and minimum for pan 12 with the lowest salinity.

It has been mentioned earlier that the temperature feedback effect is a function of meteorological variables that exhibit random as well as seasonal variation. Further, this relationship is not linear as manifested in the mean values of the composite effect shown in Table 1, i.e.,

$$\overline{\gamma_j'} \neq (\overline{\gamma_j})' \tag{14}$$

where $\overline{\gamma_j'}$ is the mean over the cycles of the γ_j' values and $(\overline{\gamma_j})'$ is based on mean values of $\overline{\alpha_j'}$ and $\overline{F_j'}$ for the entire duration of the experiment.

From the above, it is clear that the computation of evaporation from a saline water body should implicitly or explicitly include both the salinity and the temperature feedback effects.

At this point it is interesting to ask how the temperature feedback and the composite effects for a small water body (pan) compare with the corresponding effects for a large water body (lake) that has a different wind speed function. This has important implications on the use of pan experiments to study the effect of salinity, or other factors such as the addition of dye or waste heat, on evaporation.

Table 2 shows computed mean monthly equilibrium temperatures, T_E, for saline and fresh lakes and pans subjected to Dead Sea meteorological conditions. T_E is the water temperature at which no net surface heat transfer occurs; it was computed from historical data on incident radiation and empirical surface heat transfer formulae described by *Ryan et al.* [1974]. In these computations, all water bodies were assumed to be perfectly insulated, and a pan coefficient of 0.7 [*Viessman et al.*, 1977] was assumed in relating pan to lake evapora-

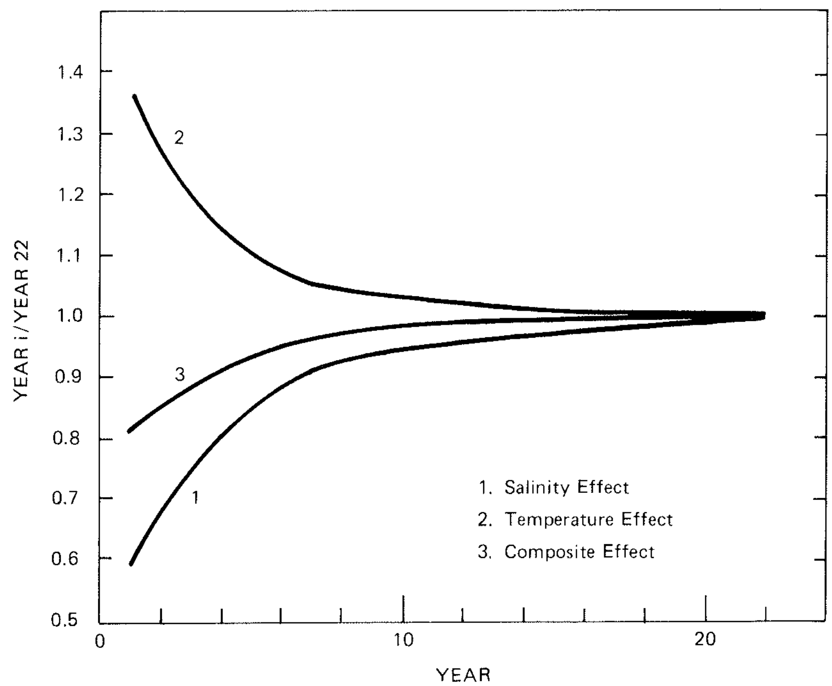

Fig. 2. Salinity, temperature feedback, and the composite effect of salinity on evaporation for the Dead Sea.

tion, i.e.,

$$E_p = \frac{1}{0.7} E_L \tag{15}$$

where E_P and E_L are the rates of evaporation from a pan and a lake. Note that E_L can be calculated from (1). The saline lake and pan were assumed to have salinity (27.2%) and ionic composition representative of the Dead Sea. A number of observations can be drawn from these results.

First, values of α computed for the pan using (7) with equilibrium water temperatures are slightly less (about 3% on average) than corresponding values for the lake, since lake equilibrium temperatures are higher than pan temperatures. Thus one is making a small but systematic error if one computes the ratio of saltwater to freshwater lake evaporation directly from corresponding measurements from insulated pans. Second, as observed by its monthly variation, α is very sensitive to meteorological conditions and, in particular, relative humidity. Finally, Table 2 also shows that both equilibrium temperatures and α values computed using annual mean meteorology are considerably larger than the annual mean values based on monthly averaged values, i.e.,

$$\bar{T}_E(T_a, \psi, W) < T_E(\bar{T}_a, \bar{\psi}, \bar{W}) \tag{16}$$

$$\bar{\alpha}(T_a, \psi, W) < \alpha(\bar{T}_a, \bar{\psi}, \bar{W}) \tag{17}$$

where overbars represent mean values. While the numerical values given in Table 2 reflect the specific assumptions being made (i.e., perfect insulation and pan coefficient of 0.7), the qualitative conclusions are general. In particular, the last two observations support the conclusions of *Salhotra et al.* [1985] that it is inaccurate to use a constant value of α to characterize the time-varying ratio of saltwater to freshwwater evaporation.

APPLICATION OF THE β APPROACH TO THE DEAD SEA

The β approach to account for the effect of salinity on evaporation was incorporated into a time-varying, one-dimensional numerical model which coupled heat, salt, water, and mechanical energy balances to compute the rate of evaporation from the Dead Sea [*Salhotra*, 1986]. The model was run on a daily time step and included vertical mixing due to wind and penetrative convection to compute daily temperature and salinity stratification within the lake. The surface temperature and salinity were used to compute daily evaporation rates. Since the lake temperatures were computed on the basis of an energy budget in which the evaporation term accounts for the effect of salinity, the temperature feedback effect is inherent in the model computations. The model mixing parameters were calibrated using vertical temperature and salinity stratification data from the Dead Sea over a period of 5 years, and the model was later used to predict lake levels, annual evaporation, and vertical stratification with the proposed Mediterranean–Dead Sea Hydropower Project in operation [*Weiner*, 1980]. This project envisages the diversion of about 53 m^3/s of water from the Mediterranean Sea into the Dead Sea (initial salinity approximately equal to 27.2%) to generate about 1850 MW/yr of hydropower. The simulation was begun in 1984 and was continued for 30 years by assuming a repeating 3-year cycle of meteorological conditions. Figure 1 shows the computed annual evaporation and mean surface temperature for the first 22 years, by which time reasonably asymptotic conditions have been reached. As expected, dilution of the surface (from about 27.2% in 1984 to 10.0% after 22 years of simulated power plant operation) increases evaporation and reduces surface temperature. The increase in evaporation due to reduced salinity is partially compensated by decreased evaporation caused by a drop in surface temperature, the negative feedback effect.

TABLE 3. Comparison of α Values and Water Temperature for Experimental Pans, Simulation Results and a Pan and Lake at Equilibrium With Dead Sea Meteorology

Case	T_s*	T_{fresh}†	α	$\bar{T}_a$
Equilibrium pan	25.0	22.5	0.77	23.6
Equilibrium lake	26.4	24.0	0.78	23.6
Experimental pan	22.2	19.6	0.69	23.3
Simulation result	26.3	23.5	0.81	23.6

*Salinity, 25.8%.
†Salinity, 9.2%.

TABLE 5. Comparison of Mean β Values for Pans 15, 16, and 17 Based on Pan Data (β_{pan}) and Data From *Marcus* [1984]

	Pan 15	Pan 16	Pan 17
w, %	63.1	77.6	91.2
β_{pan}*	0.83 (0.03)	0.78 (0.03)	0.73 (0.04)
β_m†	0.84 (0.01)	0.80 (0.01)	0.73‡ (0.0)

Parentheses indicate standard deviation.
*From *Salhotra et al.* [1985].
†From *Marcus* [1984].
‡Extrapolated value.

The magnitudes of the various effects can be illustrated by normalizing results for year i with those of year 22. From (9), one can define

$$\frac{\bar{\gamma}_i}{\bar{\gamma}_{22}} = \frac{\bar{E}_i \bar{F}_{22}}{\bar{E}_{22} \bar{F}_i} \tag{18}$$

where $\overline{E_i}$ is the simulated annual average evaporation rate (including both salinity and temperature effects) and $\overline{F_i}$ is a characteristic temperature effect computed from (10) based on annual average meteorology conditions and simulated water temperatures. Thus $\bar{\gamma}_i$ represents an annual average decrease in evaporation due to salinity. Figure 2 shows the annual variation in the salinity effect ($\overline{\gamma_i/\gamma_{22}}$), the temperature effect ($\overline{F_i/F_{22}}$), and the composite effect ($\overline{E_i/E_{22}}$). For the first year, $\overline{E_1/E_{22}} = 0.81$, and the magnitude of the feedback effect is 1.36. From (18), $\overline{\gamma_1/\gamma_{22}}$ is thus 0.59. This implies that the reduction in evaporation due to the salinity affect alone is 41%, while there is an increase in evaporation of 36% due to the temperature effect. The composite effect is a relatively modest decrease in evaporation of 19%.

The above model results can be compared with the pan data and the simulated equilibrium pan and lake subjected to annual average meteorological conditions. Since there were no pans with salinity exactly equal to that computed for the Dead Sea in year 1 or year 22, the data for pan evaporation were interpolated to estimate evaporation for two hypothetical pans with salinities similar to those of year 1 and year 22. The ratio of evaporation for these pans was 0.69 or considerably less than the simulated ratio for the Dead Sea (0.81) or the ratios computed for the equilibrium pan (0.77) and lake (0.78).

TABLE 4. Computed Values of β From Direct Measurements of Saturation Vapor Pressure of Mixture of Dead Sea and Mediterranean Sea Water

		Temperature, °C						
Sample	w*	15	20	25	30	35	Mean	Standard Deviation
1	38.8	0.88	0.88	0.89	0.89	0.88	0.88	0.01
2	50.0	0.85	0.87	0.87	0.86	0.85	0.86	0.01
3	64.7	0.86	0.87	0.86	0.85	0.84	0.86	0.01
4	73.1	0.85	0.84	0.83	0.80	0.78	0.82	0.03
5	82.7	0.81	0.80	0.79	0.78	0.78	0.79	0.01
6	87.2	0.76	0.76	0.76	0.76	0.76	0.76	
7†	91.2	0.72	0.72	0.73	0.74	0.73	0.73	

From *Marcus* [1984].
*Weight percent of Dead Sea water in mixture.
†Based on extrapolation of saturation vapor pressure values using samples 5 and 6.

The range is primarily due to the range in temperature feedback effects, as the four water bodies show very different surface temperature (Table 3). In particular, the experimental pans show much lower temperatures, since they were not adequately insulated. A secondary effect distinguishing pan and lake ratios is the difference in the wind speed functions as discussed earlier.

DIRECT MEASUREMENT OF SATURATION VAPOR PRESSURE OF THE DEAD BRINES

Marcus [1984] reported direct laboratory measurements of the saturation vapor pressure for different mixtures of Dead Sea and Mediterranean Sea brines with the Dead Sea water composition in the mixture ranging from 38.8% to 87.2% by weight and for temperatures varying from 15°C to 35°C. On the basis of these measurements and by using (3), the β values for the mixtures are shown in Table 4. The value of β for mixture 7 has been obtained by linearly extrapolating the saturation vapor pressure for mixtures 5 and 6 and dividing by the saturation vapor pressure of fresh water at the appropriate temperature. Note that the relative proportion of Dead Sea water in sample 7 is the same as that for one of the pans (pan 17) analyzed by *Salhotra et al.* [1985].

Table 5 shows a comparison of the mean β values for evaporation pans 15, 16 and 17 based on our earlier analysis of the pan data and values interpolated from data reported by *Marcus* [1984]. For pan 15, with 63.1% Dead Sea brines, the variation in the two means is 1.2%, and for pan 16 with 77.6% Dead Sea brines, the corresponding variation is 2.6%. For pan 17 the mean β value obtained by the two methods is identical.

It is important to note that the field experiments and the controlled laboratory experiments were conducted at two different periods. Sufficient data were not available to ascertain whether the Mediterranean and the Dead Sea samples used in the two experiments had identical ionic compositions. Thus the observed small differences in the β values could result from either measurement errors or slight differences in chemical composition and total salinity of the mixtures.

CONCLUSIONS

It is shown that the composite effect of salinity on evaporation consists of a salinity effect and a negative temperature feedback effect. These effects are quantified and compared for the case of evaporation pans and a large lake. The ratio of saltwater to freshwater evaporation rates differed slightly in simulations including lake and insulated pans, but the experimentally observed ratios for uninsulated pans were considerably less, highlighting the role of water surface temperature.

Values of the activity coefficient of water in a saline solution (β) are presented for mixtures of Dead Sea and Mediterranean Sea waters based on direct measurements of the saturation vapor pressure. These values compare well with β values obtained previously using analytical techniques and the analysis of evaporation pan data.

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