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Evaporation in the Laboratory and at Sea

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ABSTRACT

A short-fetch water-wind tunnel has been used to measure the evaporation rate for wind velocities between 200 and 800 cm/sec and for three water-air temperature differences. Sverdrup's assumption of a molecular diffusion sublayer at the naviface has been used to compare laboratory evaporation measurements with existing measurements at sea. Using interpolation and adjustments for widely different conditions, the laboratory measurements agreed with Defant's average sea data to within 9%. The mean diffusion sublayer thickness for the average sea conditions is calculated to be 0.25 cm compared with 0.08 cm for the laboratory.

Introduction. According to Defant (1961: 227), an hypothesis of Sverdrup assumes that there exists a thin sublayer in the turbulent wind field that is generating waves on a water surface. In this region, water-vapor transport by evaporation is controlled by molecular diffusion. Above the diffusion sublayer, water-vapor transport is very much faster due to turbulence. Sverdrup's is a statistical model wherein the diffusion sublayer varies in thickness with wind velocity, and the turbulent eddies randomly penetrate down into the layer. The sublayer may occasionally disappear. However, it is postulated that the sublayer will be re-formed so that a mean-thickness concept can be introduced.

Sverdrup's hypothesis may be interpreted to contain the approximation that the air immediately above the diffusion sublayer is perfectly mixed compared with the air in the sublayer, where molecular diffusion takes place. Eddy diffusion in the turbulent air above increases only slightly the effective thickness of the molecular diffusion sublayer.

The purpose of this paper is to present the results of direct evaporation measurements in a short-fetch water-wind tunnel and to compare them with existing measurements at sea on the basis of the above assumptions.

1. Accepted for publication and submitted to press 15 June 1969.
Background. The change in (gradient of) water-vapor mass concentration across the diffusion sublayer is

\[(\Delta M) = M_w - M_a H \quad \text{gm/cm}^3,\]  

where \(M_w\) is the mass concentration of water in the saturated air immediately in contact with the water at temperature \(T_{wi}\); \(M_a\) is the mass concentration of saturated water vapor in the turbulent air at temperature \(T_a\) above the diffusion sublayer; and \(H\) is the relative humidity of the turbulent air.

Mass transport of water vapor across the diffusion sublayer by molecular diffusion occurs because of the gradient of mass concentration. Therefore, the mass of water evaporated per square centimeter per second is

\[E_e = \frac{D(\Delta M)}{\rho} \quad \text{gm/cm}^2\text{sec}^{-1},\]  

where \(E\) is the evaporation rate, \(\rho\) the density of water, \(D\) the diffusivity of water vapor in air, \(\delta\) the effective mean diffusion sublayer thickness, and \(\Delta M\) the mass concentration gradient of water vapor across the diffusion sublayer.

**Laboratory Experiments.** The laboratory water-wind channel was 90 cm long, 7.5 cm wide, 26 cm deep, and the water depth was 16 cm. The 10-cm-high column of air was drawn over the water surface with a blower that was vented into a relatively large well-ventilated room. The blower was placed at one end of the tank. The incoming turbulent air was at room temperature and relative humidity. Both temperature and humidity remained constant to within \(\pm 3\%\). The exhaust from the short-fetch water-wind tunnel was also found to be within \(\pm 3\%\). At the higher evaporation rates, the water temperature dropped somewhat during a set of measurements. The average water temperature during a given run was used. The average wind speed was measured with a small commercial wind-velocity probe placed 5 cm above the water and near the center of the channel. A spring-balance arrangement weighed the water-wind tunnel before and after each experiment to determine the weight (volume) of water evaporated. The evaporation rate was determined by knowing the volume of water lost over the evaporation area of the tunnel during the time of an experiment.

The results of the experiments are given in Fig. 1. As a first approximation it is evident that

\[E = s \bar{U}_5 \quad \text{cm/sec},\]  

where \(E\) is the evaporation rate, \(\bar{U}_5\) the mean wind velocity at a 5-cm height, and \(s\) the slope (dimensionless) of the lines.

**Comparison with Sea Measurements.** Defant (1961: 230) has given a set of evaporation measurements obtained at sea for seven latitudinal zones, from
Figure 1. Evaporation rate vs average wind speed at 5 cm above water for three different water temperatures in a short-fetch water-wind tunnel. Air temperature and relative humidity held constant.

50°N to 55°S. In order to minimize individual evaporation-rate measurement errors and to simplify the comparison, averages of Defant’s data have been used. The conditions for the laboratory experiments are very different, as is indicated in Table I, and it is necessary to make allowances for these differences before a meaningful comparison can be made.

First, \((\Delta M)^*/\rho\) has been determined on the basis of \(T'_w\) and \(T'_a\) at sea, but
Table I. Laboratory and sea-evaporation data.

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<tbody>
<tr>
<td></td>
<td>$T_w$</td>
<td>$T_a$</td>
<td>$T_w-T_a$</td>
<td>$H$</td>
<td>$(\Delta M)$</td>
<td>$\bar{U}$</td>
<td>$E$</td>
</tr>
<tr>
<td></td>
<td>(°C)</td>
<td>(°C)</td>
<td>(°C)</td>
<td>(°C)</td>
<td>(10$^{-6}$ gm/cm)</td>
<td>(cm/sec)</td>
<td>(10$^{-6}$ cm/sec)</td>
</tr>
<tr>
<td>Lab</td>
<td>31.4</td>
<td>24.6</td>
<td>+6.8</td>
<td>0.47</td>
<td>22.6</td>
<td>200–800</td>
<td>43–179</td>
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<tr>
<td></td>
<td>22.2</td>
<td></td>
<td>−2.6</td>
<td></td>
<td>9.1</td>
<td>−</td>
<td>21–86</td>
</tr>
<tr>
<td></td>
<td>15.8</td>
<td></td>
<td>−8.8</td>
<td>−</td>
<td>2.8</td>
<td>−</td>
<td>11–45</td>
</tr>
<tr>
<td>Def</td>
<td>19.6</td>
<td>18.9</td>
<td>+0.7</td>
<td>0.80</td>
<td>4.0</td>
<td>630</td>
<td>3.6</td>
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$H$ has been determined in the laboratory. This gave $(\Delta M)''/\varrho = 9.3(10^{-6})$. The data in Table I, relating $(\Delta M)/\varrho$ to $s$, were next used to interpolate $s'' = 0.111(10^{-6})$. Three correction factors were applied to $s''$ to make it comparable to $s'$. The first of these was the ratio of $H/H' = 0.59$.

According to Roll (1965: 136), $\bar{U}_{1000}' = 630$ is approximately equivalent to $\bar{U}_5'' = 250$ cm/sec. Thus the second correction factor is $250/630 = 0.40$.

By combining (2) and (3), the following for the average diffusion sublayer thickness was obtained:

$$\delta = D(\Delta M)/\varrho \bar{U}$$  \hspace{1cm} (4)

From this, $\delta'' = 0.08$ cm for the laboratory case where $D = 0.22$ cm$^2$/sec, $\varrho = 1$ gm/cm$^3$, and the aforementioned values of $(\Delta M)''$, $s''$, and $\bar{U}_5''$ were used. In like manner, $\delta' = 0.25$ cm was determined for the sea conditions where $D$ and $\varrho$ are very nearly the same for purposes of our discussion here; and the ('$) values of the other variables were used. These calculations indicate that the diffusion layer in the laboratory was $0.08/0.25 = 0.32$ thinner than at sea. This is the third correction factor to be applied to $s''$ so that it can be properly compared with $s'$. The calculated value is designated as $s'_c = 0.111 (10^{-6})(0.59)(0.40)(0.32) = 0.0062(10^{-6})$ compared with $s' = 0.0057(10^{-6})$. The error is less than 9%.

REFERENCES

Defant, Albert

Roll, H. U.