Report on the application of an evapotranspiration equation to the WACA Dome

P R. Scott

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Report on the Application of an Evapotranspiration Equation to the WACA Dome

P.R. Scott

Resource Management Technical Report 93
Disclaimer

The contents of this report were based on the best available information at the time of publication. It is based in part on various assumptions and predictions. Conditions may change over time and conclusions should be interpreted in the light of the latest information available.

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1. Introduction

The West Australian Cricket Association (WACA) has initiated the use of a large plastic ventilated chamber (dome) to assist in the management of the pitch area at the WACA ground in Perth. The dome serves to keep rainfall off the pitch, but may also be used as a management tool to alter environmental conditions, and consequently, the evapotranspiration rate. This report provides some theoretical background on the calculation of evapotranspiration from the dome and some suggestions for further work.

2. Aim

To examine the possibility of changing the evapotranspiration rate from the pitch by altering environmental conditions immediately above it.

3. Method

The dome can be compared to the ventilated chamber system used to measure evapotranspiration by Greenwood et al. (1979, 1981, 1982, 1985a, 1985b), Nulsen (1984) and Scott and Sudmeyer (1986). Air is forced into the dome using industrial fans and allowed to escape through various outlets. It is a relatively simple matter to complete the water balance and calculate the evapotranspiration from the vapour pressure of the incoming and outgoing air, air speed through the chamber, and the temperature.

The density of water vapour is given by:

\[ P_v = \frac{216.8 \, P_w}{T} \]

Equation (1)

Where

- \( P_v = \) density of water vapour (g/m\(^3\))
- \( P_w = \) vapour pressure (mb)
- \( T = \) temperature of water vapour (°K)

A water balance approach to the dome allows vapour densities to be used to calculate the evapotranspiration rate:

\[
\text{Rate of output of water vapour from the dome} - \text{Rate of input of water vapour to the dome} = \text{Rate of accumulation of water vapour in the dome.}
\]

If we assume that the outside conditions are changing so slowly that the dome has come to a steady state with no net accumulation, then input is broken up into the flow of vapour in through the fans, and the evaporation from the pitch surface. The output of water vapour is simply the outflow through the exhaust tubes.
Substituting

\[ V_f P_{in} + E_t A - V_f P_{out} = 0 \]  
Equation (2)

Where \( V_f \) is the volumetric rate of air flow into the dome (m\(^3\)/s)
\( A \) is the basal area under the dome (m\(^2\))

Solving the equation for \( E_t \):

\[ E_t = \frac{V_f (P_{out} - P_{in})}{A} \]  
Equation (3)

The basal area of the dome was estimated to be 879 m\(^2\). Substituting from equation (1), the evapotranspiration rate in g/m\(^2\).s is:

\[ E_t = \frac{216.68}{\Omega K} x \Delta mb x V_f \]  
Equation (4)

By conversion of units (1 mm/hr = 1 g/m\(^2\).s x 3.6)

\[ E_t = \frac{0.88743}{\Omega K} x \Delta mb x V_f \]  
Equation (5)
The sensitivity of the formula was tested by changing a single variable while keeping the others constant. It should be noted that this approach tests only the formula under given conditions. Steady state conditions are assumed, and also that the air within the dome is well mixed. The rate at which the turf and pitch can supply moisture to the air is considered to be constant in this approach. Obviously the actual Et rate will be influenced not only by the atmospheric exchanges, but also by the ability of the turf and pitch soil to provide moisture to meet the atmospheric demand. Under certain conditions, however, this supply rate is likely to become limited. Therefore the results tabled give an indication of the effects on the potential rate of evapotranspiration, assuming a continued supply, that may result from changing various operational characteristics of the dome.

Air flow rates were measured on the dome using a pitot shaft and Alnor velometer and found to be about 4.8 m$^3$/s with both fans operating. Vapour pressure deficit of the incoming and outgoing air was measured with Delta-T aspirated psychrometers on September 19 and 20, 1987. (Results from these measurements are in Appendix 1.)
4. Results

Table 1. The effect of different flow volumes on the potential evapotranspiration rate at various vapour pressure differences. Assume the temperature is $15^\circ$C ($288^\circ$K) and that the air is not warmed in the chamber.

$$Et = 0.00308134 \times \Delta mb \times V$$

* Based on chamber volume $2,458 \text{ m}^3$. 
Figure 2. Effect of volume rate of flow on the calculated potential evapotranspiration rate for the WACA Dome. Assume temperature = 15°C and no warming within chamber.
Table 2. The effect of temperature on the potential evapotranspiration rate at various vapour pressure differences. Assume volume rate of flow is 4.8 m³/s and that the air is not warmed within the chamber

\[ Et = \frac{4.26 \times \Delta mb}{K^o} \]

<table>
<thead>
<tr>
<th>Vapour Pressure Difference ((\Delta mb))</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>250</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.008</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
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<td>1</td>
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<td>2</td>
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<td>0.071</td>
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<td>6</td>
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<td>0.129</td>
<td>0.127</td>
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<tr>
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<td>0.229</td>
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<td>0.301</td>
<td>0.296</td>
<td>0.291</td>
<td>0.286</td>
<td>0.281</td>
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</tbody>
</table>

K°\( = \) 283  288  293  298  303
Figure 3. Effect of temperature on the potential evapotranspiration rate for the WACA Dome. Assume volume rate of flow = 4.8 m$^3$/s and no warming within chamber.
Table 3. Effect on the potential evapotranspiration rate calculation of air warming in the chamber at various vapour pressure differences. Assume volume flow if 4.8 m$^3$/s, temperature is 15°C, and relative humidity (of incoming air) is 35% (i.e. vapour pressure = 6 mb)*

<table>
<thead>
<tr>
<th>Amount of warming (°C)</th>
<th>1</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour Pressure Difference (mb)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.007</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>1</td>
<td>0.015</td>
<td>0.014</td>
<td>0.013</td>
</tr>
<tr>
<td>5</td>
<td>0.075</td>
<td>0.074</td>
<td>0.072</td>
</tr>
<tr>
<td>10</td>
<td>0.150</td>
<td>0.148</td>
<td>0.146</td>
</tr>
</tbody>
</table>

$E_\ell (\text{mm/hr})$

$E = \left(\frac{216.68 \times m_b^2 - 216.68 \times 6}{K^\circ} - \frac{216.68 \times 6}{288}\right) \times 0.020$  
Equation (6)**

$= \left(\frac{216.68 \times m_b^2 - 4.514}{K^\circ}\right) \times 0.020$

where $m_b^2$ is the outlet V.P. and $K^\circ$ is the outlet temperature.

*Note: This indicates only that the difference in air temperature of the incoming and outgoing air has little effect on the outcome of the equation. For example: even if the exhaust air is 5°C warmer than the inlet air, for a given vapour pressure difference it makes little difference whether 288 K (15°C) or 293 K (20°C) is used in the formula. It is not an indication of how air warming in the chamber influences evaporative demand (see Table 4, Figure 5 and discussion).

**Note: Equation 6 derivation:

$Et = \frac{V_f (P_{out} - P_{in})}{A}$

$= \frac{216.68 \ P_{wout}}{T} - \frac{216.68 \ P_{win}}{T} \ \frac{V_f}{A}$
Figure 4. Effect of air warming in the chamber on the potential evapotranspiration rate calculation for the WACA Dome. Assume volume rate of flow = 4.8 m$^3$/s, temperature = 15°C and relative humidity = 35% (i.e. vapour pressure = 6 mb). (See Notes; Table 3)
Table 4. Effect of warming the air going into the chamber on atmospheric demand for water (vapour pressure deficit). Assume temperature = 15°C, relative humidity = 50%, i.e. vapour pressure = 8.5 mb and vapour pressure deficit = 8.5 mb

<table>
<thead>
<tr>
<th>Warming amount (°C)</th>
<th>Resultant change in vapour pressure (mb)</th>
<th>Resultant initial pressure (mb)</th>
<th>Saturated vapour pressure (mb)</th>
<th>Increase in vapour pressure deficit (mb)</th>
<th>Resultant vapour pressure deficit (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>8.5</td>
<td>18.2</td>
<td>1.2</td>
<td>9.7</td>
</tr>
<tr>
<td>2</td>
<td>-0.1</td>
<td>8.4</td>
<td>19.4</td>
<td>2.5</td>
<td>11.0</td>
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<td>3</td>
<td>-0.1</td>
<td>8.4</td>
<td>20.6</td>
<td>3.7</td>
<td>12.2</td>
</tr>
<tr>
<td>5</td>
<td>-0.1</td>
<td>8.4</td>
<td>23.4</td>
<td>6.5</td>
<td>15.0</td>
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<tr>
<td>10</td>
<td>-0.2</td>
<td>8.3</td>
<td>31.7</td>
<td>14.9</td>
<td>23.4</td>
</tr>
</tbody>
</table>
Figure 5. Effect of warming on atmospheric demand for water. Assume initial temperature = 15°C, relative humidity = 50% (i.e. vapour pressure = 8.5 mb and vapour pressure deficit = 8.5 mb).
5. Discussion

It has already been noted that all of the above calculations are based on there being no change to the rate at which the pitch and turf can supply moisture to the atmosphere. This is obviously dependent upon the moisture status of the soil, and the resistances to moisture transfer from the soil, roots and leaves to the atmosphere. The analysis does provide a useful guide to the sort of potential evapotranspiration rates that can be expected under given conditions.

Figure 1 is most significant: the large effect of increasing the volume of air passing through the dome is evident. It emphasizes the importance of ventilation rate in influencing the potential rate of moisture removal from the dome. By manipulating this factor alone, significant changes in the rate of evapotranspiration could be achieved (until some other factor becomes limiting). From the initial investigations on September 19 and 20, 1987 the flow rates through the two fans were measured at 14.55 and 14.98 m/s resulting in a total flow through the dome of 4.8 m³/s. As can be seen from Table 1, doubling the flow rate through the dome effectively doubles the potential to remove moisture from the pitch.

Bourgault du Coudray (1988) estimates the dome volume to be 2458 m³ resulting in a turnover time for the air within the dome of 8.5 minutes at the above flow rate (see Table 1). Evaporation could be suppressed by lowering ventilation rates until they become the evaporation limiting factor.

At high ventilation rates it is likely that soil or plant properties would become the limiting factor. These calculations presume a steady state exists within the dome. The error associated with this assumption relates to how fast the air is exchanged in the dome (the turnover time) compared to the changes in atmospheric conditions. Bourgault du Coudray (1988) has estimated the error associated with this effect using the data set from Appendix 1. He found it to be usually less than 5% and never more than 25% in terms of evapotranspiration rate.

Figure 2 shows that the equation is relatively insensitive to temperature, and Figure 3 confirms that errors associated with the warming of the air (natural or artificial) within the chamber will have a minimal effect on the calculation of evapotranspiration, i.e. measuring VPD at different inlet and outlet temperatures will have little effect on the calculation.

The potential effect of artificially raising the temperature of the air within the chamber however, is better illustrated in Figure 4. If we assume that there is no limit to the rate at which the soil and turf can supply moisture to the atmosphere, the transport of water from the pitch surface may be calculated using an exchange coefficient (Teare and Peet, 1983):
\[ Et = k (P_{ws} - P_{wa}) \]

Equation (7)

where

- \( Et \) = evapotranspiration rate
- \( k \) = constant (would be totally dependent upon ventilation if the soil and plant resistance remain constant)
- \( P_{ws} \) = saturated vapour pressure
- \( P_{wa} \) = actual vapour pressure

and \( (P_{ws} - P_{wa}) \) = vapour pressure deficit (VPD).

Clearly, with the above assumptions, the rate of evapotranspiration is very dependant upon the VPD, and as Figure 4 illustrates, this can be manipulated by warming the air within the chamber. For the stipulated conditions, the VPD of the air entering the chamber could be doubled by warming the air by approximately 6°C. Further work is needed to assess the effectiveness of warming in terms of both evapotranspiration and plant growth (particularly if lights are to be used as the heat source) as it is likely to change soil and plant resistances to moisture transfer. The linear effect of increasing VPD on the potential evaporation rate shows that there is considerable scope to manipulate moisture removal from the pitch by warming. If lighting is used, it has the added advantage of being able to increase photosynthesis and growth of the turf during winter.
6. Evapotranspiration Measurements

Appendix 1 shows the calculated evapotranspiration from September 19 and 20, 1987. On a warm, fine afternoon (19/8) the evapotranspiration rate from the dome peaked at 0.25 mm/hr. On a cool, rainy day (20/8) the evapotranspiration rate averaged only 0.04 mm/hr (some of this was probably condensation being removed from the walls at the chamber). The vapour pressure difference between incoming and outgoing air for the former is about 18 mb, whereas for the latter it is about 3 nib. This gives an indication of the sort of accuracy required for vapour pressure measurements if more information is required on evapotranspiration from within the dome. Similarly, the accuracy requirement of air flow rate measurements through the fans can be judged from Figure 1.

Recent measurements taken with a sling psychrometer (Bourgault du Coudray, 1988) are shown in Table 5. The evapotranspiration rate was calculated using equation 5. The volume flow rate of air is assumed to be 4.8 m$^3$/s, as at 19/8/1987. The evapotranspiration rate calculated for the 9/6/1988 is similar to 20/8/1987 and is lower than for 10/6/1988, again reflecting lower evapotranspiration rates under cooler and more humid conditions.

<table>
<thead>
<tr>
<th>Date</th>
<th>Relative humidity (%)</th>
<th>Dry temperature ($^\circ$C)</th>
<th>Vapour Pressure</th>
<th>$\Delta$mb</th>
<th>$Et$ (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In</td>
<td>Out</td>
<td>In</td>
<td>Out</td>
<td>In</td>
</tr>
<tr>
<td>9/6/88</td>
<td>90</td>
<td>78</td>
<td>18</td>
<td>18</td>
<td>18.6</td>
</tr>
<tr>
<td>10/6/88</td>
<td>79</td>
<td>66</td>
<td>22</td>
<td>20.5</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Note that vapour pressure is calculated from relative humidity and temperature via standard tables. It is a simple matter to take sling psychrometer and airflow measurements to enable a rough calculation of the evapotranspiration rate from the pitch when under the dome. Knowledge of this rate will assist groundstaff to manipulate the moisture content of the pitch surface. Therefore, it is hoped that the dome will not only prove useful in keeping incident rainfall off the pitch area, but may be used to manipulate the moisture content of the pitch by altering environmental conditions. With a more thorough understanding of the dynamics of evapotranspiration from the pitch and turf the dome can be used more effectively to also manipulate plant growth.
7. Conclusion

A theoretical treatment of the evapotranspiration equation reveals that it is very sensitive to air flow rate, but relatively insensitive to temperature. For the dimensions of the W.A.C.A. dome simple measurements of vapour pressure (using a sling psychrometer) and air flow rate (using a suitable technique) can be used to estimate evapotranspiration from the pitch area. The potential evapotranspiration rate can be easily manipulated by changing the air flow rate through the dome. Warming the air entering the chamber will serve to increase the potential evapotranspiration by increasing VPD, and with effects on plant growth may provide a useful tool in combination with varying the dome air flow rate. Further assessment of the effect of warming is required. Once the characteristics of the dome and its effects on evapotranspiration and turf growth are better understood, it should provide a useful management tool for the ground staff.
8. Acknowledgements

Thanks are due to Dr W.D. Scott (Murdoch University), Tony Passchier (ALCOA), Phil Bourgault (Murdoch University), Rob Sudmeyer and Kim Burke (WADA) and the ground staff at the WACA for their kind assistance.

9. References


Appendix 1

WACA DOME

MEAN TRANSPIRATION (L/min) USING Eqs 2.3, 4.5 vs TIME

[Graph showing transpiration rates over time]