On the attribution of changing pan evaporation

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1. Introduction

Evaporative demand, measured by pan evaporation, has declined in many regions over the last several decades. It is important to understand why. Here we use a generic physical model based on mass and energy balances to attribute pan evaporation changes to changes in radiation, temperature, humidity and wind speed. We tested the approach at 41 Australian sites for the period 1975–2004. Changes in temperature and humidity regimes were generally too small to impact pan evaporation rates. The observed decreases in pan evaporation were mostly due to decreasing wind speed with some regional contributions from decreasing solar irradiance. Decreasing wind speeds of similar magnitude has been reported in the United States, China, the Tibetan Plateau and elsewhere. The pan evaporation record is invaluable in unraveling the aerodynamic and radiative drivers of the hydrologic cycle, and the attribution approach described here can be used for that purpose. Citation: Roderick, M. L., L. D. Rotstayn, G. D. Farquhar, and M. T. Hobbins (2007), On the attribution of changing pan evaporation, Geophys. Res. Lett., 34, L17403, doi:10.1029/2007GL031166.

2. Attribution Using the PenPan Model

The PenPan model is based on Penman’s combination equation [Penman, 1948]. It assumes a steady state energy balance, which for a Class A pan requires periods of at least a week and the applications described later use monthly input data. The radiative and aerodynamic components are based on the Linacre [1994] and Thom et al. [1981] models respectively. In brief, the evaporation rate from the pan ($E_p$ kg m$^{-2}$ s$^{-1}$) is expressed as the sum of radiative ($E_{p,R}$) and aerodynamic ($E_{p,A}$) components,

$$E_p = E_{p,R} + E_{p,A} = \left( \frac{s}{s + a\gamma} R_{n} \right) + \left( \frac{a\gamma}{s + a\gamma} f_0(u)D \right)$$

with $s$ (Pa K$^{-1}$) the change in saturation vapour pressure ($e_s$, Pa) with temperature evaluated at the air temperature ($T_a$, K) two metres above the ground, $R_n$ (W m$^{-2}$) the net irradiance of the pan, $\lambda$ (J kg$^{-1}$) the latent heat of evaporation, $a$ ($= 2.4$ here) the ratio of effective surface areas for heat and vapour transfer, $\gamma$ ($= 67$ Pa K$^{-1}$) the psychrometric constant, $D$ ($= e_s - e_{in}$, Pa) the vapour pressure deficit at two metres and $f_0(u)$ (kg m$^{-2}$ s$^{-1}$ Pa$^{-1}$) the vapour transfer function [Thom et al., 1981],

$$f_0(u) = 1.39 \times 10^{-5} (1 + 1.35u)$$

where $u$ (m s$^{-1}$) is the mean wind speed at two metres above the ground. The net irradiance of the pan is,

$$R_n = (1 - A_p)R_{p,sp} + R_{l,in} - R_{l,ou}$$

The last two terms are the incoming ($R_{l,in}$) and outgoing ($R_{l,ou}$) long-wave irradiance, with $R_{l,ou}$ calculated assuming the pan is a black body radiating at temperature $T_p$. The first term is the net short-wave irradiance, with $A_p$ ($= 0.14$ here) the pan albedo and $R_{p,sp}$ the incoming short-wave irradiance of the pan. $R_{p,sp}$ is greater than the global solar irradiance ($R_g$) because of additional interception by the walls of the pan [Rotstayn et al., 2006].
For attribution, the change in pan evaporation rate is given by differentiating equation (1),

\[
\frac{dE_p}{dt} = \frac{dE_{p,R}}{dt} + \frac{dE_{p,A}}{dt}
\]  

(4)

The term \( \frac{dE_{p,A}}{dt} \) is then partitioned into three components, denoted \( U^* \), \( D^* \), \( T^* \) for changes due to changing wind speed, vapour pressure deficit and temperature respectively. The components are defined by,

\[
\frac{dE_{p,A}}{dt} \approx \frac{\partial E_{p,A}}{\partial u} \frac{du}{dt} + \frac{\partial E_{p,A}}{\partial D} \frac{dD}{dt} + \frac{\partial E_{p,A}}{\partial s} \frac{ds}{dt} + \frac{\partial E_{p,A}}{\partial T_a} \frac{dT_a}{dt} = U^* + D^* + T^*
\]  

(5)

3. Materials and Methods

Data were collated from existing Australian Bureau of Meteorology (BoM) digital records: class A pan evaporation and wind speed (IDCIDC05.200506), temperature and humidity (IDCHCO2.200506) and radiation (NCCSOL Vers 2.209). We estimated monthly averages when 25 daily observations were flagged as validated by the BoM. Months not satisfying this criterion were omitted. \( T_a \) and humidity was measured in Stevenson screens, while \( u \) was measured using an anemometer 2 m above the pan. Starting with the 60 or so high quality sites previously identified [Roderick and Farquhar, 2004; Jovanovic et al., 2005], we identified a subset of 41 sites (auxiliary Table S1) having near-complete records of \( E_p \) and the observations needed to calculate \( E_{p,A} \).

As in many regions [Stanhill, 1997] the radiation database [Forgan, 2005] is the most heterogeneous of the meteorological databases. Of the 41 sites, 26 have some measurements of \( R_s \) (auxiliary Table S1) in the 1975–2004 period, but only seven have complete 30-year records. Observations of \( R_{in} \) are more restrictive with 11 sites having observations, the earliest from 1995. For 1975–2004, we estimated \( R_{in} \) at any site having \( R_s \) observations using the FAO56 approach [Allen et al., 1998],

\[
R_{in} = \sigma T_a^3 \left( 1 - \left( 0.34 - 0.14 \sqrt{e_a/1000} \right) \right)
\]

\[
\cdot \left( 1.35 R_s / \left( R_s (0.75 + 2 \times 10^{-5} z) - 0.35 \right) \right)
\]

(6)

with \( R_s \) (W m\(^{-2}\)) the top of atmosphere solar irradiance, and \( z \) (m) the site elevation. Equation (6) includes water vapour but ignores other greenhouse gases (e.g., \( \text{CO}_2 \)) and aerosols (e.g., dust). For the 30-year period considered here, the effect of trends in the ignored greenhouse gases on \( E_p \) should be small compared to the known trends in \( E_p \). Further, recent simulations with the CSIRO climate model suggest that changes in dust-loading over Australia were also small between the 1950s and 1990s [Rotstayn et al., 2007].

Digital metadata (BoM) showed no site location changes at any of the 41 sites. We examined the observations for obvious problems, especially discontinuities due to, for example, unreported changes in site location. At Darwin Airport, there was an obvious problem with \( u \) measurements before 1977 (auxiliary Figure S3). All analyses at that site are for 1977–2004. In several other instances, we identified what initially appeared to be suspect \( E_p \) observations. For example, at Alice Springs the very low \( E_p \) during 1975–1978 look anomalous when viewed in isolation. However, they were quantitatively consistent with the concurrent low values of \( u \), \( D \), and \( R_s \) (auxiliary Figure S3). The same was found when examining other apparently anomalous situations.

4. Results

4.1. Evaluation of the PenPan Model

We first used the PenPan model to calculate \( E_p \) using complete (post-1995) observations \( (R_s, R_{in}, T_a, u, e_r, e_u) \). The agreement between modelled and observed \( E_p \) at the 11 sites (auxiliary Figure S1, \( R^2 = 0.95 \), \( n = 903 \), RMSE = 22 mm m\(^{-1}\)) was excellent. Next, we used the available \( R_{in} \) observations to evaluate the FAO56 equation. There was no evidence of a change in the slight bias (~6 W m\(^{-2}\)) over time (results not shown) and we concluded that equation (6) was satisfactory for the intended purpose (auxiliary Figure S2, \( R^2 = 0.97 \), \( n = 916 \)). Finally, we used equation (6) to estimate \( R_{in} \) and thereby calculated \( E_p \) at the 26 sites for any month with observations of \( R_s, T_a, u, e_r \) and \( e_u \). The comparison with \( E_p \) observations was excellent (Figure 1).

\(^{1}\text{Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/}\ 2007gl031166. Other auxiliary material files are in the HTML.
Table 1. Observed (OBS) and Model-Calculated (CALC) Trends in Pan Evaporation Rate ($dE_p/dt$, in mm a$^{-2}$) at 7 Sites Having Near-Continuous Data for 1975–2004$^a$

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</table>

$^a$OBS, observed trends; CALC, model-calculated trends. Pan evaporation rate ($dE_p/dt$) is given in mm a$^{-2}$. The modelled trend is the sum of the radiative (Rad = $dE_p,R/dt$) and aerodynamic (Aero = $dE_p,A/dt$) components per equation 4. The aerodynamic component is partitioned into components due to changing wind speed ($U^*$), vapour pressure deficit ($D^*$) and temperature ($T^*$) per equation 5. See auxiliary Figure S3 for data and calculations at the sites.


Figure 2. Trends in observed pan evaporation rate and its components at 41 sites for the period 1975–2004. (a) Observed pan evaporation rate. (b) Radiative component of pan evaporation rate calculated as the difference between Figures 2a and 2c. (c) Aerodynamic component of pan evaporation rate. The trend in the aerodynamic component is further partitioned (equation 5) into the change due to changing (d) wind speed, (e) vapour pressure deficit, and (f) air temperature. The change in each panel, averaged across all 41 sites is (a) $-2.0$ mm a$^{-2}$, (b) $+0.6$ mm a$^{-2}$, (c) $-2.6$ mm a$^{-2}$, (d) $-2.7$ mm a$^{-2}$, (e) $0.0$ mm a$^{-2}$, and (f) $0.0$ mm a$^{-2}$. Details and trends are available for each site in auxiliary Table S1. (Note: The magnitude of the trend is scaled to the dot area per the legend.)
4.2. Applying the Attribution Approach

In order to test whether the approach was feasible, we first used the seven “elite” sites having complete observations for 1975–2004, where we calculated $E_{\text{p,}A}$ and $E_{\text{p,R}}$ and thereby closed the energy balance. The trends in those two components should sum to the observed $E_p$ trend (equation 4) within error limits. The estimated uncertainty in the model calculations (24 mm m$^{-1}$, Figure 1) is equivalent to an uncertainty in the trend estimate over the 30-year period of 1.8 mm a$^{-1}$ (±1 sd). With that uncertainty, the observed and calculated trends were within 95% confidence intervals at all seven sites (Table 1).

While most pan evaporation sites considered here, or anywhere, do not have radiative observations, we did have near-complete records of the aerodynamic component at each site. To apply the approach at all 41 sites, we estimated the trend in the radiative component as the difference between the trends in observations and aerodynamic components (i.e., $dE_{\text{p,R}}/dt = dE_{\text{p}}/dt - dE_{\text{p,A}}/dt$). The results, including the separation of the aerodynamic component into individual components ($U^*$, $D^*$, $T^*$ per equation 5) are shown in Figure 2.

Much of the trend in $E_p$ observations (Figure 2a) was due to changes in the aerodynamic component (Figure 2c), and the majority of that was due to changes in wind speed (Figure 2d) with generally minor changes due to changes in both vapour pressure deficit and air temperature (Figures 2e and 2f). However, as expected [Roderick and Farquhar, 2004], there was spatial variation in the results. A notable feature is the decrease in the radiative component shown in the northwest (Figure 2b). Also of note are the two sites showing relatively large increases in $E_p$ in the centre (Alice Springs, 133.89°E, 23.80°S) and south (Woomera, 136.81°E, 31.16°S). At Woomera there were obvious problems with the data. At Alice Springs, the trend was very sensitive to the starting date because of very low $E_p$ values during 1975–1978 (auxiliary Figure S3).

To put the changes in perspective, the trend in $D$ averaged over all 41 sites was −0.2 Pa a$^{-1}$ (auxiliary Figure S4) compared to a background average of 1205 Pa, or less than 1% over the 30 years. In contrast, the trend in $u$ averaged over all 41 sites was −0.01 m s$^{-1}$ a$^{-1}$ (auxiliary Figure S4) against a background average of 2.3 m s$^{-1}$: a reduction of 13% over the same period. The change in $u$ was occurring more or less equally in all seasons (auxiliary Figure S5).

5. Discussion

Previous research reported a trend in pan evaporation rate, averaged over 61 Australian sites for 1975–2002, of −3.3 mm a$^{-2}$ [Roderick and Farquhar, 2004]. This was later updated (an addendum is available from the authors) to −3.2 mm a$^{-2}$ to account for the installation of bird guards. The trend for 1975–2004 over the same 61 sites is lower at −2.4 mm a$^{-2}$ (results not shown) because of the high pan evaporation rates during the drought conditions prevailing over much of southeast Australia since 2002. For the 41 sites used here, the averaged trend for 1975–2004 was similar at −2.0 mm a$^{-2}$.

Improvements could be made to the PenPan model, particularly in the calculation of the pan albedo and the treatment of incoming and outgoing long-wave irradiance. Similarly, the meteorological databases are subject to ongoing improvements [Coughlan et al., 2005]. With those caveats, the model performed satisfactorily (Figure 1, Table 1) given the well-known difficulties in making long-term measurements of, and modelling, micrometeorological phenomena. According to the attribution analysis (Figure 2), the reasons for changing pan evaporation differed between sites: there was an indication of a decrease in the radiative component in northwest Australia consistent with increased rainfall and cloud cover in that region [Smith, 2004; Rotstayn et al., 2007]. However, decreases in the aerodynamic component were more important and primarily due to decreasing wind speed. These results are consistent with recent research [Roderick and Farquhar, 2006; Rayner, 2007]. The importance of decreasing wind speed and/or radiation as a reason for decreasing pan evaporation has also been found in the USA [Hobbins, 2004], parts of China [Xu et al., 2006a] and other countries.
et al., 2006a] and the Tibetan Plateau [Shenbin et al., 2006; Zhang et al., 2007].

[16] Whether the “stilling” reported here is local, i.e., attributable to changes in the immediate environment of the pans (e.g., growing trees or other obstacles progressively obstructing the air flow), or a more regional phenomenon is difficult to assess. Rayner [2007] investigated that by comparing the BoM wind observations against two alternative sources, (1) wind fields in the NCEP reanalysis, and (2) wind calculated using BoM surface air pressure observations. The results were inconclusive because the trends derived from (1) and (2) were inconsistent, and neither result was consistent with the BoM surface observations.

[17] Some of the wind speed decreases reported here are no doubt due to local effects. Alternatively, the very widespread nature of the stilling is by itself some evidence of a more robust regional effect. Indeed, the changes reported here are very similar to those reported elsewhere (Table 2). Whilst largely unanticipated in the climate change impacts community, previous analyses have predicted a slowing in the overall circulation rate in tropical regions and, presumably, a reduction in averaged wind speed in those regions with greenhouse warming [Betts, 1998; Held and Soden, 2006; Vecchi et al., 2006]. Although not strictly comparable to surface winds, the summary compiled by Lorenz and DeWeaver [2007] shows that climate models generally predict changes in zonally averaged mid-latitude wind speeds (at 850 hPa) of almost 0.5 to −1.5 m s⁻¹ over the 21st Century with largely complementary increases nearer the poles. This would qualitatively fit the pattern in the observations (Table 2, increase in Antarctica, decrease elsewhere). The model projections are equivalent to trends of −0.005 to −0.015 m s⁻¹ a⁻¹ and are of the same order as the observed trends (Table 2). In contrast to the terrestrial-based anemometer records (Table 2), recently reported satellite retrievals indicate increases in oceanic wind speed averaging 0.008 m s⁻¹ a⁻¹ for 1987–2006 [Wentz et al., 2007]. This emphasizes the urgent need for research on the wind measurements and the modelling given the scientific importance as well as the widespread interest in wind power generation.

6. Conclusion

[18] When forced with radiation, temperature, humidity and wind observations, the PenPan model simulated the pan evaporation observations well. Over Australia, that approach revealed differences between sites, but on the whole, decreasing wind speed was found to be the main reason for decreasing pan evaporation. The observed decrease in wind speed, was similar to the decreases reported over other terrestrial surfaces. Our results show that the extensive world-wide network of pan evaporimeters could be used to recover information about changes in the radiative and aerodynamic drivers of evaporative demand. This would be extremely useful because there are many more pan evaporimeters than radiometers.

[19] Acknowledgments. We thank Alan Beswick, John Carter, Edward Linacre, David Rayner and Blair Trewin for helpful discussions and Alison Saunders for expert assistance with acquiring and processing the data. We acknowledge funding from the Managing Climate Variability Program managed by Land and Water Australia (MLR, GDF), the Australian Greenhouse Office (LDR) and a Gary Comer Award (GDF). We acknowledge the BoM and especially the numerous BoM observers whose work formed the ultimate basis of this study.

References


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Auxiliary Material

August 2007

Auxiliary Figure S1  Comparison of observed and calculated pan evaporation rates. The PenPan model was forced with observations ($R_a$, $R_{l,in}$, $T_a$, $e_s$, $e_a$, $u$). Locations (11 sites) shown in the inset. Best fit regression; $y = 0.97 x + 9.6$, $R^2 = 0.95$, $n = 903$ (1:1 line shown). The RMSE is 22 mm mth$^{-1}$.

Auxiliary Figure S2  Comparison of observed and calculated incoming long wave irradiance ($R_{l,in}$). Calculations per the FAO56 model (see Eqn 6 in main text). Site locations ($n = 11$) as per Fig. A. Best fit regression; $y = 1.01 x + 6.7$, $R^2 = 0.97$, $n = 916$ (1:1 line shown). The RMSE is 13 W m$^{-2}$.
Auxiliary Figure S3  Monthly time series for the seven “elite” sites listed in Table 1. From the top, panels show; observed (line) and PenPan based calculations (×) of pan evaporation; rainfall; wind speed; air temperature; saturated (eₙ, top) and actual (eₐ, bottom) vapour pressure; global solar irradiance. The title of each plot gives the BoM station number and the name.

Auxiliary Figure S3a
Auxiliary Figure S3b (cont’d)
Auxiliary Figure S3c (cont’d)
Auxiliary Figure S3d (cont’d)
Auxiliary Figure S3e (cont’d)
Auxiliary Figure S3f (cont’d)
Auxiliary Figure S3g (cont’d)

76031 - MILDURA AIRPORT

Ep (mm mth⁻¹)

Rainfall (mm mth⁻¹)

U (m s⁻¹)

Ta (°C)

e, es (Pa)

Rs (W m⁻²)

V (m m胸怀)
Auxiliary Figure S4  Trends in (A) wind speed and (B) vapour pressure deficit at 41 sites for the period 1975-2004. The change in each panel, averaged across all 41 sites is (A) -0.01 m s⁻¹ a⁻¹ and (B) -0.2 Pa a⁻¹.

Auxiliary Figure S5  Trends in wind speed at 41 sites for the period 1975-2004 in four seasons (DJF, MAM, JJA, SON). The change in each panel, averaged across all 41 sites is, (A) (DJF) -0.01 m s⁻¹ a⁻¹, (B) (MAM) -0.01 m s⁻¹ a⁻¹, (C) (JJA) -0.01 m s⁻¹ a⁻¹, and (D) (SON) -0.01 m s⁻¹ a⁻¹.
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Auxiliary Table S1  Trends and averages, indicated by overbar in annual pan evaporation (\(E_p\)), and model-based calculations of the radiative (\(E_{p,R}\)) and aerodynamic (\(E_{p,A}\)) components of pan evaporation at 41 sites for the period 1975-2004 along with the number (\(n\)) of observations used in the respective calculations. \(U^*, D^*, T^*\) (see Eqn 5) are estimates of the change in the aerodynamic component due to changes in wind speed, vapour pressure deficit and temperature respectively. The trends \((dE_p/dt, dE_{p,R}/dt, dE_{p,A}/dt)\) are the slopes of a linear regression (ordinary least squares). The trends were first calculated separately for each month, and because a linear regression was used, the annual trend at the site could be calculated from the 12 monthly trends. The advantage of this procedure is that we did not have to estimate missing data. Decomposition of the aerodynamic component \((dE_{p,A}/dt = U^* + D^* + T^*,\) Eqn 5) followed the same procedure, with each of the appropriate variables held at their mean monthly values when evaluating the partial derivatives.

# Data for site 14015 (Darwin Airport) is for 1977-2004.

Note 1. The BoM evaporation pans are fitted with a standardised mesh screen, called a bird-guard. During the 1970s the BoM retro-fitted bird-guards on some pans and these reduce evaporation by about 7% [Hoy and Stephens, 1979; van Dijk, 1985], so data recorded prior to bird-guard installation were reduced by 7%. Nine (of 41) sites required adjustment with the last bird-guard installed in November, 1976. The BoM bird-guard reduces the solar irradiance at the water surface by about 6% [Wallace, 1994], very close to the 7% cited above. This implies that the bird-guard reduces the radiative and aerodynamic components by about the same amount, and we reduced the PenPan model estimate of each component by 7%.

Note 2. Before 1988, the Australian \(R_s\) measurements were calibrated assuming that the mid-summer clear sky global solar irradiance \((R_s)\) should be the same from year to year [Frick et al., 1987; Forgan, 2005]. The measurements were subsequently adjusted by the assumed sensor drift. Unfortunately, it is not possible to re-process the data as neither the original observations or the applied correction is available (B. Forgan, pers. comm.). The statistical approach used prior to 1988 assumes no trends in non-cloud atmospheric elements, of which the most important are aerosols and water vapour. The aerosol assumption is plausible in Australia but cannot be evaluated because the original measurements are unavailable. The water vapour assumption is less reasonable [Arking, 1999] but the effects should be relatively small over the 30-year period considered here. Note that changes in \(R_s\) due to changes in the amounts and optical properties of clouds will be preserved in the observations and this is expected to be the most important variable in Australia.
References


Hoy, R. D., and S. K. Stephens (1979), Field Study of Lake Evaporation - Analysis of Data from Phase 2 Storages and Summary of Phase 1 and 2, Australian Water Resources Council, Canberra, Australia.
