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Pan Evaporation Trends and the Terrestrial Water Balance. I. Principles and Observations

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Abstract

Pan evaporation is just that – it is the evaporation rate of water from a small dish located at the ground-surface. Pan evaporation is a measure of the evaporative demand over terrestrial surfaces. Declines in pan evaporation have now been reported in many regions of the world. The trends vary from one pan to the next, but when averaged over many pans, they are typically in the range of −1 to −4 mm a^{-2} (mm per annum per annum). In energetic terms, a trend of −2 mm a^{-2} is equivalent to −0.16 W m^{-2} a^{-1} and over 30 years this is a change of −4.8 W m^{-2}. For comparison, the top-of-atmosphere forcing due to doubled CO_2 is estimated by the Intergovernmental Panel on Climate Change (IPCC) to be ~3.7 W m^{-2}. Hence, the magnitude of the pan evaporation trend is large. What is of even greater interest is the direction – a decline – given the well-established warming of the last 30–50 years. In this article, the first in a two part series, we describe the underlying principles in using and interpreting pan evaporation data and then summarise the reported observations from different countries. In the second article, we describe the interpretation of the trends in terms of changes in the terrestrial water balance.

1 Introduction

On average, the annual precipitation in Canberra, Australia, is about 620 mm across 104 rainy days – a little more than that in London, UK, where it is 590 mm across 153 days. Given very similar precipitation in both places, why is the London region so much greener and appear so much wetter than the Canberra region? In short, the difference is largely due to the much higher evaporative demand in Canberra. So how might the available water and landscape greenness change with global warming?

The first problem faced in examining issues of changing available water and landscape greenness is that the evapotranspiration rate (E_a) – the transfer of water from the land surface to the atmosphere, is extremely difficult to measure. Beyond water balance methods of no predictive capacity, one is generally constrained to examine the maximal E_a rate under given meteorological conditions, that is, E_a for an unlimited moisture supply, here called the atmospheric evaporative demand. In practice, this rate is most frequently and widely measured by pan evaporation, which is a straightforward measurement from a straightforward device: simply the evaporation rate of water from a dish located at the ground-surface and refilled daily. Traditionally, these simple pan evaporation measurements have been extensively used in irrigation scheduling, but they have recently come under more scientific scrutiny as they reveal hydroclimatologic trends and patterns worldwide.

There are networks of these devices in many different countries and analyses of the data collected, when averaged over many individual pans, show declines over the last 30–50 years (Gifford 2005; Peterson et al. 1995). What does this tell us about changes in the hydrologic cycle? What does it tell us about the impacts of climate change? At first glance, the observations appear surprising because the near-surface air temperature has been increasing and a widespread view is that this should lead to increased evaporative demand (e.g. see any of the four major IPCC reports from 1991, 1995, 2001 and 2007). That would be true provided all the other drivers of evaporative demand remain constant. We have even heard it argued that the decline in pan evaporation rate must be some sort of measurement artefact because everyone knows that it should have increased! Our view is the opposite: the best science often happens when confronted with surprising results. In this context, the fact that pan evaporation has declined in the face of increasing near-surface air temperature demonstrates that all else is not constant and that something very interesting must be happening.

In this article, the first in a two-part series, we describe the underlying principles in using and interpreting pan evaporation data and then summarise the available observations from many different countries. In the second article of the series we describe the interpretation of the pan evaporation trends in terms of changes in the terrestrial water balance.

2 *Background*

2.1 TERMINOLOGY

A glance through a leading environmental physics text reveals that evaporation (or evapotranspiration) is not very sensitive to changes in temperature when the vapour pressure deficit of the air is kept constant (Monteith and Unsworth 1990, p. 187). Instead, that text notes that evaporation is typically more sensitive to variations in radiation, humidity and wind speed. In contrast, a glance through any physics text on the kinetic theory will locate a statement asserting that evaporation is very sensitive to changes in temperature. Why are these statements so different? Of course, the answer is that the texts are referring to different rates. The environmental text is referring to the *net* transfer, because that is the most commonly used measure in environmental applications. The physics text is referring to evaporation as the (one-way) transfer from a liquid phase to a gas phase. Sometimes, such as in isotopic studies of water fluxes, it is useful to consider separately the one-way fluxes (Farquhar and Cernusak 2005). However, for the most part, environmental applications are usually based on the net transfer. To give an example, assume a closed beaker half filled with liquid water. The water in the beaker is assumed to be at thermodynamic equilibrium so that the masses of both the liquid and adjacent vapour phases are not changing over time. Under the convention where we consider one-way fluxes, evaporation is still occurring but is exactly balanced by condensation (gas-to-liquid transfer). Under the environmental convention, there is no *net* transfer between phases and the evaporation rate is said to be zero. Those different definitions do not hinder communication in environmental applications, because scientists know that the evaporative flux is usually the *net* transfer.

With that in mind, one often hears the statement, especially in the media, that because of global warming, evaporation must increase. At face value, that statement is easily supported by the kinetic theory. However, it is confusing, because it does not recognise that the evapotranspiration being referred to is the *net* transfer. This is one of those unfortunate circumstances where the language in widespread use is not as precise as it could be. The lack of precision has little impact in science and engineering, because everyone knows what is meant: the problem is that the general public do not. One consequence is that we need to be very careful how we communicate our results to the general public, because changes in the surface water balance are of widespread and vital interest. Of course, the real challenge is to explain to the general public how the earth's surface can warm while pan evaporation declines – the main topic of these articles.

2.2 MEASURING PAN EVAPORATION

Figure 1 shows a typical evaporimeter. Each day, the water lost (or gained) is replenished (or removed) to bring the water level back to a fixed height, measured by a vertical rod in the stilling well near the centre of the pan. After accounting for rainfall additions (using measurements made at adjacent rain gauges), it is possible to estimate the mass of water that has evaporated. The straightforward procedure is akin to sticking a ruler into a cup of water. The pan shown in Figure 1 has the standard dimensions applicable to all US Class A pans: 4 feet (1.21 m) in diameter, 10 inches (0.254 m) deep, and located on a wooden platform about 6 inches (0.15 m) above the ground. The US Class A pan is a very common installation, but is by no means universally implemented (Brutsaert 1982). Other types of pan are made of fibreglass or concrete; others are sunk into the ground. Some are larger, while others are smaller, such as the micro-pans widely used throughout China that are 0.2 m in diameter, 0.1 m deep, contain water

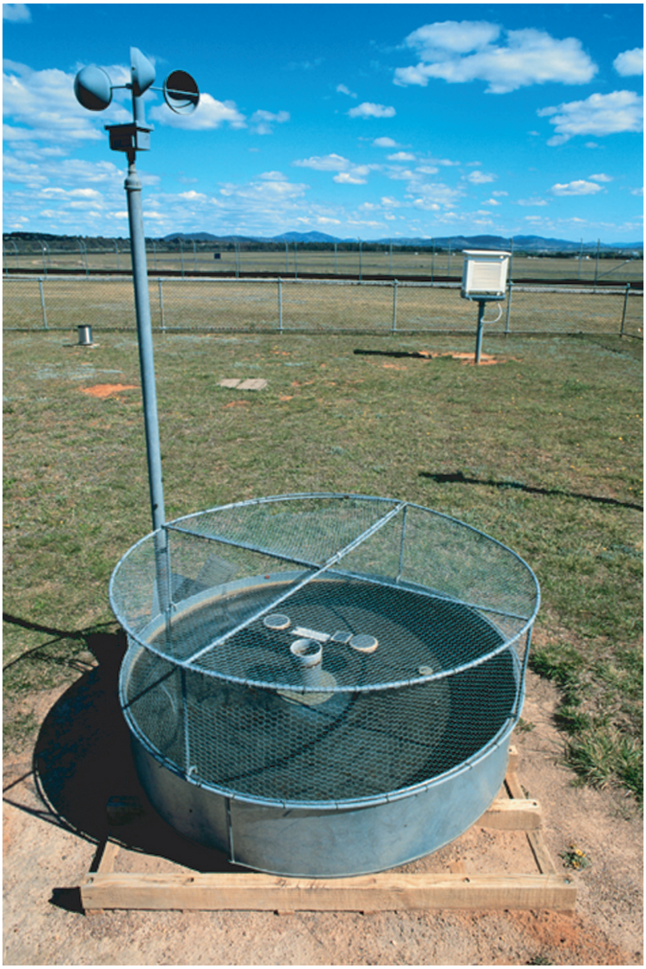

Fig. 1. The Class A pan evaporimeter at Canberra Airport. This pan is one of about 300 maintained by the Australian Bureau of Meteorology throughout Australia. Water in the pan is replenished and measured daily along with the minimum and maximum water temperature and precipitation. Australian pans are fitted with bird guards that reduce the daily pan evaporation rate by about 7% (van Dijk 1985).

to a depth of about 0.02 to 0.03 m, and are located on a wooden platform about 0.7 m above the ground (McVicar et al. 2007).

The daily pan evaporation measurements are aggregated into longer periods, typically weeks or months (see Section 2.4), and they are multiplied by a pan coefficient to estimate the evaporative demand. The underlying physical basis for a pan coefficient is that the surface area for the exchange of energy (water surface plus pan walls) is larger then the surface area for the exchange of mass (Riley 1966). Hence, the pan coefficient will vary depending on the ratio of those two areas and will therefore depend on the size and installation details of the pan (e.g. McVicar et al. 2007). For example, the standard US Class A pan is raised above the ground (Figure 1) and therefore intercepts more radiation than a plane water surface located at ground level (Linacre 1994). Traditionally, pan coefficients are assumed to vary with humidity and wind speed (Allen et al. 1998), but as pointed out by Linacre (1994), radiation is also important. This is an area where research would be welcome. Over longer periods such as months to years (see below), the pan coefficient for a US Class A pan is ~0.7 (Stanhill 1976).

2.3 ALTERNATIVE MEASURES OF EVAPORATIVE DEMAND

An alternative approach to estimating evaporative demand was advocated by Monteith (1981). The idea is to estimate an upper limit to evapotranspiration using a Penman-type approach (Penman 1948) requiring measurements of radiation, temperature, humidity and wind speed (Allen et al. 1998). This would be a very useful approach if those data were widely available. In general, suitable temperature, humidity and wind speed measurements are sometimes available, but radiation measurements are rarely available. To use Australia as an example, pan evaporation is currently recorded at approximately 300 sites. In contrast, solar radiation measurements are made at less than 20 sites, and near-continuous solar radiation data over the last 30 years are available at only seven sites (Roderick et al. 2007). The situation for long-wave radiation is even more restrictive: in Australia there are eight measurement sites with the oldest starting in 1995 (Roderick et al. 2007). Worldwide, the longest record of long-wave radiation measurements that we are aware of, is from the Swiss Alps and began in 1992 (Philipona et al. 2004). The paucity of radiation measurements (Stanhill 1997) means that the detailed calculations suggested by Monteith can be completed at too few sites to get a general idea of how evaporative demand is changing over time. One popular proxy for solar radiation measurements is the use of measurements of sunshine hours to estimate global solar irradiance. The problem here is that the relationship between sunshine hours and global solar irradiance has changed over time (Stanhill and Cohen 2005), presumably due to changes in the optical characteristics of the atmosphere and clouds and in cloud cover and type. Consequently, evaporation pans remain the instrument of choice for those interested in a general overview of how evaporative demand has changed.

2.4 PRACTICAL USE OF PAN EVAPORATION MEASUREMENTS

Pan evaporation measurements are widely used to estimate evaporative demand, because the equipment is readily available, affordable and simple to operate. For these reasons, evaporimeters are also very popular among farmers, especially irrigation farmers, and a few minutes searching on the internet will reveal much practical advice on how to schedule irrigation using evaporimeters. The underlying principle of irrigation scheduling is to increase the supply to meet the evaporative demand estimated by the evaporimeter measurements. Of course, as irrigation proceeds there are feedbacks between the irrigated surface and atmosphere, for example, increased absolute humidity, that alter the evaporative demand and lead to ongoing adjustments to the irrigation regime. Those feedbacks will be implicit in the measurements made by the evaporimeter (Ozdogan and Salvucci 2004) so that the irrigation regime will adapt over time. It is unknown when a pan evaporimeter was first used, but Brutsaert (1982) noted that Halley (of comet fame) used pans in a series of evaporation experiments in the late 1600s.

When using pans for practical applications like irrigation scheduling, or for examining trends in evaporative demand over time, it is important to understand, and account for, the dynamics of heat storage in the pan, as such storage substantially affects the diurnal and day-to-day variations in pan evaporation rate. This will be unfamiliar to those scientists and engineers used to dealing with the transpiration rate of individual leaves (and vegetated surfaces) whose negligible thermal mass maintains them in a quasi-steady state with respect to their heat balance over periods of minutes (Cowan 1965). One consequence of this negligible thermal mass is that the transpiration rate from well-watered vegetation growing in humid conditions typically follows the diurnal solar cycle. In contrast, the pan is 'well watered' but has a non-negligible thermal mass and the diurnal and short term dynamics can be quite different from vegetated surfaces. For example, detailed measurements over the course of a day show that water in a typical pan often warms up in the morning and the evaporation occurs preferentially in the mid-afternoon (Molina Martínez et al. 2006).

The importance of thermal mass in an evaporimeter can be readily understood by noting that the change in heat storage in the pan is a function of both the mass of water and of the difference in water temperature between the start and end of the period in question. The change in heat storage is balanced by the fluxes and described by,

$$mc(T_{w,t1} - T_{w,t0}) = \int_{t0}^{t1} (R_n - \lambda E_{pan} - H)dt \quad (1)$$

where m is the mass of water in the pan, c (~4200 J kg^{-1} K^{-1}) is the specific heat capacity of water, T_w is the bulk water temperature at times t_0 ($T_{w,t0}$) and t_1 ($T_{w,t1}$), R_n is the net irradiance of the pan, λ (~2.45 MJ kg^{-1}) the latent heat of vaporisation, E_{pan} is the pan evaporation rate and H is the net sensible heat exchange from the pan. For steady-state conditions, the heat storage would be zero.

The storage effect will be important when it is a relatively large fraction (e.g. > 10%) of the energetic equivalent of the integrated evaporation over the same period. To demonstrate the underlying principle, we use pan evaporation measurements and water temperature data taken for a full year at Canberra, Australia (Figure 2). The Australian Bureau of Meteorology measure pan evaporation daily at 09:00 hours. They also record the minimum and maximum water temperature over the previous 24-hour period using a floating thermometer (visible in Figure 1). For demonstration purposes, we assume that the minimum water temperature occurs at 09:00 hours. While not necessarily true, any error introduced by this assumption will not alter the resulting interpretation.

The data show that on a daily basis the absolute magnitude of the energy change due to storage can be up to about five times (–4.7, see Figure 2a) larger than the integrated evaporation, especially during periods of low evaporative flux (winter). On a weekly time-step, the relative importance of heat storage is smaller, because the evaporative flux is integrated over a longer period. Despite that, during winter heat storage can still be as high as 40% of the integrated evaporation but is smaller (< 10%) during summer (Figure 2b). Hence, a steady-state heat balance cannot be safely assumed over weekly periods during winter. On a monthly basis, the maximum (absolute) storage change was 8% of the integrated evaporation and generally much lower (< 2%). Hence, on a monthly basis, the energy balance of the pan can be safely assumed to be at steady state.

The key points here are that the integration period has to be sufficiently long that a steady-state energy balance can be safely assumed and that this period can be easily calculated given measurements of pan evaporation and water temperature. During summer, that period is of the order of a week but during winter it is safer to use a month, at least in Canberra. Hence, day-to-day variations in pan evaporation will not necessarily mimic the actual evapotranspiration from well-watered vegetation. However, over longer time periods, it has long been known that pan evaporation, when multiplied by the pan coefficient, is a good measure of the evapotranspiration from well-watered vegetation (McIllroy and Angus 1964; Rose et al. 1972). That is consistent with our understanding of the dynamics of heat storage in evaporation pans.

3 Applications of Pan Evaporation Data

3.1 SOIL WATER BALANCE MODELS

Soil water balance models use measurements of pan evaporation, multiplied by a pan coefficient, to set an *upper limit* on the evapotranspiration that can occur from the soil and plants surrounding the pan. There are many different varieties of models, but most are basically variations on a 'bucket model'. For example, a 'leaky' bucket model includes a transfer to groundwater via percolation through the base of the bucket. In the simplest form,

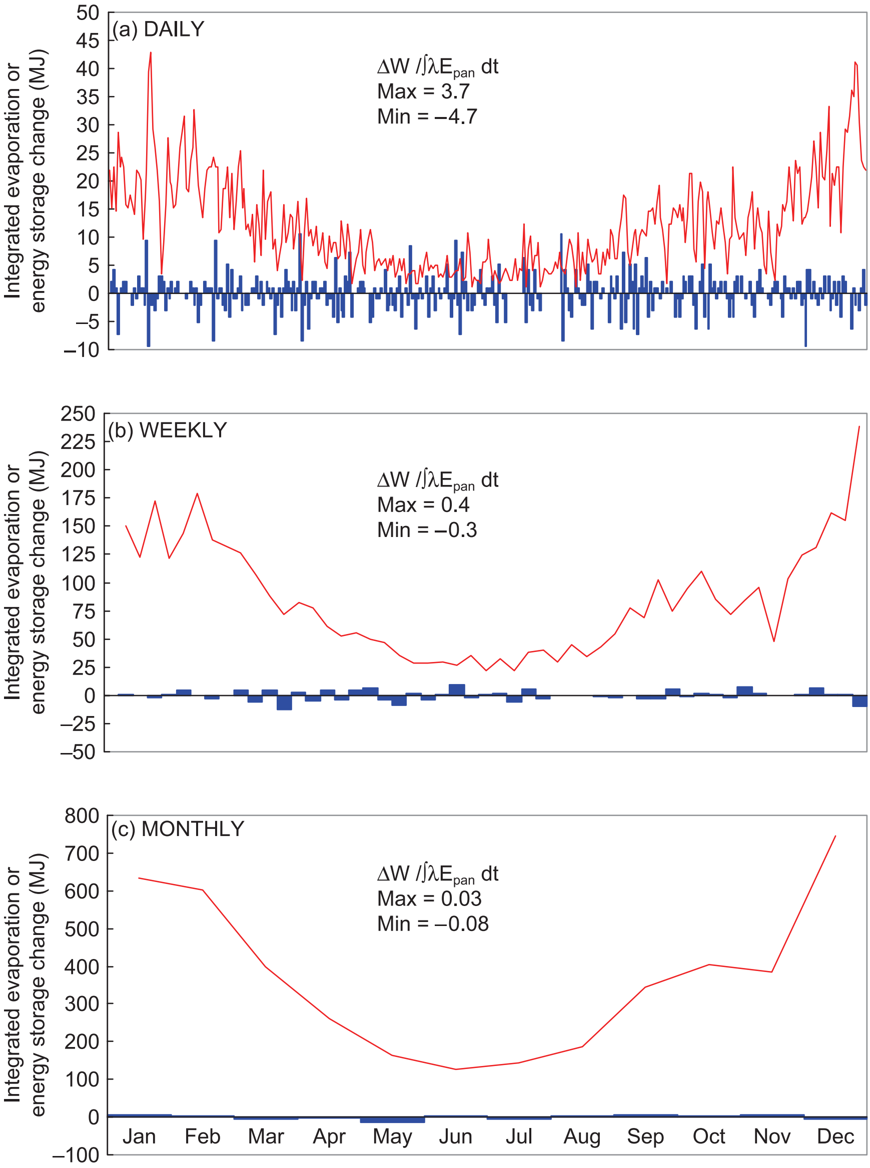

Fig. 2. Measurements of the integrated evaporation (line, $\int \lambda E_{pan} dt$) and the change in energy storage in the water (vertical bar, ΔW) at Canberra, Australia, over a complete year for the following time-steps: (A) daily; (B) weekly; and (C) monthly. The change in energy storage in the water is estimated using Eqn (1) assuming a water mass of 250 kg (ΔW [J] = 250 [kg] × 4200 [J kg^{-1} K^{-1}] × ($T_{w,t1} - T_{w,t0}$)[K]). The observed evaporative flux has been integrated over the relevant period ($\int \lambda E_{pan} dt$) and the minimum and maximum values of the ratio $\Delta W / \int \lambda E_{pan} dt$ are shown on each panel. Data are for the year 2000 and supplied by the Bureau of Meteorology.

the bucket does not leak and fills with precipitation (P) (and irrigation where appropriate) and empties through actual evapotranspiration (E_a) and runoff (Q). The bucket model is described by,

$$\frac{dS}{dt} = P - E_a - Q \quad (2)$$

with S the moisture stored in the bucket. The subscript a is a reminder that E_a is the 'actual evapotranspiration' rate, that is, the sum of evaporation from soil and transpiration from plants. The terms P, E_a and Q are all rates but for brevity we drop that qualifier from hereon.

When there is sufficient available water to meet the evaporative demand, evapotranspiration proceeds at the above-noted upper limit which is sometimes denoted the potential evaporation rate. In many cases, particularly where the wet area is extensive, this potential rate is dominated by the radiative component and the evaporative conditions are traditionally known as energy-limited. When the available water is not sufficient to meet the evaporative demand, actual evapotranspiration will be less than the upper limit and the conditions are said to be water-limited. This framework indicates that in water-limited environments, over periods for which changes in soil water are small, such as annual (or sometimes longer) periods, the trend in actual evapotranspiration is usually very close to the trend in precipitation. Exceptions can occur. For example, when there is a large change in rooting depth, such as when deep-rooted perennials are planted onto former crop land, the soil water is drawn down as the plants grow and rooting depth increases and, during this root-growth period, actual evapotranspiration can exceed precipitation (Calder et al. 1997). These are transient situations and eventually the system will again reach a state where removals of water are in balance with additions. This also highlights the point that the maximum available soil water is partly determined by vegetation (Donohue et al. 2007; Guswa 2008).

3.2 OTHER APPLICATIONS OF PAN EVAPORATION DATA

Estimating how precipitation is partitioned into actual evapotranspiration and runoff is important, but is not the only reason for using pan evaporation data. The ratio of supply to demand, often estimated as the ratio of precipitation to pan evaporation (or some variation thereof), has also been extensively used as a fundamental basis for understanding the climatic controls on vegetation distributions (Specht 1972; Stephenson 1990), following early work showing that forest to grassland boundaries could be mapped by the ratio of precipitation to pan evaporation (Transeau 1905). In closely related work, agricultural scientists have long known that variations in productivity were related to both transpiration and the evaporative demand via water-use efficiency (i.e. carbon uptake per unit of transpiration) as was first demonstrated by the use of pan evaporation data nearly 100 years ago (Briggs and Shantz 1913). The significance of this early work was recently reviewed by Landa and Nimmo (2003). Hence, pan evaporation data have also found widespread use by agronomists (Fischer 1979; Stanhill 2002). The literature is vast and longstanding.

4 Pan Evaporation Trends

Because of their numerous practical applications, many countries maintain standardised networks of evaporimeters. Those long-term data can be used to examine trends in evaporative demand. Of course, there are caveats: for example, ensuring no changes in observing practice, instrument location, the surroundings (e.g. buildings or trees progressively obstructing the air flow), and so on. With those caveats in mind, reports to date, when averaged over large numbers of pans, have indicated widespread declines in evaporative demand over the last 30–50 years. These are detailed in this section.

Studies reporting pan evaporation trends are summarised in Table 1. Note that at individual sites the trends can be either positive or negative. However, when restricted to studies using 10 or more sites, the trends averaged across sites fall in a typical range of −1 to −4 mm a^{-2} (units are mm per annum per annum) with the exception of larger decreases throughout India (−12.0 mm a^{-2}) and Thailand (−10.5 mm a^{-2}). For Australia, the study of Kirono and Jones (2007) reported a smaller decrease (−0.7 mm a^{-2}) than the two other Australian studies (−2.5 mm a^{-2}, see Jovanovic et al. 2008, and −3.2 mm a^{-2}, see Roderick and Farquhar 2004), perhaps because of the smaller number of sites and a different approach to 'homogenising' the data.

Overall, a trend of −2 mm a^{-2} is reasonably typical. Over 30 years, that equates to a reduction in annual pan evaporation of 60 mm a^{-1}. For comparison with climate change science, it is more convenient to use energetic units. To convert between depth and energetic units, note that a 1-mm depth of water is equivalent to 1 kg m^{-2} and with a latent heat of vaporisation of 2.45 MJ kg^{-1}, we have,

$$1\frac{\text{mm}}{\text{a}^2} = 1\frac{\text{kg}}{\text{m}^2\text{a}^2} \times 2.45 \times 10^6\,\frac{\text{J}}{\text{kg}} \times \frac{1\text{a}}{365 \times 24 \times 60 \times 60\text{s}} = 0.078\,\text{W m}^{-2}\text{a}^{-1} \quad (3)$$

Hence, in energetic terms, a trend in pan evaporation of −2 mm a^{-2} corresponds to (−2 × 0.078~−0.16)~−0.16 W m^{-2} a^{-1}. Over 30 years, this is a change of ~−4.8 W m^{-2}. For comparative purpose, the top-of-atmosphere radiative forcing due to instantaneously doubled CO_2 is estimated to be ~3.7 W m^{-2} (Forster et al. 2007), while model estimates give the trend in top-of-atmosphere energy imbalance of the planet for the period 1961–2003 as 0.02 W m^{-2} a^{-1}, leading to an energy imbalance in 2003 of ~0.8 W m^{-2} at the top of the atmosphere (Hansen et al. 2005). Clearly, the trends in pan evaporation are large and warrant detailed investigation.

Table 1. Averaged trends in pan evaporation (dE_{pan}/dt in mm a^{-2}, mm per annum per annum) from various regions[e].

dE_{pan}/dt	Region	Details	Reference
–2.2	USA	1948–1993 (MJJAS), 746 sites	Lawrimore and Peterson 2000; Peterson et al. 1995
–3.7	Former Soviet Union	1960–1990, 10 sites	Golubev et al. 2001; Peterson et al. 1995
–12.0	India	1961–1992, 19 sites	Chattopadhyay and Hulme 1997
–3.0	China	1955–2000, 85 sites	Liu et al. 2004
–3.1	China (Yangtze River basin)	1960–2000, 150 sites	Liu and Zeng 2004; Xu et al. 2006a,b
–3.9	China	1955–2000, 85 sites	Qian et al. 2006
–2.8	China (Yangtze River basin)	1961–2000, 115 sites	Wang et al. 2007
–3.2[a]	Australia	1975–2002, 61 sites	Roderick and Farquhar 2004
–2.5	Australia	1970–2005, 60 sites	Jovanovic et al. 2008
–0.7	Australia	1970–2004, 28 sites	Kirono and Jones 2007
–10.5	Thailand	1982–2001, 27 sites,	Tebakari et al. 2005
–2.0	NZ	~1970's–~2000, 19 sites	Roderick and Farquhar 2005
–4.5[b]	Tibetan Plateau	1966–2003, 75 sites	Zhang et al. 2007
Studies with fewer than 10 sites			
+4.3	Israel	1964–1998, 1 site	Cohen et al. 2002; Möller and Stanhill 2007
–24[c]	Turkey	1979–2001 (JJAS), 1 site	Ozdogan and Salvucci 2004
–1.0[d]	Canada	~1965–2000 (MJJAS), 4 sites	Burn and Hesch 2007
+13.6	Kuwait	1962–2004, 1 site	Salam and Mazrooei 2006
+0.6	Ireland	1960–2004, 1 site	Black et al. 2006
–5.1	Ireland	1976–2004, 1 site	Black et al. 2006
+0.8	Ireland	1964–2004, 8 sites	Stanhill and Möller 2008
–1.2	UK	Various time periods, mostly ~1900–~1968, 7 sites	Stanhill and Möller 2008
+2.1	UK	1957–2005, 1 site	Stanhill and Möller 2008

[a]Trend for 1975–2004 over the same 61 sites was –2.4 mm a^{-2} (Roderick et al. 2007).
[b]This study uses micro-pans (0.2 m diameter, 0.1 m deep) that have a pan coefficient of about 0.4 (McVicar et al. 2007). Hence, if Class A pans were used (pan coefficient ~0.7) the reported trend would be roughly halved, that is, –2.2 mm a^{-2}.
[c]This pan was located in an expanding irrigation area.
[d]Also reported calculations of lake evaporation showing a trend for 1971–2000 averaged across 48 sites of ~–1 mm a^{-2}.
[e]An additional study from Brazil (da Silva 2004) showing increases in E_{pan} was not included, because we were unable to extract realistic trends from the data presented in that article.

5 Summary

Evaporimeters have long been used to provide estimates of evaporative demand, but there is an alternative approach available – one that calculates evaporative demand from measurements of radiation, temperature, humidity and wind speed. The problem is, of course, that those data are available at very few sites anywhere in the world. Instead, perhaps because of their simplicity, many countries have chosen to maintain networks of evaporation pans. Indeed, these pans are, by and large, the only practical measure of evaporative demand we have available.

Analyses of the pan evaporation data averaged over many pans from many different countries has revealed declines that are typically in the range of -1 to -4 mm a^{-2} (Table 1). In energetic terms, a trend of say -2 mm a^{-2} is equivalent to -0.16 W m^{-2} a^{-1}. For comparison, estimates of the top of the atmosphere radiative forcing over the last 40 years are an order of magnitude lower at about 0.02 W m^{-2} a^{-1} (Hansen et al. 2005). Clearly, the pan evaporation trend is large, and combined with the fact that it has, on average, declined, warrants further and detailed investigation.

What does a decline in pan evaporation mean? In short, it means a decline in evaporative demand. However, there is no simple universal translation of the observed pan evaporation trend into a trend in the actual evapotranspiration, that is, the evaporation and transpiration from plants and soil. The reason for that should be clear from the article – pan evaporation measures the evaporative demand – but the actual evapotranspiration also depends on the supply as well as the demand. Interpreting the trends in terms of a supply-demand framework is the primary focus of the second article in this series.

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