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Pan Evaporation Trends and the Terrestrial Water Balance. II. Energy Balance and Interpretation

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Abstract

Declines in pan evaporation have been reported across the USA, former Soviet Union, India, China, Australia, New Zealand and Canada, among other places. The trend is large – approximately an order of magnitude larger than model-based estimates of top of the atmosphere radiative forcing. The pan evaporation trend also has a different sign (i.e. decline) from commonly held conceptions. These are a remarkably interesting set of observations. In the first article of this two-part series, we discussed the measurements themselves and then presented summaries of the worldwide observations. In this, the second article, we outline the use of energy balance methods to attribute the observed changes in pan evaporation to changes in the underlying physical variables, namely, radiation, temperature, vapour pressure deficit and wind speed. We find that much of the decline in pan evaporation can be attributed to declines in radiation (i.e. dimming) and/or wind speed (i.e. stilling). We then discuss the interpretation of changes in the terrestrial water balance. This has been an area of much misunderstanding and confusion, most of which can be rectified through use of the familiar and longstanding supply/demand framework. The key in using the pan evaporation data to make inferences about changes in the terrestrial water balance is to distinguish between water- and energy-limited conditions where different interpretations apply.

1 *Introduction*

There have been consistent reports of declines in pan evaporation over the last 30–50 years (Gifford 2005; Peterson et al. 1995). For example, the USA, former Soviet Union, India, China, Australia, New Zealand and Canada all show declines in pan evaporation (Roderick et al. 2009). Data like those inevitably challenge scientific understanding and many questions arise, including the following: (i) how is that possible if the air near the surface has been warming? and (ii) what does this mean for the terrestrial water balance?

Initially, it was thought that declining pan evaporation also meant declining actual evapotranspiration, that is, the evaporation and transpiration from soil and plants (Peterson et al. 1995). The topic has evoked some confusion – possibly because scientists not intimately involved with land surface studies have been looking for a consistent message. For example, the enhanced greenhouse effect is expected to lead to increases in near-surface air temperature and this is a relatively consistent message. So does declining pan evaporation mean declining actual evapotranspiration? The answer is, in short, 'not necessarily' (Brutsaert and Parlange 1998; Roderick and Farquhar 2004). Briefly, inferences about changes in the terrestrial water balance based on declining pan evaporation are more complex than a simple increase/decrease scenario, because pan evaporation measures the atmospheric demand while actual evapotranspiration depends on the demand and – crucially – the supply.

In this the second article of this two-part series, we begin by describing the use of energy balance methods to attribute the observed changes in pan evaporation to changes in the underlying physical variables, namely, radiation, temperature, vapour pressure deficit and wind speed. Following that we return to the interpretation and show how the observed trends in pan evaporation can be used to interpret changes in the terrestrial water balance via the supply/demand framework.

2 Attribution of the Trends via the Energy Balance of the Pan

2.1 THEORETICAL FRAMEWORK

Why has pan evaporation decreased? One way to approach this question is to examine the combined mass and energy balance of the pan. We know that changes in the storage of energy in the pan must equal the sum of all the heat fluxes, namely, the net irradiance along with the evaporative and sensible heat fluxes. For periods over which the energy storage can be neglected, we can assume a steady state – monthly periods are generally ideal for that purpose (Roderick et al. 2009). With that basis one can use a Penman (1948) approach to examine how declining pan evaporation is related to changes in the driving meteorological variables; radiation, temperature, humidity and wind speed.

2.2 THE PENPAN MODEL

Rotstayn et al. (2006) followed the mass and energy balance approach and combined the aerodynamic model developed by Thom et al. (1981) with the radiative model of Linacre (1994). Their final model, called PenPan, was formulated for use at monthly time scales and expresses the pan evaporation rate (E_{pan}, kg m^{-2} s^{-1}) as the sum of radiative ($E_{pan,R}$) and aerodynamic ($E_{pan,A}$) components,

$$E_{pan} = E_{pan,R} + E_{pan,A} = \left(\frac{s}{s + a\gamma} \frac{R_n}{\lambda} \right) + \left(\frac{a\gamma}{s + a\gamma} f_q(u) D \right) \tag{1}$$

with s (= de_s/dT, Pa K^{-1}) the change in saturation vapour pressure (e_s, Pa) (see Figure 1) 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, λ (J kg^{-1}) the latent heat of vaporisation, a (= 2.4 here) the ratio of effective surface areas for heat and vapour transfer, γ (~67 Pa K^{-1}) the psychrometric constant, D (= $e_s - e_a$, Pa, where e_a is the actual vapour pressure at 2 m) the vapour pressure deficit at two metres and $f_q(u)$ (kg m^{-2} s^{-1} Pa^{-1}) is an empirical vapour transfer function (Thom et al. 1981),

$$f_q(u) = 1.39 \times 10^{-8}(1 + 1.35u) \tag{2}$$

where u (m s^{-1}) is the mean wind speed at two metres above the ground.

First note that a is set as constant, while γ and λ in Eqn (1) are also more or less constant. Therefore, we see that pan evaporation would increase with increases in the net irradiance of the pan (R_n), the air temperature (via the sensitivity of s to T_a, Figure 1b), the vapour pressure deficit (D) and/or wind speed (u). Here we are considering changes in D, rather than changes in the individual components of D (= $e_s - e_a$). The basis is that with greenhouse warming we expect e_s to increase (with temperature) but we also expect e_a to increase, and hence we treat those changes together in terms of changing D. This is based on theory and observations showing that the warming associated with the enhanced greenhouse effect has led to increased absolute humidity in the atmosphere such that the relative humidity near the surface has, on average, remained roughly constant (Arrhenius 1896; Dai 2006; Held and Soden 2000, 2006; Roderick and Farquhar 2002; Wentz et al. 2007). This means that the direct effect on E_{pan} of a change in T_a is through changes in s, which increases rapidly with T_a. However, the sensitivity of E_{pan} to T_a is much smaller as s appears in the ratios $s/(s + a\gamma)$ and $a\gamma/(s + a\gamma)$ (see Eqn 1) that are themselves much less responsive to temperature than is s (Figure 1c). Hence, for typical temperature changes – say the global trend over the last 30 years of 0.015 K a^{-1} – the direct temperature effect on pan evaporation (i.e. with vapour pressure deficit, D, considered separately) is typically ~0.1 mm a^{-2} and is much smaller than the observed trends (Roderick et al. 2007). Note that the same conclusion would follow for T_a declining at the same rate.

Consequently, the observed declines in pan evaporation must be primarily due to some combination of changing R_n, u and D. The sensitivity to R_n is easy to understand (Eqn 1), but the sensitivity to u and D is more subtle (Figure 2). To see that, the product $f_q(u)D$ can be differentiated with respect to time,

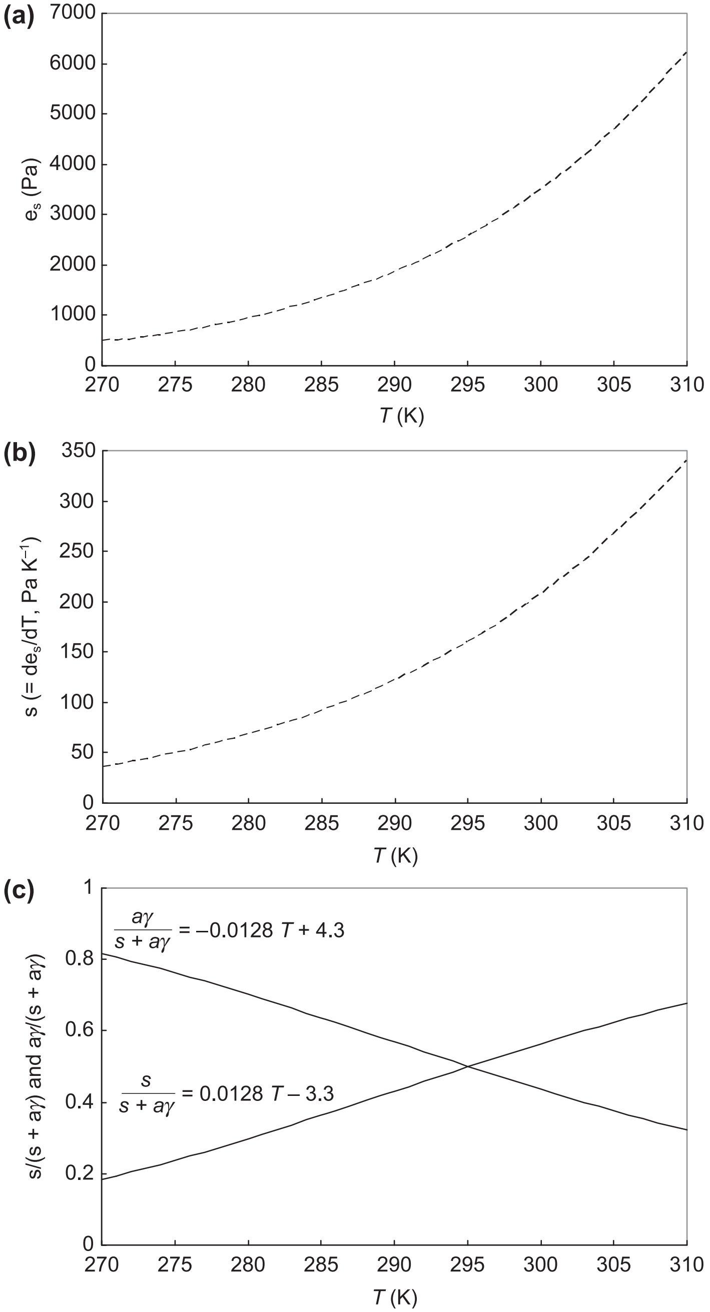

Fig. 1. Temperature sensitivity of the saturated vapour pressure and related terms. (A) Saturated vapour pressure (e_s) as a function of temperature (i.e. the Clausius-Clapeyron curve). (B) Slope of the saturated vapour pressure-temperature relation ($s = de_s/dT$). (C) Variation in terms in the PenPan formulation (Eqn 1).

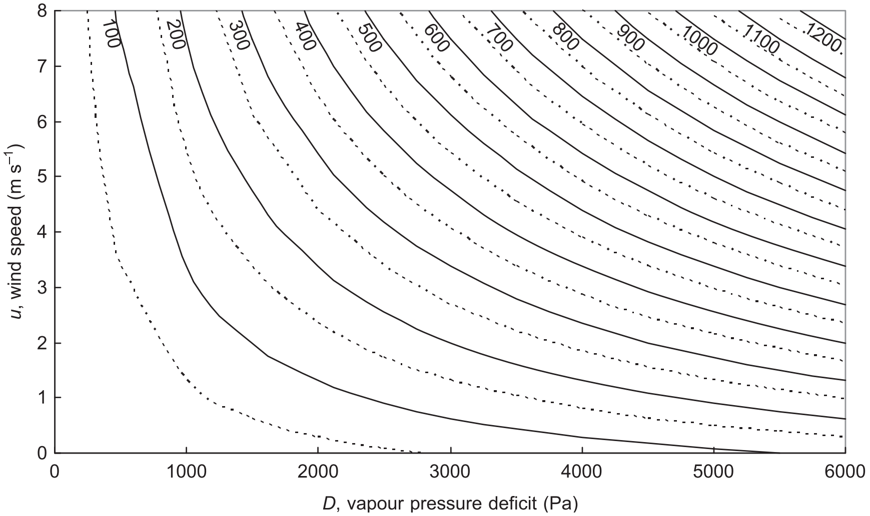

Fig. 2. Response of the aerodynamic component of pan evaporation, $E_{pan,A}$, to windspeed u and vapour pressure deficit D. Calculations are based on the aerodynamic part of Eqn (1) and assume a temperature of 20°C. $E_{pan,A}$ contours are shown at intervals of 50 W m^{-2} and labelled at 100 W m^{-2} intervals. Note that 100 W m^{-2} ~ 3.5 mm day^{-1}.

$$\frac{d(f_q(u)D)}{dt} = f_q(u)\frac{dD}{dt} + D\frac{df_q(u)}{dt} \tag{3}$$

From Eqn (3) we see that changes in pan evaporation rate will be very sensitive to changes in u when D is high, such as in typical arid environments. Similarly, in regions with high u, changes in pan evaporation rate are very sensitive to changes in D.

2.3 ATTRIBUTION USING A MASS AND ENERGY BALANCE APPROACH

Applying the above framework (Eqn 1) over Australia, Roderick et al. (2007) found that much of the decline in pan evaporation was due to declining wind speed with some region-specific declines in radiation also found to be important. Changes in E_{pan} due to changes in D, while variable from place to place, were generally small. The latter is in line with the previously discussed notion that the warming associated with the enhanced greenhouse effect would lead to increased absolute humidity in the atmosphere such that the relative humidity remained roughly constant. The importance of declining wind speed in Australia was also found independently by Rayner (2007) and confirmed by more detailed analyses (McVicar et al. 2008).

In earlier studies, it was more common to indirectly examine changes in pan evaporation rate (Chen et al. 2005; Shenbin et al. 2006; Thomas 2000)

Table 1. Overview of declining pan evaporation in terms of changes in radiation (R_n), vapour pressure deficit (D) and wind speed (u) showing increases (↑) and decreases (↓). Changes that are highly variable spatially and/or small are denoted by ~ (Local)

Region	R_n	D	u	References
Former Soviet Union	↓	?	?	Roderick and Farquhar 2002
Australia	~ (Local)	~ (Local)	↓	Rayner 2007; Roderick et al. 2007; McVicar et al. 2008
China	↓	~ (Local)	↓	Chen et al. 2005; Gao et al. 2007; Thomas 2000; Wu et al. 2006; Xu et al. 2006a
USA	↓	~ (Local)	↓	Hobbins 2004; Hobbins et al. 2004; Liepert 2002; Milly and Dunne 2001
Canada	↓	~ (Local)	↓	Burn and Hesch 2007; Cutforth and Judiesch 2007
Tibetan Plateau	~ (Local)	~ (Local)	↓	Shenbin et al. 2006; Zhang et al. 2007b
Thailand	↓	?	?	Tebakari et al. 2005
India	↓	↓	?	Biggs et al. 2007; Chattopadhyay and Hulme 1997; Ramanathan and Ramana 2005

by calculating the reference evapotranspiration rate (Allen et al. 1998). That approach is broadly equivalent to calculating pan evaporation rate. The main difference is that the calculation of reference evapotranspiration assumes a ground cover of short green grass instead of a pan. The first study we know of that did this was over China, and reported that declines in wind speed and solar radiation were the dominant reasons for declining reference evapotranspiration with local variability in vapour pressure deficit (Thomas 2000). The same conclusion would hold as an explanation for declining pan evaporation there.

There are now sufficient mass and energy balance studies to afford us a general qualitative overview of how trends in R_n, u and D have contributed to changes in pan evaporation in different regions (Table 1). The summary shows that declining u was dominant on the Tibetan plateau and in Australia. However, the combination of declining u and R_n is more common. The effect of changing D is indicated as local throughout Table 1, with some sub-regions experiencing increases in D while others show decreases (e.g. for the USA, see Hobbins et al. 2004; for China, see Thomas 2000, and for Australia, see Roderick et al. 2007), but, on balance, those studies did not identify coherent continental-scale trends in *D*. As noted above, this is in line with expectations, if the relative humidity remains roughly constant with increasing temperature (Held and Soden 2006). The exception appears to be India, where measurements show quite large increases in relative humidity (Chattopadhyay and Hulme 1997; Dai 2006). The reason remains unknown, but one suggestion is that widespread increases in irrigation throughout India has increased evapotranspiration and humidified the air (Biggs, T.W., 2007, personal communication).

The importance of declining solar irradiance, that is, dimming (Liepert 2002; Stanhill and Cohen 2001) associated with increasing aerosols and/or clouds as an explanatory factor for declining pan evaporation, was realised some time ago (Linacre 2004; Roderick and Farquhar 2002). Whether that trend continues is unclear: recent observations from some regions, especially in Europe, show a reversal of the previous trend with increases in global solar irradiance (Wild et al. 2005), while some regions, such as Canada (Cutforth and Judiesch 2007) and Norway (Grimenes and Thue-Hansen 2006), have shown continuing declines in global solar irradiance. In addition, calculations based on satellite observations show a small but continuing dimming over the global terrestrial surface but increases in global solar irradiance over the oceans (Pinker et al. 2005). It is difficult to determine exactly what has happened to the radiation regime because of the chronic lack of radiometers world-wide (Stanhill 1997).

The identification of stilling, that is, declining wind speed, is more recent, but the phenomenon appears widespread over terrestrial surfaces (Roderick et al. 2007). The question as to why wind speed as recorded by anemometers (and evaporimeters) has reduced over many terrestrial surfaces, while satellite-based microwave measurements suggest increases in wind speed over oceans (Wentz et al. 2007), has yet to be resolved.

One notable study not listed in Table 1 was a single-pan study from Turkey (Ozdogan and Salvucci 2004). It was not listed in Table 1 because the aim of that research was not to establish regional changes. Instead, those authors made clever use of a large 'natural' experiment – the progressive development of a large irrigation area in an arid environment – to study the local water cycle in the context of Bouchet's complementary relationship (see below). They found that warm-season pan evaporation decreased progressively from ~1400 mm in 1979 to ~800 mm by 2001 as the irrigation area expanded. Increasing irrigation would tend to humidify the air by increased evapotranspiration and, as might be expected, decreasing *D* was part of the reason for decreasing pan evaporation. However, what was somewhat surprising was that the observed decline in pan evaporation was mostly attributed to a large and steady decline in wind speed, from a little over 3 m s^{-1} in 1979 to a little over 1 m s^{-1} by 2001 (Ozdogan and Salvucci 2004). In a follow-up study, those authors used a meso-scale model to examine the changes. The model results suggested that the development of the irrigation area was associated with changes (increases) in the near-surface air pressure and associated local circulations that led to the decreases in wind speed (Ozdogan et al. 2006). The linkage between the local and meso-scales in the Ozdogan-Salvucci-Anderson approach may help explain why stilling has been observed in so many terrestrial regions.

3 Ecohydrologic Interpretation of the Trends

The energy balance approach (Section 2) gives a physical framework for interpreting the observed changes in pan evaporation in terms of the energy balance of the evaporimeter. However, that approach does not directly contribute to understanding how the pan evaporation changes are related to changes in actual evapotranspiration and hence in the terrestrial water balance. That is considered in this section.

3.1 INTERPRETATION USING THE SUPPLY/DEMAND FRAMEWORK

Interpretation using the supply/demand framework is based on the water- and energy-limited framework described previously (Roderick et al. 2009). In energy-limited conditions, declining pan evaporation usually means declining actual evapotranspiration. If precipitation were constant then we would also expect increasing runoff and/or soil moisture. Observations from largely energy-limited regions show decreasing actual evapotranspiration with increasing runoff and/or soil moisture (Golubev et al. 2001; Labat et al. 2004; Peterson et al. 2002; Robock and Li 2006; Robock et al. 2005) and are consistent with the predictions.

In water-limited regions, changes in evapotranspiration are more controlled by changes in supply (i.e. precipitation) than in demand. Consider as an extreme example a desert environment like Death Valley, California. We know that as in many other regions, pan evaporation has declined in Death Valley (Huntington et al. 2007). Because that environment is extremely water-limited, there is little runoff and we know that over annual or longer periods the actual evapotranspiration would more or less equal the precipitation. Therefore, if the precipitation increased, then actual evapotranspiration would likely increase, and vice versa if precipitation decreased. The point here is that in a water-limited environment, one cannot deduce the change in actual evapotranspiration from pan evaporation trends without examining how the supply – precipitation – has changed. That is easily done by inspecting the precipitation data and can be supplemented by the use of water balance models where necessary (Hobbins et al. 2008).

3.2 BOUCHET'S COMPLEMENTARY RELATIONSHIP

Brutsaert and Parlange (1998) pointed out that the observed decline did not necessarily mean declining actual evapotranspiration. They went further and argued that the observed decline in pan evaporation could be interpreted as evidence for increasing actual evapotranspiration. This is discussed in detail below (Section 3.3). They based their argument on Bouchet's theory of a complementary relationship between actual and potential evaporation rates. Hence, before discussing their article, it is useful to examine the complementary relationship.

Bouchet's complementary relationship was originally formulated by reference to an African desert oasis where there is a small (wet) oasis surrounded by an extensive dry region (Bouchet 1963). The water supply is limited over the surrounding dry region so that most of the net radiant energy will be partitioned into sensible heat. In contrast, most of the heat flux from the (wet) oasis will be partitioned into the evaporative component, because the water supply is plentiful there. The basic idea is that by various advective processes, the sensible heat originating from the dry surroundings becomes available to, and ultimately enhances the evapotranspiration from, the adjacent wet oasis. Under water-limited conditions, the analogy is that the evaporimeter is like a small oasis amid a larger dry region. These ideas are summarised in Figure 3. The enhancement of pan evaporation rate noted above is depicted by the curve labelled kE_{pan}/E_o (Figure 3b) and occurs as the surrounding landscape dries out (wets) and moves to lower (higher) moisture availability.

Bouchet's idea was in some respects an extension of the water- and energy-limited framework (Ramírez et al. 2005, also see Figure 3). In that context, one advantage of Bouchet's approach is that it would dispense with the need to specify land surface details (e.g. depth of the soil water bucket, vegetation properties). Perhaps for that reason it has been extensively investigated in those parts of the hydrologic community interested in estimating catchment water yield, that is, runoff. The Bouchet framework has not been pursued to the same extent in the agricultural and ecological sciences, because those communities are also interested in (i) soil and vegetation properties, (ii) studying the water-use efficiency of photosynthesis, and (iii) mapping vegetation distributions (Roderick et al. 2009).

Bouchet's hypothesis has generated much research (Brutsaert 2006; Brutsaert and Stricker 1979; Crago and Crowley 2005; Hobbins et al. 2001, 2004; Kim and Entekhabi 1997; Parlange and Katul 1992; Ramírez et al. 2005; Szilagyi 2001a; Xu et al. 2006b; Yang et al. 2006), but a detailed theory remains elusive (cf. Lhomme and Guilioni 2006; Szilagyi 2001b) and research is ongoing. Using annual catchment data from the USA, Hobbins et al. (2004) were able to show reasonable agreement with complementarity, that is, the sum $0.7 \times E_{pan}$ and E_a was roughly constant. The source of variation in that study was a mixture of space, that is, data from different catchments, and time, that is, the same catchments in different years. However, when time is used as the source of variation, the observed enhancement in pan evaporation as the surroundings dried was found to be greater than purely complementary, with the enhancement in pan

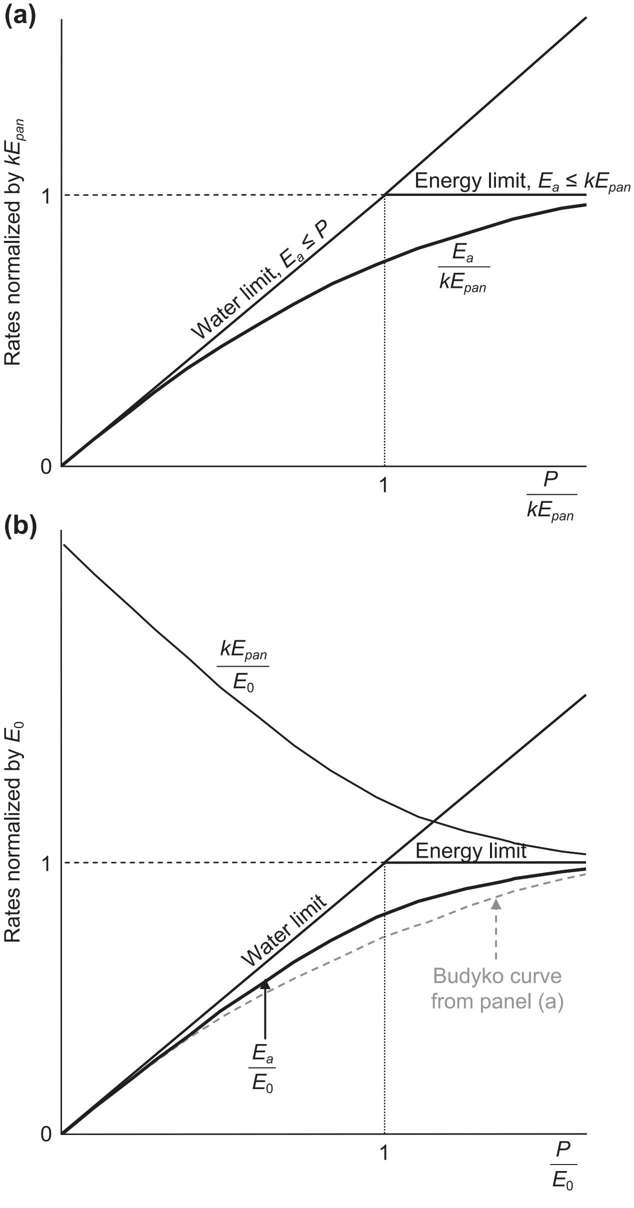

Fig. 3. Qualitative comparison between the (top panel) classical Supply/Demand framework and (bottom panel) Bouchet's Complementary Relationship. In the supply/demand framework, actual evapotranspiration (E_a) and precipitation (P) are normalised by 'potential evaporation' measured as a pan coefficient (k) multiplied by pan evaporation rate (E_{pan}). The straight lines denote water and energy limits on E_a leading to the characteristic hyperbola known as a Budyko curve. In Bouchet's complementary relationship, E_a, P and $k \times E_{pan}$ are all normalised by the evaporative equivalent of the net irradiance (E_o) of the landscape. Note that in some formulations E_o is replaced by the Priestley-Taylor wet area evaporation.

Table 2. Predicted changes in actual evapotranspiration (E_a) with declining pan evaporation per the BP98 (Brutsaert and Parlange 1998) and RF02 (Roderick and Farquhar 2002, 2004) interpretations.

Conditions	BP98	RF02
Energy-limited	E_a decreasing	E_a decreasing
Water-limited	E_a increasing	E_a changes mostly depend on changes in precipitation E_a could increase if precipitation increased

evaporation closer to a factor of five (Kahler and Brutsaert 2006). Research into that asymmetry is ongoing (Pettijohn and Salvucci 2006; Szilagyi 2007).

3.3 INTERPRETATION USING BOUCHET'S COMPLEMENTARY RELATIONSHIP

As noted above, the Brutsaert and Parlange (1998) interpretation of declining pan evaporation, hereafter denoted BP98, was inspired by Bouchet's complementary relationship. BP98 noted that as a water-limited environment becomes wetter, and actual evapotranspiration increases, potential (and pan) evaporation will tend to decline. Therefore, they argued that declining pan evaporation could be interpreted as evidence for increasing actual evapotranspiration and an overall wetting up of terrestrial surfaces (Brutsaert and Parlange 1998). Over the last several years, we have frequently read or reviewed articles that propose that the BP98 view is opposite to the Roderick and Farquhar view (Roderick and Farquhar 2002, 2004), hereafter denoted RF02. The problem initially arose because some of the earlier workers implied that declining pan evaporation means declining actual evapotranspiration (Peterson et al. 1995). BP98 pointed out that this interpretation is not necessarily true. RF02 further distinguished between water- and energy-limited conditions in their interpretation. The BP98 and RF02 interpretations are summarised in Table 2 and below.

BP98 began by noting that in energy-limited environments, changes in actual evapotranspiration would typically follow changes in pan evaporation as in the traditional supply/demand framework. Therefore, in energy-limited environments, declines (increases) in pan evaporation imply declines (increases) in actual evapotranspiration. In their conclusion, BP98 did not raise this point again so it appears as if they were arguing for increasing actual evapotranspiration everywhere. That is not so. Therefore, we have agreement between the BP98 and RF02 interpretations in the energy-limited environments that cover roughly half the terrestrial surface (with the other half being water-limited) (Nemani et al. 2003). In water-limited conditions, the RF02 (supply/demand) interpretation is that changes in evapotranspiration mostly depend on changes in supply (precipitation plus other sources such as irrigation where appropriate). The BP98 interpretation proposes that declining pan evaporation is indicative of increasing actual evapotranspiration via feedbacks between the pan and surrounding environment that underpin the complementary relationship. In water-limited conditions, the BP98 and RF02 interpretations can be reconciled if the decline in pan evaporation were coincident with increasing supply (precipitation and/or irrigation). Certainly, that has been observed throughout many parts of the USA (Szilagyi et al. 2001; Walter et al. 2004) and increases in precipitation have been observed in many other terrestrial regions (Huntington 2006; Zhang et al. 2007a). As noted by BP98, that would be expected in a warmer and wetter world where, on a global basis, increased evapotranspiration (mostly from the ocean; Wentz et al. 2007) must result in a globally averaged increase in precipitation. Climate models do predict a globally averaged increase in precipitation and hence also predict a globally averaged increase in evapotranspiration of about 2% for every °C of warming (Held and Soden 2006). In summary, we can reconcile the BP98 and RF02 interpretations provided that precipitation (supply) has increased in those water-limited environments where pan evaporation (demand) has declined.

While this global-scale reconciliation is encouraging, we hasten to add that there are several water-limited regions where the interpretations are difficult to reconcile. For example, in southeastern Australia, pan evaporation has generally declined over the last 30 years but precipitation has also generally declined over the same period (Roderick and Farquhar 2004). On an annual basis, much of that region is extremely water-limited with minimal runoff, so the decline in precipitation implies a decline in actual evapotranspiration that is concurrent with a decline in pan evaporation (that is, in turn, mostly due to declining wind speed as described in Section 2.3). Many parts of China show similar patterns (Wu et al. 2006; Yang et al. 2006). The RF02 supply/demand interpretation can accommodate that fact, but the BP98 interpretation (in the form used in their 1998 paper) does not.

3.4 BOUCHET'S COMPLEMENTARY RELATIONSHIP AND THE SUPPLY/DEMAND FRAMEWORK

As noted above, the idea underlying the application of Bouchet's complementary relationship is the prediction that as a water-limited environment become drier, say, by reduced precipitation, and actual evapotranspiration decreases, the potential (and pan) evaporation measured at a site located within that landscape will tend to be enhanced. This is commonly observed (see references in the previous section), but it is by no means the universal cause of such increases, because, as noted previously, there are some water-limited regions where precipitation and pan evaporation have both declined. For the moment, we ignore those exceptions and just assume that the pattern predicted by the Bouchet hypothesis holds. So one obvious question arises: how would an enhancement of the pan evaporation rate affect predictions of trends in actual evapotranspiration that are made using the supply/demand framework in water-limited conditions? In short, it would have no impact on the predicted trends, because the pan evaporation measurement is used to specify an upper limit to evapotranspiration, and when water-limited, the actual evapotranspiration is largely determined by supply and not demand.

While not expressed in this way previously, Bouchet's argument can be reformulated to state that in water-limited environments, as supply increases the demand declines and vice versa. While there are many places where this pattern has held, we again caution that this interpretation is not general because, as noted above, there are water-limited regions where supply and demand have both declined.

3.5 MORE CONFUSION

In Sections 3.3 and 3.4, we discussed perceived conflicts in the interpretation of pan evaporation trends, and, with one exception, resolved those conflicts. Unfortunately, there are also other sources of confusion in this field including the failure to adequately describe the 'type' of evaporation being referred to, and the use of temperature data alone to calculate an upper limit on evapotranspiration. These and other sources of confusion are discussed below.

The first problem is the common failure to distinguish evapotranspiration, often called 'actual evapotranspiration', from various other estimates, for example, pan evaporation, potential evaporation, lake evaporation, point evaporation, areal evaporation, and so on. For example, the IPCC 4th Assessment Report incorrectly asserts that evaporation increases with temperature. Taken literally, this means actual evapotranspiration. Elsewhere, in the same report it is asserted, again incorrectly, that potential evaporation increases with temperature. These are of course very different statements. To minimise confusion, we need to ensure that the types of evaporation are adequately described. A related issue is the interpretation whereby, in water-limited environments, increasing actual evapotranspiration implies increasing supply and that in turn means 'wetter'. Many papers interpret increasing actual evapotranspiration as 'drying' presumably, because it is a withdrawal. However, in water-limited environments, withdrawals can only occur if there have been additions. As dryland farmers often say, it can't evaporate if it hasn't rained!

The second and potentially more important problem is the continuing widespread use of empirical functions based on temperature to estimate evaporative demand. There are several, but the best known is the Thornthwaite formula (Thornthwaite 1948). Writing over 30 years ago, Jensen (1973) said of the Thornthwaite formula, '. . . because it can be computed from temperature and latitude, it has been one of the most misused empirical equations generating inaccurate estimates of evapotranspiration for arid and semiarid irrigated areas.' The difficulty in using the Thornthwaite formula in climate change studies is obvious: a steady increase in temperature over time will translate into a *calculated* steady increase in evaporative demand over time (Moonen et al. 2002). Of course, that conflicts with pan evaporation observations as well as estimates of potential evaporation synthesised from measurements of radiation, humidity and wind speed (Chen et al. 2005). If the Thornthwaite formula is replaced by more physically realistic estimates of evaporative demand then the conclusions about water balance trends in a region can change from drying to wetting (Hobbins et al. 2008; Sheffield and Wood 2008). It is important to get the direction of change (i.e. up or down) in evaporative demand correct!

It is ironic that Thornthwaite did so much to develop the supply/demand framework (Thornthwaite 1948) and yet the use of his temperature function can lead to such problems when used in climate change scenarios (McKenney and Rosenberg 1993; Rosenberg et al. 1989). To be fair, in the original research, Thornthwaite prepared a climatology, that is, time was not a source of variation, and he clearly expected that a better approach for estimating evaporative demand would be developed. It is also ironic that the principles underlying a better approach were published by Penman in his famous paper on evaporation in 1948 – the same year as the Thornthwaite publication. Many applications continue to use the Thornthwaite formula and justify it on the basis that it is the only approach for which data are readily available (e.g. Gordon et al. 2005; Palmer 1965). While it is true that the data needed to apply the Thornthwaite formula are readily available, we also know that this formula – or any approach based solely on temperature measurements – is only considering a small part of the physics (Section 2.2) and will often give an incorrect sign for the change over time in evaporative demand when considering global warming (Chen et al. 2005; Hobbins et al. 2008; Moonen et al. 2002). The time to stop using the Thornthwaite formula, or any formula based solely on temperature, has long passed. Better formulated alternatives are available and they paint a very different picture of globally averaged changes over the past 50 years – one of decreasing droughts (Sheffield and Wood 2008).

The study of evaporation can be a complex area and problems can occur even among specialists because of the not-so-obvious assumptions. For example, in earlier research, Morton (1983) used Bouchet's idea to propose a method for estimating actual evapotranspiration. Morton chose to formulate potential evaporation in his suite of models without explicitly considering variation in wind speed, because he believed that any changes in vapour transfer due to wind speed would be cancelled by changes due to surface roughness and that, in any case, wind speed measurements were unreliable. Therefore, if the wind speed changes over time, as appears to be widespread over land (Roderick et al. 2007) and ocean (Wentz et al. 2007), the Morton evaporation models will not respond to those changes and the calculated trend in evaporative demand could have a different sign from the pan evaporation trend (e.g. Kirono et al. 2008).

In summary, care is needed because the results of water balance analyses currently being performed may be used to restructure entire industries and associated communities, for example, irrigation, agriculture, or to plan new water impoundments, or to prompt the construction of desalination plants, and so on. The stakes are high. We need to do the analyses with the best available theory.

4 Summary

Evaporimeters have long been used to provide estimates of evaporative demand. That is not surprising because they are simple, robust, and affordable instruments. The trick in using pans is in the interpretation. For that, the classical supply/demand framework is invaluable. The principles underlying this framework are well known within individual disciplines, especially in agriculture and engineering. The use of the pan evaporation record to interpret changes in the surface water balance relies on distinguishing between energy-limited and water-limited conditions. In energy-limited conditions, declining pan evaporation generally implies declining actual evapotranspiration. If precipitation were constant then one would also expect increasing runoff and/or soil moisture. In water-limited conditions, the interpretation is not so straightforward because actual evapotranspiration is then controlled by the supply and not the demand. In such circumstances, one has to inspect how the supply (i.e. precipitation) has changed before coming to a conclusion about how actual evapotranspiration and other components of the terrestrial water balance have changed (e.g. Hobbins et al. 2008).

The growing realisation that the pan evaporation record provides the only direct measurement of changing evaporative demand has also re-invigorated research into new uses of these valuable data. The use of Bouchet's complementary relationship has been prominent (e.g. Brutsaert and Parlange 1998; Hobbins et al. 2004). As the ideas are being refined it is important to recognise that in the supply/demand framework (Roderick et al. 2009, section 3.1), the source of variation is time. That means that at some times, a given region is energy-limited while at other times, the same region may be water-limited. In contrast, Bouchet's idea was based on the difference between a wet oasis and a surrounding dry landscape, where the essential source of variation was space. What we are working towards is a melding of these two formulations.

Perhaps the most important point to emerge from the pan evaporation story is the fundamental importance of long-term records. Imagine where we would be if the organisations and people who envisaged, developed and maintained the evaporimeter networks over long periods had not been so diligent and persistent; we would still have a record of rainfall and perhaps runoff measurements in a few basins. But without the pan evaporation measurements we would have had no process-level understanding and hence no capacity to analyse how the terrestrial water balance has changed and hence less security in predicting how it might change. Fortunately, this is not the case. It is up to us to use the data wisely.

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Short Biographies

Michael Roderick originally studied and worked as a land surveyor before completing a PhD on satellite remote sensing of vegetation at Curtin University of Technology in 1994. He has been at the Australian National University since 1996 where he conducts research related to water at scales ranging from plant cells to catchments to the globe with an emphasis in recent years on ecohydrology.

Micheal Hobbins received a BEng in Civil Engineering from Leeds University in 1989, a PhD in Hydrology from Colorado State University in 2004, and is currently a post-doctoral research fellow at the Australian National University. His research interests are in the field of regional to large-scale evaporation dynamics, and he most recently published on potential evaporation as a metric of drought estimation across Australia and the spatial distribution of water availability across the USA.

Graham Farquhar originally studied physics and subsequently completed a PhD on plant water relations and stomatal dynamics at the Australian National University in 1973. He is a Professor of Environmental Biology at the Australian National University, where he conducts research on photosynthesis and transpiration, making particular use of stable isotopes. He is a member and Vice President of the Australian Academy of Science and a Fellow of the Royal Society of London.

Note

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