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A critical overview of pan evaporation trends over the last 50 years

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Abstract Despite the observed increases in global average temperature, observations across the world show that the rate of pan evaporation at a regional scale has been steadily decreasing over the past 50 years. This is known as the pan evaporation paradox. This paper reviews current reported pan evaporation trends, examines available theoretical explanations about this "paradox", and discusses current research gaps and priorities. It concludes that: (1) three major potential causes of pan evaporation, solar radiation, vapour pressure deficit (VPD) and wind speed, have been changing in the last 50 years. The magnitude of changes and importance of each of these three causes varies from region to region, as does the pan evaporation trend, although overall there is a decreasing trend. (2) Currently two existing theories explaining the pan evaporation trends have limits and are only valid in some specific regions and seasons. Neither of them provides a fundamental physical-based theory that could be applied everywhere. (3) Further investigations are needed before we can fully understand the global evapotranspiration trend in global warming scenarios.

1 Introduction

Free water surface evaporation is one of the most important components of the hydrological cycle and a major portion of water loss of water bodies, such as rivers, lakes, and reservoirs (Fu et al. 2004a). It is also an important weather variable

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that has numerous applications related to decision making in agriculture, forestry, ecology, hydrology, and other fields (Bruton et al. 2000).

In general, there are two ways to estimate the free water surface evaporation: one is to calculate it according to meteorological parameters and the other is to measure it directly in the field (Fu et al. 2004a). One of the simpler techniques is to directly measure the water evaporation in the field from an evaporation pan, which is an apparently simple integrated measurement of complex meteorological interactions, such as solar radiation, temperature, humidity, and wind speed. Although pan evaporation cannot fully represent lake evaporation, it has been found as proportional to actual evaporation of moist surfaces, such as lakes or irrigated fields (Kahler and Brutsaert 2006), and also calculated reference crop evapotranspiration (Brouwer and Heibloem 1986; Grismer et al. 2002; Snyder et al. 2005; Ertek et al. 2006). Because pans of various designs have produced data for many regions throughout the world for long periods, attempts have also been made to use these data to estimate actual evaporation even in non-moist environments. However, as pan evaporation measurements were never intended for this purpose, this has remained an elusive goal (Kahler and Brutsaert 2006).

One of the expected consequences of global warming is that the air near the surface should be drier, which should result in an increase in the rate of evaporation from terrestrial open water bodies including evaporimeters. However, despite the observed increase in average temperature, observations from many regions of the world show that the rate of pan evaporation at a regional scale has been steadily decreasing over the past 50 years. For example, Peterson et al. (1995) showed that, on average, pan evaporation had decreased over the USA, Former Soviet Union (FSU) and Eurasia for the period from 1950 until the early 1990s. Liu et al. (2004) documented that pan evaporation measurements at 85 weather stations in China for 1955–2000 had declined at an average rate of 29.3 mm per decade. Roderick and Farquhar (2004) found that pan evaporation in Australia declined on average by 4.3 mm a^{-2} for 1970–2002 and 3.3 mm a^{-2} for 1975–2002. The similar decreasing pan evaporation was also been observed in Canada (Burn and Hesch 2007), India (Chattopadhyay and Hulme 1997), Venezuela (Quintana-Gomez 1998), Italy (Moonen et al. 2002), Turkey (Ozdogan and Salvucci 2004), Puerto Rico (Harmsen et al. 2004), New Zealand (Roderick and Farquhar 2005), Thailand (Tebakari et al. 2005), and Tibetan plateau (Zhang et al. 2007).

The objectives of this paper are therefore: (1) to review the current reported pan evaporation trends; (2) to examine available theoretical explanations of this “paradox”; (3) to discuss the uncertainties associated with the observed pan evaporation trends; and (4) to identify the research gaps and priorities for pan evaporation.

2 Pan evaporation measurement

The procedures involved with pan evaporation measurements are (following Brouwer and Heibloem 1986): (1) the pan is installed in the field; (2) the pan is filled with a known quantity of water (the surface area of the pan is known and the water depth is measured); (3) the water is allowed to evaporate during a certain period of time (usually 24 h). For example, each morning at 07:00 local time a water depth measurement is taken. The rainfall, if any, is measured simultaneously; (4) after

24 h, another water depth measurement is taken; (5) the amount of evaporation per time unit (the difference between the two measured water depths, plus precipitation amount during the same period if any) is calculated using:

$$E_{\mathrm{Pan}} = P + (n_1 - n_2) \tag{1}$$

Where E_{Pan} denotes daily pan evaporation (mm/day), P is daily precipitation (measured at the same site and the same time, and with the same unit as pan evaporation), and n_1 and n_2 are water surface heights measured in the evaporation pans for the previous and present measurements, respectively.

3 Observed pan evaporation trends over the last 50 years

Starting with Peterson et al. (1995), numerous studies have reported observations of decreasing pan evaporation over large areas in different regions throughout the world over the past 50 years (Table 1 and references in Section 1). Evaluating these studies indicates three characteristics of the pan evaporation trend: (1) the decreasing trend is not universal; (2) the instruments/ methods used for pan evaporation measurement vary; and (3) there are uncertainties associated with observed data.

3.1 No universal pan evaporation trend

Although many observations across the world indicate a general trend of pan evaporation decrease over the last 50 years, the current pan evaporation decreasing trend is not universal (Table 1). For example, several stations have an increasing trend of 26–30 mm a^{-2} of pan evaporation in Australia, although the overall decreasing trend is significant (Roderick and Farquhar 2004). Pan evaporation in Israel's central plains even shows a small but statistically significant increasing trend (Cohen et al. 2002). There has also been an increase in both potential and pan evaporation from the Tibetan Plateau, through central China, to southeast China during the period 1971–2000 (Xu et al. 2005).

Of 228 warm-season (May–October) pans across the conterminous USA, 60% show decreasing pan evaporation and 40% indicate increasing pan evaporation trends, especially in the Northwest, the Northeast, regions around the Gulf of Mexico, South Carolina, and southern Florida (Hobbins et al. 2004). In the winter (Jan–Feb) and pre-monsoon (Mar–May) seasons, observation stations on the east coast of India showed a slight increasing trend of pan evaporation (Chattopadhyay and Hulme 1997). In Puerto Rico, significant decreasing pan evaporation was observed at Lajas and Rio Piedras, but significant increasing pan evaporation was observed at Gurabo and Adjuntas (Harmsen et al. 2004). Four out of eight studied Irish Class A evaporation pan series between 1963 and 2005 showed significant linear trends, three of increasing and one of decreasing evaporation. These significant changes ranged between –0.1 and +0.1 mm year^{-1} equivalent to annual changes between -0.22 and $+0.15$% (Stanhill and Möller 2008). Five out of eight studied UK sunken evaporation tank series between 1885 and 1968 showed statistically significant linear trends, three of them decrease and two increase: These ranged in size between -3.7 and $+2.1$ mm year^{-1}, equivalent to annual changes of -1.05 to $+0.40$% of the mean (Stanhill and Möller 2008).

Table 1 Some observations of trends in pan evaporation

Region	Period	Seasonal	Trend in pan evaporation	Interpretation of trend for actual evaporation	Reference
North of the European Russia (taiga)	1951–1990	May to Sep	−5.8%/10 years	Decrease by ~3–4%/10 years	Peterson et al. (1995); Golubev et al. (2001)
South of the European part of FSU (steppe, forest-steppe, and forest)	1951–1978		−8.9%/10 years	Increase by ~4–6%/10 years	
Siberin (taiga)	1951–1988		−3.0%/10 years	Decrease by ~2%/10 years	
Siberin (steppe and forest-steppe)	1951–1988		−1.8%/10 years	Increase	
Central Asia and Kazakhstan (steppe, semi-desert, desert)	1952–1989		0.2%/10 years	No change	
Northeast USA	1957–1998		0.8%/10 years	Uncertain	
Southeast USA	1957–1998		0.8%/10 years	Decrease	
Great Lakes zone	1957–1998		−2.1%/10 years	Uncertain	
Midwestern USA	1957–1998		−3.4%/10 years	Increase by 1–2%/10 years	
Great Plain	1957–1998		−1.6%/10 years	Increase by ~0.8%/10 years	
Mountainous West	1957–1998		−2.1%/10 years	Increase by ~1%/10 yrs	
USA west of 122° W; north of 45° N	1961–1998		−3.0%/10 years	Increase	

China	1955–2000	May to Sep	−29.3 mm/10 years		Liu et al. (2004)
	1971–2000		Increase		Xu et al. (2005)
	1961–2000		$-24.9 \sim 10.4$ mm a^{-2}		Zuo et al. (2006)
Australia	1970–2002	Annual	-4.3 mm a^{-2}		Roderick and Farquhar (2004)
	1975–2002	Annual	-3.3 mm a^{-2}		
New Zealand	varies	Annual	-2.1 mm a^{-2}		Roderick and Farquhar (2005)
Israel	1964–1998	Annual	$+3.67$ mm a^{-2}		Cohen et al. (2002)
Thailand	1982–2000	Annual	Decrease		Tebakari et al. (2005)
Ireland	1963–2005		$-0.1 \sim 0.1$ mm a^{-2}		Stanhill and Möller (2008)
England and Scotland	1885–1968		$-3.7 \sim 2.1$ mm a^{-2}		Stanhill and Möller (2008)
Italy			Decrease		Moonen et al. (2002)
Venezuela			Decrease		Quintana-Gomez (1998)
India	1961–1992	Four seasons	Decrease		Chattopadhyay and Hulme (1997)
		Mar to Sep	-11.4 mm a^{-2}		
USA	1950–2002	Annual	(−) 28 out of 44 (+) 16 out of 44	Increase	Hobbins et al. (2004)
	1950–2002	May to Oct	(−) 137 out of 228 (+) 91 out of 228	Increase	

Therefore, it can be concluded that there is no universal observed pan evaporation trend. The physical process of pan evaporation is complicated and the evaporation pan is, as already stated, an apparently simple integrated measurement of complex meteorological interactions, such as solar radiation, temperature, humidity, and wind speed. The variations of these meteorological variables change from region to region and from season to season, hence the lack of a universal pan evaporation trend. Accordingly, it is also hard to use a universal theory to explain the observed pan evaporation trends of the last 50 years.

Another relevant issue is the quality control of data for homogeneity. A high-quality monthly pan evaporation dataset of 60 stations has been developed for monitoring long-term pan evaporation trends over Australia (Jovanovic et al. 2008). The quality control process involved examination of historical station metadata together with an objective test comparing candidate series with neighbouring stations. Appropriate inhomogeneity adjustments were applied using established methods to produce the first homogeneous pan evaporation dataset for Australia. Analysis of these data reveals that Australian annual mean pan-evaporation shows large interannual variability with no trend over the 1970–2005 period (Jovanovic et al. 2008). Previous studies using unadjusted data had shown a decline in pan evaporation (e.g. Roderick and Farquhar 2004; Rayner 2007), highlighting the importance of checking data for homogeneity before drawing conclusions about long-term trends (Jovanovic et al. 2008).

3.2 Inconsistent instruments/methods

The instruments/methods used for pan evaporation measurement vary, thus the reported values of pan evaporation decreasing trends are often not directly comparable, although the Class A evaporation pan is a common instrument. Different types of pans exist. As the size, structure, depth, installation mode, colour, material and position of the pan have a significant influence on the measured result, the measurements are pan specific. For example, Fu et al. (2004a) compared the conversion coefficients for 13 different evaporation pans with a 20 m^2 evaporation tank. The results indicated that the conversion coefficients for annual evaporation varied from 0.60 for a ϕ20 pan (with a diameter of 20 cm) to 1.07 for a modified E601 pan (Fu et al. 2004a). The Class A evaporation pan can overestimate free water evaporation by 45% in April, while compared with a 20 m^2 evaporation tank, based on 5-year observation (Fu et al. 2004a). Therefore, a trend from this relatively small evaporation pan is possible due to instrument variability.

The World Meteorological Organization (WMO 1966, 1976) suggests the following instruments as standard equipment for measuring free water surface evaporation: a FSU's 20 m^2 evaporation tank (20 m^2 in area or 5 m in diameter, 2 m in depth buried to within 7.5 cm of its rim), a FSU GGI-3000 (area 3,000 cm^2), and a USA Class A evaporator. However, 20 m^2 evaporation tanks are expensive to build and maintain and can only be found at a few research experimental stations. The FSU GGI-3000 pan could only be found in Russia, some FSU countries and China. The most popular evaporation pan in literature is the USA Class A evaporation pan. In China the ϕ20 pan and modified GGI-3000, called E601 evaporator, are common.

The Class A Evaporation pan is circular, 120.7 cm (4 ft) in diameter and 25.4 cm (10 in.) deep. It is made of galvanized iron or Monel metal (0.8 mm). The pan is mounted on a wooden open frame platform which is 15 cm above ground level. The soil is built up to within 5 cm of the bottom of the pan. The pan must be level. It is filled with water to 5 cm below the rim, and the water level should not be allowed to drop to more than 7.5 cm below the rim. The water should be regularly renewed to eliminate extreme turbidity. The pan, if galvanized, is painted annually with aluminium paint. Screens over the pan are not a standard requirement and should preferably not be used. Pans should be protected by fences to keep animals from drinking (Brouwer and Heibloem 1986).

A GGI 3000 evaporator has a surface area of 3,000 cm^2 (61.8 cm in diameter) and a depth of 68.7 cm, of which 60 cm depth is a cylinder and 8.7 cm in the bottom is a cylindrical cone. It is usually buried in the ground in an effort to minimize the effects of the exposed side wall. Its rim is usually 7.5 cm above the ground level (Fu et al. 2004a).

An E601 evaporator has the same dimensions as GGI 3000, but has two modifications. First, when installing, the E601 is supported by a 22.5 cm high grid on the bottom, so its rim is 30 cm above the ground instead of 7.5 cm as for the GGI 3000. Second, it has four arc water troughs of 20 cm in width. These four troughs comprise a circle in order to reduce the effects of turbulence generated by the pan itself and in particular by the rim of the pan (Jacobs et al. 1998; Fu et al. 2004a).

Figure 1 shows that Class A pan overestimated the free water surface evaporation from March to July and underestimated the evaporation in November, compared with the GGI 3000 and E601 evaporation pans, where the monthly evaporation amount from a 20 m^2 evaporation tank is treated as a standard in this case. The data was observed at Nansihu Experimental Station of China from 1985 to 1990 (Fu et al. 2004a). These differences make the pan evaporation trends from different pans incomparable and a possibility of observed trends coming from instrument variability, although the differences in their annual values are smaller than those of monthly values.

The problems involved in the use of different evaporators were recognized at the beginning of the scientific era (as discussed in Stanhill 2002). Thus, in 1781, Cotte concluded from his comparison of evaporators that ‘Experiments to determine the influence of the dimensions of the containing vessel on the rate of evaporation show that… there is as much variation in the results as there is in the form of the vessel

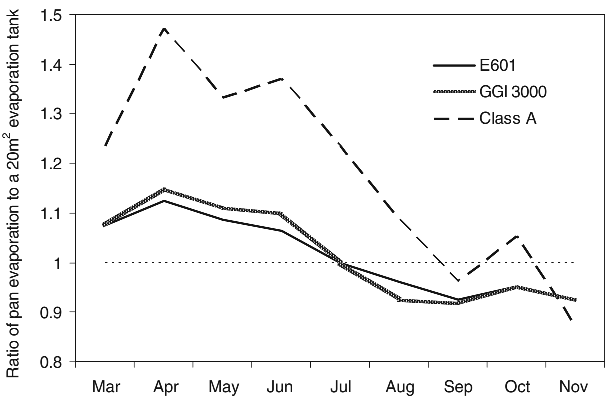

Fig. 1 Ratio of pan evaporation to a 20 m^2 evaporation tank for three popular evaporators at different months in Nansihu Experimental Station, Shandong, China (dataset 1985–1990)

used' (Livingston 1908; Stanhill 2002). A century later Symons (1867) confirmed this conclusion, in his 1867 paper on evaporation and evaporimeters, that 'evaporation is the most desperate branch of the desperate science of meteorology'.

3.3 Uncertainties of observed pan evaporation trend

Most of the literature indicating a negative pan evaporation trend does not discuss the uncertainty of observed pan evaporation data. This may weaken our confidence about the observed trends. Robinson (1999) has shown that in the UK failure to ensure such consistency led to overestimation of the trend in evaporation. Jovanovic et al. (2008) have shown that pan evaporation in Australia would disappear after the quality control of data for homogeneity. Several potential uncertainties include, but are not limited to, instrumentation installation and maintenance, observational practice, shift/ movement of site location, and period studied.

3.3.1 Evaporation pan installation/maintenance

The installation of bird-guards subsequent to initial installation of pans to stop birds and mammals drinking the water, was found to reduce measured pan evaporation rates by about 7% (Gifford et al. 2005). Fu et al. (2004a) found that the installation modes, structures, and composition (material) of the evaporation pans also had impacts on pan evaporation measurements. Painting the pans may also affect the pan evaporation (Brouwer and Heibloem 1986). The level at which the water is maintained in the pan is also important; resulting errors may be up to 15% when water level in the Class A pan fall 10 cm below the accepted standard of between 5 and 7.5 cm below the rim (Brouwer and Heibloem 1986). It is the main reason in Australia the water level of evaporation pan is restored to a fixed level daily by bailing or adding water.

3.3.2 Station locations

Many meteorological sites have moved during the period of record, with moves from town centres to airports being particularly common (Trewin and Collins 2005). The influence of urbanization on climate records, as well as influences of changes in the local ground surface or local shelter, has occurred in many parts of world in the last 50 years. The presence of obstacles near a site is particularly critical for wind and wind-influenced variables (such as evaporation). In one example, a site move from a sheltered to an open site at Rabbit Flat, in the Australian arid zone, led to a 32% increase in pan evaporation, determined using 2 years of overlapping records between the two sites (Trewin and Collins 2005).

Hobbins et al. (2004) has homogenized the time series of 172 pans around 326 abrupt data-shifts, finding 280 shifts were due to changes in pan location, with the rest due to unspecified changes. Thus Hobbins et al. (2004) homogenized 43% of the annual data and 55% of the warm-season data in their study. An important concern is that of how to guarantee the accuracy of homogenized data. For example, are the errors involved in homogenization larger than the pan evaporation trend that the researcher is attempting to detect?

3.3.3 Automatic observation

There have been many systematic changes in instrumentation, including the general trend to automation of the observation network. A comparison of automatically and manually collected pan evaporation data indicated that daily pan evaporation amounts from the automated observations were generally less than the evaporation measurements from the manual observations (Bruton et al. 2000). Daily pan evaporation measurements calculated from 15-min averages of water height in Class A evaporation pans of the Georgia Automated Environmental Monitoring Network (AEMN) were compared to daily pan evaporation data collected at National Weather Service (NWS) cooperative stations. Data from 1991 to 1996 at the Griffin location and data from 1993 to 1997 data at the Watkinsville location, both in the state of Georgia USA, were used. Data sets consisted of 733 and 808 daily evaporation totals from Griffin and Watkinsville, respectively. Average total annual pan evaporation from the manual observations was 537 mm for Griffin and 1,051 mm for Watkinsville. The average total annual pan evaporations from the automated pans were 414 and 676 mm, respectively, for the same locations and the same periods (Bruton et al. 2000). The automated observation reduced the pan evaporation by 22.9–35.7% (Fig. 2). The daily automated pan evaporation data included many low values for days in which considerable pan evaporation should normally occur (Bruton et al. 2000). Records of water height from the automated observations showed that mechanical problems with the sensor used in the automated pan evaporation system were responsible for much of the difference seen between the automated and manual observations (Bruton et al. 2000). Improved maintenance of the automated observations was recommended to justify replacement of the manual observations, as was a change in the design of the float mechanism (Bruton et al. 2000). More comparison studies are needed to clarify this conclusion, as many stations have adopted the automated observed system and the magnitude of difference in two operational practices is much larger than the pan evaporation trends being reported.

The observation accuracy of precipitation is also critical to pan evaporation estimates using Eq. 1 (Bonacci 1991). Four experiments were made (Gunderson 1989) to document and account for differences in evaporation data that were calculated

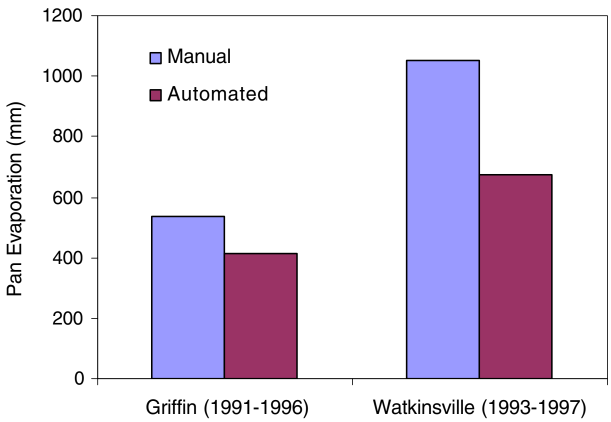

Fig. 2 Pan evaporation decrease due to automated observation (data from Bruton et al. 2000 and plotted by authors)

using pans equipped with float-activated recorders and pans with hook gauge/rain gauge instrumentation. Paired in-pan comparisons indicated that evaporation pans and standard (8 in. orifice) rain gauges record significantly different amounts of rain, which results in differences in calculated evaporation on rainy days. Monitoring networks with evaporation pans should have uniform instrumentation that accurately records rainfall into the pans for consistent results (Gunderson 1989). Bonacci (1991) showed that the evaporation measured by a class A pan was smaller than the "actual" pan evaporation by between 5% and 20% due to the fact that the class A pan orifice and the rain gauge orifice were at different elevations.

3.3.4 Study period

The study period and length also have impacts on the trend. For example, in Australia 14 out of 30 stations show a decreasing trend in pan evaporation, 13 no trend, and three an increasing trend during 1970–2002, but 23 out of 61 stations show a decreasing trend, 33 no trend, and five an increasing trend if the period 1975–2002 is used (Roderick and Farquhar 2004). This is similar for other meteorological variables. For example, rates of dew point temperature increase were 0.42°C/100a for a 1951–1990 dataset, but 2.16°C/100a for a 1961–1990 dataset (Robinson 2000).

Hutchinson et al. (2005) reported that the 1970s dominated the period of declining pan evaporation in Australia but that in the mid-1990s there was a switch to a continental average increasing pan evaporation trend. These variations with time and space were found to relate, statistically, with annual rainfall and saturated vapour pressure (Gifford et al. 2005). In Australia the decadal average to 2004 does not show a decrease in pan evaporation (Gifford et al. 2005), while 1970–2002 and 1975–2002 have a statistically significant decreasing trend (Roderick and Farquhar 2004).

3.3.5 Study season

Some studies use seasonal pan evaporation instead of annual values, where water freezes in winter season and no pan evaporation data are available. A recent simulation of the present climate with the ECHAM4 GCM shows that a hemisphere evaporates more in winter than in summer. This result is supported by the European Re-Analysis (ERA; Ohmura and Wild 2002) of the European Centre for Medium-Range Weather Forecasts (ECMWF). Normalized pan evaporation data in Bet Dagan, Israel showed no significant time trend for dry months, but a significant increase was found for wet months (Cohen et al. 2002). In the literature, there is often no reporting about these differences between warm and cold months.

3.3.6 Ageing

The overall variation in pan evaporation is not constant with time because of ageing, surface deterioration and repainting (Brouwer and Heibloem 1986). A large temperature differential across the pan-substrate boundary leads to a consistently positive heat flow from the soil towards the sunken pan (Oroud 1998). This additional heat source could increase annual evaporation from the sunken pan by about 5% and 8% in July and January, respectively (Oroud 1998). This is larger than the currently reported pan evaporation decreasing trends. In time, grass often grows in the wetter micro-environment under the evaporation pan, which could reduce the heat transfer from soil to pan, and therefore decrease pan evaporation.

4 Theoretical explanations and their limits

There are basically two theories used to explain secular pan decreasing trends: the first is the use of a combination equation, sometimes called the Penman approach, to calculate the climatic influences on the energy balance of the pan. Once a combination equation has been proven it is possible differentiate the equation and separately examine component sensitivity to the principal atmospheric variables.

The second approach is to establish a variant of the complementary relationship between actual evaporation, potential evaporation or its pan evaporation surrogate and wet area evaporation. This gives a reference frame to discuss the probable impact of changes in actual evaporation due to rainfall changes and trends in pan evaporation.

4.1 Energy balance

Much of the literature have been discussed the simple and multiple correlations between trends in pan evaporation and solar irradiance or global dimming. This theory, a typical model is developed by Roderick and Farquhar (2002), attributes the decrease of pan evaporation to the decrease in solar irradiance. Many studies support this theory (Peterson et al. 1995; Thomas 2000; Cohen et al. 2002; Ohmura and Wild 2002; Liu et al. 2004; Liu and Zeng 2004; Linacre 2004). However, this explanation for decreasing pan evaporation is unsatisfactory for several reasons. First, based on this model, the terrestrial actual evaporation should also decrease due to solar irradiance decline, in wet environments where water supply is not a limit for actual evaporation. This is not consistent with actual evaporation estimates from water budget modelling in the USA and FSU (Golubev et al. 2001; Hobbins et al. 2004; Kahler and Brutsaert 2006).

Secondly, the rate of pan evaporation decline is not always consistent with the decreased magnitude of solar irradiance. For example, the relationship between pan evaporation trend rate and decreased solar irradiance trend rate in eight climatic regions of China (Fig. 3) does not show any positive correlation (Liu et al. 2004).

Thirdly, this model requires that the VPD remains nearly constant, which is not always true. For example, Roderick and Farquhar (2002) concluded that average VPD remained very nearly constant by using the following equation and assuming that the dew point temperature increases at about twice the rate of the average temperature:

$$\delta D = s\delta T - s_d \delta T_d \tag{2}$$

It is true that "when above the freezing point, the dew point will in general set a lower limit on the minimum temperature" (Roderick and Farquhar 2002). However, this does not imply that the dew point must also be increasing faster than average temperature. The overall dew point for 178 stations in USA in the last 50 years has been increased by 0.42°C/100 year (Robinson 2000). But it is "attributed to a range of changes, from changes in the frequency of the various 'air mass' types influencing a station, to changes in the intensity of one or more these air masses, and to changes in the local vertical exchanges of energy and moisture" (Robinson 2000). The increase of dew point could be the result of higher humidity, which is partly caused by changes

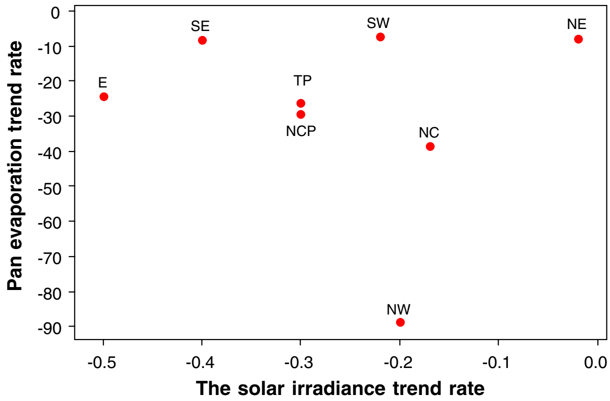

Fig. 3 Relationship between pan evaporation trend rate (mm a^{-1} decade^{-1}) and decreased solar irradiance trend rate (MJ m^{-2} day^{-1} decade^{-1}) in eight climatic regions of China (*E*—East China; *SE*—Southeast China; *TP*—Tibet Plateau; *NCP*—North China Plain; *SW*—Southwest China; *NC*—North Central China; *NE*—Northeast; *NW*—Northwest China; data from Liu et al. (2004) and plotted by authors)

in evaporation rate (Robinson 2000), because dew point temperature is a function of specific humidity and atmospheric pressure (Gaffen and Ross 1999).

As these changes are different from station to station, the dew points can be increasing at one station and decreasing at another, or increasing in a season and decrease in another (Robinson 2000). The national average unweighted 178 station values indicate the dew point temperature increase by 1.44°C/100a, 0.63°C/100a, 1.43°C/100a, and −1.82°C/100a for the spring, summer, autumn, and winter seasons, respectively during 1951–1990 period (Robinson 2000). These values vary to 3.09°C/100a, 1.84°C/100a, 0.55°C/100a, and 3.18°C/100a if 1961–1990 time period was used (Robinson 2000). There may be some regions where ∼0.3°C per decade increase of dew point temperature has been observed, but this is not the general magnitude of dew point temperature changes in the last 50 years in the USA.

Moreover, Gaffen and Ross (1999) indicate that night-time dew point temperature increases generally exceed the daytime increases whereas Robinson (2000) indicates that the rates of dew point temperature increases are generally higher in the daytime than the night. Therefore, it is hard to conclude that the dew point temperature must also increase faster than average temperature based on the observed increase in minimum temperature.

This assumption is also not always consistent with the observed data. Liu et al. (2004) have shown that VPD trends are a mixture of decreases and increases in eight regions of China. Moreover, the pan evaporation decrease is significant from the arid northwest to the humid southeast in China. VPD, however, showed a statistically significant increase in the southeast, north central China, and the North China Plain (Liu et al. 2004). Cohen et al. (2002) found an increase VPD trend in Israel. Hobbins et al. (2004) showed that VPD had decreased over 75% of the conterminous US. The spatial mean trend is a decrease of 0.012 hPa/year for a 42-year decrease of 0.504 hPa or 10.1% of the mean.

An update version of this model, PenPan, based on Penman's combination equation, significantly improves the model performance by incorporating an aerodynamic term $E_{P,A}$ (Roderick et al. 2007) as:

$$E_P = E_{P,R} + E_{P,A} = \left(\frac{s}{s+a\gamma}\frac{R_n}{\lambda}\right) + \left(\frac{a\gamma}{s+a\gamma} f_q(u)\, D\right) \tag{3}$$

Where Rn is the net irradiance of the pan and has three elements: incoming shortwave radiation, incoming and outgoing long-wave irradiance.

"When forced with radiation, temperature, humidity and wind observations, the PenPan model simulated the pan evaporation observations well", with the incoming long-wave irradiance ($R_{l,in}$) calculated with the FAO56 approach (Allen et al. 1998),

$$R_{\mathrm{l,in}} = \sigma T_a^4 \left\{ 1 - \left(0.34 - 0.14\sqrt{e_a/1000} \right) \cdot \left(1.35 R_s / \left(R_0 \left(0.75 + 2 \times 10^{-5} z \right) \right) - 0.35 \right) \right\} \tag{4}$$

with Ro (W m^{-2}) the top of atmosphere solar irradiance, and z (m) the site elevation.

For attribution, the change in pan evaporation rate is the sum of changes of the radiative ($E_{P,R}$) and aerodynamic ($E_{P,A}$) components. The term $\mathrm{d}E_{P,A}/\mathrm{d}t$ is then further partitioned into three components, denoted U^*, D^*, T^* for changes due to changing wind speed, vapour pressure deficit and temperature respectively (Roderick et al. 2007),

$$\frac{\mathrm{d}E_{P,A}}{\mathrm{d}t} \approx \frac{\partial E_{P,A}}{\partial u}\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{\partial E_{P,A}}{\partial D}\frac{\mathrm{d}D}{\mathrm{d}t} + \frac{\partial E_{\mathrm{P,A}}}{\partial s}\frac{\mathrm{d}s}{\mathrm{d}T_a}\frac{\mathrm{d}T_a}{\mathrm{d}t} = U^* + D^* + T^* \tag{5}$$

The results indicate that this updated model explains the majority of the previously unexplained pan evaporation trend in Australia that could not be explained by only taking solar radiation into account. For example, at Alice Springs Airport, the observed pan evaporation trend is 25.8 mm a^{-2} for 1975–2004. Solar radiation can only explain 2.0 mm a^{-2} of the pan evaporation trend while the aerodynamic term accounts for the 19.4 mm a^{-2} (Roderick et al. 2007). At Darwin Airport, solar radiation explains −6.0 of the −17.0 mm a^{-2} of the observed pan evaporation trend while the aerodynamic term for the −9.3 mm a^{-2} (Roderick et al. 2007).

In general, much of the trend in pan evaporation observations in Australia was due to changes in the aerodynamic component, and the majority of that was due to changes in wind speed with generally minor changes due to changes in both vapour pressure deficit and air temperature (Roderick et al. 2007). This is consistent with the results of Rayner (2007), who has also concluded that trends in daily average wind speed are a dominant factor affecting pan evaporation trends in Australia.

Whether the results of (Roderick et al. 2007) are 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" and needs further investigation.

"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", as currently the calculation of outgoing long-wave irradiance is assumed the pan is a black body radiating at air temperature T_{a} (Roderick et al. 2007). The model also needs to be applied in wider range of environments, including other countries, to verify whether it can explain other observed pan evaporation trends.

4.2 Complementary relationship

Bouchet (1963) appears to have been the first researcher to promulgate the complementary concept formally in general terms (Kahler and Brutsaert 2006). Based on this complementary theory, Brutsaert and Parlange (1998) suggested that a decrease in pan evaporation could signal an increase in actual evaporation. The observed data of the large-scale conterminous US (Lawrimore and Peterson 2000; Hobbins et al. 2004; Walter et al. 2004) and Yellow River basin of China (Liu et al. 2006) and regional shorter timescale scale (Kahler and Brutsaert 2006) have confirmed the complementary relationship. Zhang et al. (2004) have found that the complementary relationship exist in Australia either in constant energy supply or constant water supply. Ozdogan and Salvucci (2004) also showed the complementary relationship is valid in the southeastern Turkey region.

However, this explanation for decreasing pan evaporation is also unsatisfactory for several reasons. First, it only predicts changes in pan evaporation in water-limited environments (Roderick and Farquhar 2002). The problem is that some areas are not water-limited, and in wet environments the evaporation from pans and the surrounding environment have both declined (Golubev et al. 2001). Second, if the proposed mechanism was the important one, then the VPD should have decreased. However, Liu et al. (2004) found that no significant changes of VPD have been found in China. An increase in water VPD has been reported at Bet Dagan in Israel, based on evaporation measurements between 1964 and 1998 (Cohen et al. 2002). Third, it is not firmly established that global evaporation must increase under an enhanced greenhouse climate (Ohmura and Wild 2002). When CO_2 was doubled in a simulation with the ECHAM3 general circulation model (GCM), a slight decrease in global evaporation was observed (Wild et al. 1997). A similar simulation with the GCM of the Meteorological Research Institute, Tsukuba, also showed a small decrease in global evaporation after doubling CO_2 (Ohmura and Wild 2002). In addition, Ainsworth and Long (2005) and Gedney et al. (2006) has found that plant transpiration will decrease under increased atmospheric CO_2.

Some observations also do not support the complementary relationship theory. For example, Cohen et al. (2002) concluded that the widespread reductions in potential evaporation that have been reported, although not found at Bet Dagan, were caused by global dimming rather than an increase in the rate of atmospheric moisture cycling due to global warming. Liu et al. (2004) attribute the pan evaporation decline in China to decreasing solar irradiance, not to the complementary relationship. Tebakari et al. (2005) found that the complementary relationship was not applicable in the Chao Phraya River basin of Thailand using 27 stations for the period of 1982–2000.

4.3 Wind speed

Wind speed is one important factor ignored by most literature reporting pan evaporation trends and theoretical explanations. Complex changes in surface wind speeds could be expected as the greenhouse effect changes general atmospheric circulation. Any reductions in wind speed could contribute to the observed declines in pan evaporation. There may be two reasons that changes of wind speed have been ignored: (1) The quality of observed records of near-surface wind run is generally too poor for assessing changes in the wind climate (Smits et al. 2005). Near-surface wind observations are very sensitive to changes in instrumentation, changes in the exact measuring location or measuring height and changes in local obstacles in the direct surrounds of the measurement site (Smits et al. 2005). (2) Pan evaporation is generally much more sensitive to variations in net irradiance and VPD than to variations in wind speed (Singh and Xu 1997; Roderick and Farquhar 2002).

Regarding the first reason, several studies have documented systematic changes in wind speed on the basis of station observations (Smits et al. 2005). For example, Schiesser et al. (1997) reported a significant negative trend in the number of winter storms in Switzerland north of Alps between 1864 and 1994. Pirazzoli and Tomasin (2003) reported a decrease in wind activity for the central Mediterranean and Adriatic region between 1951 and 1970 and increase from 1970 onwards. Smits et al. (2005) indicated moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) had decreased between 5% and 10% for the Netherlands for the period 1962–2002. Tuller (2004) indicates three (Cape St James, Victoria International Airport, and Vancouver International Airport) out of four stations on the west coast of Canada showed a decline in mean annual and winter wind speeds during the later 1940s or the 1950s to the early or mid 1990s. They further pointed out the increase in wind speed in the fourth station, Comox Airport, perhaps is the result of reduced friction in the vicinity of the anemometer outweighing the decrease in the regional pressure gradient (Tuller 2004). Climatology of dust storms in Mongolia based on observational data of 49 meteorological stations from 1960 to 1999 and compared them with data between 1937 and 1989 shows that the number of dusty days has tripled from the 1960s to 1990s and has decreased since 1990 (Natsgdorj et al. 2003). Groisman et al. (2004) indicates that there is a slight decrease in wind speed in the USA since 1960. Breslow and Sailor (2002) has used GCMs model output from Canadian Climate Centre and the Hadley Centre suggested that wind speed would reduce 1–3.2% in the next 50 years and 1.4–4.5% in the next 100 years.

Regarding the second reason, whilst it might be true that it takes relatively large changes in wind speed to cause a small change in pan evaporation, the magnitude of pan evaporation trend in the last 50 years is small. For example, in the case of the Netherlands (Smits et al. 2005), the magnitude change of wind speed is the same as the observed pan evaporation trend. Cohen et al. (2002) found that the decrease of potential evaporation in Israel due to decline in radiation can be offset by an increase in the aerodynamic term, which is function of VPD and wind speed. Hobbins et al. (2004) have found that the portion of the conterminous US-wide trend in actual evaporation attributable to trend in a decreasing advective budget, which is function of VPD and wind speed, amounts to an increase of 3.0 mm a^{-2}, whereas that attributable to the trend in solar radiation amounts to a decrease of 1.8 mm a^{-2}. Ozdogan and Salvucci (2004) attributed the observed decline in potential evaporation in the south-eastern part of Turkey to a decrease in wind speed and, to a lesser degree, increases in humidity. Chen et al. (2006) also reported that wind speed, and to a lesser degree relative humidity, were the most important meteorological variables affecting potential evapotranspiration decreasing trends in the Tibetan Plateau. Rayner (2007) and Roderick et al. (2007), using different Penman-style pan evaporation models, have both concluded that trends in daily average wind speed are a dominant factor affecting pan evaporation trends in Australia.

The International Panel on Climatic Change (IPCC) supports this conclusion by reporting that changes in wind speed or in the attenuation of wind at the surface due to changes in vegetation at observing sites may also play some role in apparent downward trends in pan evaporation data (McCarthy et al. 2001). While studying the pan evaporation trend in the Huang-Huai-Hai watershed of China, Guo and Ren (2005) concluded the decrease of the pan evaporation was mainly caused by the weakening solar radiation and the sunshine duration, but also pointed out that average wind speed play an important role. Chattopadhyay and Hulme (1997) showed that wind speed is one of the important factors related to pan evaporation in India, especially during monsoon (June–Sep) and post-monsoon season (Oct–Dec). Forty-years (1961–2000) observation data at 62 stations in China showed that the relationship between pan evaporation and wind speed is even stronger than that between pan evaporation and solar radiation (Zuo et al. 2006): 45 out of 62 stations show that the relationship between pan evaporation and wind speed is significant at $\alpha = 0.05$ level. The simple linear regression between pan evaporation and solar radiation, VPD and wind in Loess Plateau of China indicates that VPD has the strongest relationship with pan evaporation. However, the combination of VPD and wind could explain the same or a little larger variance than that of VPD and solar radiation (McVicar et al. 2005).

These studies clearly indicate that wind speed is an important factor often ignored in current theoretical explanations of pan evaporation trends. In the early history of the estimation of pan evaporation, Dalton (1802) started the empirical hydrodynamic approach to the evaporation problem. In 1801, in a lecture to the Manchester Society, Dalton (who also determined the law of partial pressures) stated that evaporation is proportional to the difference in vapor pressure at the surface of the water and in the air and that the velocity of the wind affects this proportionality. Subsequently, numerous researchers started to investigate evaporation based on Dalton's description with the formula (Singh 1988; Singh and Xu 1997; Sartori 2000):

$$E_0 = f(u)\,(e_s - e_a) \tag{6}$$

Where $(e_s - e_a)$ is the VPD and u is the wind speed. Singh and Xu (1997) and Sartori (2000) have reviewed various forms of $f(u)$.

5 Research gaps and priorities

The first research priority is to clarify the uncertainties to enhance our confidence in the pan evaporation trends. Some of the uncertainties discussed in Section 3.3 are relatively easy to account for, such as same period, same season, and same evaporators being used for comparison to detect the magnitude of pan evaporation trends. Some are very difficult, if not impossible, to cope with. For example, the effects of location change and automated observation system are hard to account for in an accurate way. Some studies (Hobbins et al. 2004) have tried to homogenize the dataset. However, of critical concern is how to verify the accuracy of the homogenized data as any of these activities would bring in errors to the datasets. A acceptable error produced in this process may be the same magnitude, or even larger, than the pan evaporation trend detected.

It is noted that there are some stations and seasons showing an increasing pan evaporation trend although an overall large scale decreasing trend is significant. Three major potential causes of changes in pan evaporation, solar radiation, VPD and wind speed, have been changed in the last 50 years. The magnitude of changes and importance of each of the three causes varies from place to place, so the pan evaporation trend differs from region to region. A further investigation is needed to study the regional differences and find the controlling factors for pan evaporation at different regions and watersheds. This could help us not only understand the physical processes of pan evaporation, but also explain both increasing and decreasing trends in pan evaporation over the last 50 years.

The third research priority is to analyse the evaporation and solar radiation since 1990 (Ohmura and Wild 2002), because the newly available surface observations from 1990 to the present, primarily from the Northern Hemisphere, indicate that the majority of the sites show an increase in surface solar radiation after 1990 (Wild et al. 2005). This type of study will clearly indicate whether the reported pan evaporation decreasing trend is as segment of a longer trend caused by the human-induced greenhouse effect or a short-term variation due to solar radiation (Ohmura and Wild 2002).

The next research priority is to discriminate between pan evaporation and reference potential evapotranspiration trends, accepting they are highly related. A decreasing pan evaporation trend does not necessarily mean a decreasing reference potential evapotranspiration trend. This has been most clearly demonstrated in Israel, where a pan evaporation increasing trend is statistically significant, but no changes were found in the reference crop evapotranspiration estimated with Penman's combined heat balance and aerodynamic equation (Cohen et al. 2002). One important practical use of pan evaporation is to determine the irrigation water requirement, or crop potential evapotranspiration, thus this use would be questionable if the pan evaporation and potential evapotranspiration trends have diverging directions under global climatic change scenarios.

The fifth research topic is to separately study the evaporation trends from land and from the ocean (Ohmura and Wild 2002). Depending on conditions, they can differ tremendously, especially when land evaporation is from a drying soil surface. Ocean evaporation is a significant component the global hydrological cycle and it is highly related to global precipitation. The ocean evaporation depends heavily on non-atmospheric processes such as the ocean heat flux (Ohmura and Wild 2002). Our current knowledge about ocean evaporation is still limited, although 86% of global evaporation comes from the ocean (Wentz et al. 2007). When holding the land evaporation constant, Wentz et al. (2007) have found that global evaporation has increased 12.6 ± 4.8 mm year^{-1} per decade, or $1.3\% \pm 0.5\%$ per decade for the period from July 1987 through August 2006.

Ultimately, what is important is the trend in actual evaporation. Pan evaporation matters insofar as it can offer a useful clue to the direction of the change in actual evaporation (Ohmura and Wild 2002). Two existing theories explaining the pan evaporation decreasing trend seem to produce contradictory predictions of actual evaporation. Under the global dimming theory, actual evaporation has also been decreasing because of less solar radiation and increasing cloud cover. However, the complementary relationship theory predicts an increase in actual evaporation. Ohmura and Wild (2002) called for an examination of actual evaporation in the context of its two driving components: the radiative budget and the advective budget. These budgets have been addressed only separately previously (Szilagyi et al. 2001; Roderick and Farquhar 2002; Milly and Dunne 2001). Several studies (Lawrimore and Peterson 2000; Hobbins et al. 2004; Walter et al. 2004) have documented increasing actual evaporation in the USA based on water budget theory. It seems that the actual evaporation of the Yellow River in China also increased in the last 50 years as the streamflow of the basin has significantly decreased even after allowing for abstractions with no significant change in precipitation trend (Fu et al. 2004b). In the drought of 2002, Australia experienced record high temperatures, increasing evaporation, and declining streamflow (Nicholls 2005). However, Golubev et al. (2001) showed a mixture decreasing and increasing actual evaporation trends at different regions. Linacre (2004) showed a decrease in the rate of actual evaporation from land surface in Australia.

Actual evaporation is used as an indicator of streamflow trend when using climatic change scenarios. Water resource management planning increasingly needs to incorporate the affects of global climate change in order to accurately predict future supplies (Wurbs et al. 2005; Fu et al. 2007a, b). Numerous studies have documented the sensitivity of streamflow to climatic changes for watersheds globally. However, most of these studies are based on a assumption that temperature increase results in an increase in potential evapotranspiration (Cohen et al. 1996; Arnell 2002), although the magnitude of increase depend on several other factors, such as current VPD, atmospheric water vapour content, vegetation effects, and wind speed (Arnell 2002). Then actual evaporation is estimated as a function of potential evapotranspiration and soil moisture.

Empirical relationships between streamflow, precipitation, and temperature also indicate that streamflow is positively related to precipitation but negatively related to temperature (Langbein 1949; Risbey and Entekhabi 1996; Fu et al. 2007a, b). This implies that actual evaporation will increase under global warming scenarios. For example, a 20% precipitation increase may result in a streamflow increase of 48% for the Spokane River basin if the temperature is 1°C lower but only a 4% increase if the temperature is 1.8°C higher than the long-term mean (Fu et al. 2007a, b).

6 Summary

Observational data from many regions of the world indicates a decreasing trend in regional pan evaporation, even though global average temperature has increased in the last 50 years. This means that pan evaporation trends are not determined by temperature alone.

Further investigation of reported pan evaporation trends indicates that three major potential causes of changes in pan evaporation: solar radiation, VPD and wind speed, have all changed in the last 50 years. The magnitude of changes and importance of each of the three causes varies from place to place, so the pan evaporation trend differs from region to region, although overall there is a negative trend. However, there are uncertainties associated with reported pan evaporation trends. These issues need to be further investigated before any solid conclusion can be made. These include, but are not limited to, instrumentation, installation and maintenance, observational practice, shift/movement of site location, the period and season of study, and aging.

Two theories exist to explain the observed pan evaporation decreasing trends. Each of them has gained some acceptance as well as received considerable scepticism. This indicates that the current theoretical explanations have limits, are valid in some specific regions and seasons, and are not fundamental physical theories that could be used universally. In addition, the change of wind speed seems to be ignored by these current theories.

The current research gaps and priorities include reducing the uncertainties, recognizing the pan evaporation difference at different regions, analysing the pan evaporation in the last 15 years, and discriminating between pan evaporation and ocean evaporation, potential and actual evapotranspiration.

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References

Ainsworth EA, Long SP (2005) What have we learned from 15 years of free-air CO_{-2} enrichment (FACE) experiments? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol 165:351–372

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrig. Drainage Pap. 56, Food and Agriculture Organization, Rome

Arnell N (2002) Hydrology and global environmental change. Prentice Hall, Englewood Cliffs

Bonacci O (1991) The influence of errors on precipitation measurements on the accuracy of the evaporation measurements performed by a class a evaporation-pan. Theor Appl Climatol 43:181–183

Bouchet RJ (1963) Evapotranspiration re'elle et potentielle, signification climatique, symposium. Int Assoc of Sci Hydrol Publ, vol 62. Berkeley, CA, pp 134–142

Breslow PB, Sailor DJ (2002) Vulnerability of wind power resources to climate change in the continental United States. Renew Energy 27:585–598

Brouwer C, Heibloem M (1986) Irrigation water management: irrigation water needs. FAO, Rome

Brutsaert W, Parlange M (1998) Hydrologic cycle explains the evaporation paradox. Nature 396:30

Bruton JM, Hoogenboom G, McClendon RW (2000) A comparison of automatically and manually collected pan evaporation data. Trans ASAE 43:1097–1101

Burn DH, Hesch NM (2007) Trends in evaporation for the Canadian Prairies. J Hydrol 336:61–73

Chattopadhyay N, Hulme M (1997) Evaporation and potential evapotranspiration in India under condition of recent and future climate change. Agric For Meteorol 87:55–73

Chen SB, Liu YF, Thomas A (2006) Climatic change on the Tibetan Plateau: potential evapotranspiration trend from 1961–2000. Clim Change 76:291–319

Cohen S, Strzepek KM, Yates DN (1996) Climate change and water balance components. In: Kaczmarek Z, Strzepek KM, Somlyody L, Priazhinskaya V (eds) Water resources management in the face of climatic/hydrologic uncertainties. International Institute for Applied Systems Analysis, Laxenburg

Cohen S, Ianetz A, Stanhill G (2002) Evaporative climate changes at Bet Dagan, Israel, 1964–1998. Agric For Meteorol 111:83–91

Dalton J (1802) Experimental essays on the constitution of mixed gases; on the force of steam or vapour from water and other liquids at different temperatures, both in a Torricellian vacuum and in air; on evaporation; and on the expansion of gases by heat. Manch Mem 5–11:535–602

Ertek A, Sensoy S, Gedikm I, Kucukyumuk C (2006) Irrigation scheduling based on pan evaporation values for cucumber (*Cucumis sativus* L.) grown under field conditions. Agric Water Manag 81:159–172

Fu GB, Liu C, Chen S, Hong J (2004a) Investigating the conversion coefficients for free water surface evaporation of different evaporation pans. Hydrol Process 18:2247–2262

Fu GB, Chen S, Liu C, Shepard D (2004b) Hydro-climatic trends of the yellow river basin for the last 50 years. Clim Change 65:149–178

Fu GB, Barber ME, Chen S (2007a) The impacts of climate change on regional hydrological regimes in the Spokane River watershed. J Hydrol Eng 12:452–461

Fu GB, Charles SP, Chiew FHS (2007b) A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow. Water Resour Res 43:W11419. doi:10.1029/2007WR005890
Gaffen DJ, Ross RJ (1999) Climatology and trends of US surface humidity and temperature. J Climate 12:811–827
Gedney N, Cox PM, Betts RA, Boucher O, Huntingford C, Stott PA (2006) Detection of a direct carbon dioxide effect in continental river runoff records. Nature 439:835–838
Gifford RM, Farquhar GD, Nicholls N, Roderick ML (2005) Workshop summary on pan evaporation: an example of the detection and attribution of climate change variables. In: Pan evaporation: an example of the detection and attribution of trends in climate variables. Australia Academy of Sciences, pp 4–19
Golubev VS, Lawrimore JH, Groisman PY (2001) Evaporation changes over the contiguous United States and the former USSR: a reassessment. Geophys Res Lett 28:2665–2668
Grismer ME, Orang M, Snyder R, Matyac R (2002) Pan evaporation to reference evapotranspiration conversion methods. J Irrig Drain Eng 128:180–184
Groisman PY, Knight RW, Karl TR, Easterling DR, Sun B, Lawrimore J (2004) Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. J Hydrometeorol 5:64–85
Gunderson LH (1989) Accounting for discrepancies in pan evaporation calculations. Water Resour Bull 25:573–579
Guo J, Ren GY (2005) Recent change of pan evaporation and possible climate factors over the Huang-Huai-Hai watershed, China. Adv Water Sci 16:666–672 (in Chinese)
Harmsen EW, Gonzalez-Perez A, Winter A (2004) Re-evaluation of pan evaporation coefficients at seven locations in Puerto Rico. J Agric Univ PR 88:109–122
Hobbins M, Ramirez JA, Brown TC (2004) Trend in pan evaporation and actual evapotranspiration across the conterminous US: paradoxical or complementary? Geophys Res Lett 31:L13503. doi:10.1029/2004GL019846
Hutchinson M, Sharples J, Kesteven J (2005) Spatio-temporal trends in pan evaporation over Australia 1970–2003. In: Pan evaporation: an example of the detection and attribution of trends in climate variables. Australia Academy of Sciences, pp 24–33
Jacobs AFG, Heusinkveld BG, Lucassen DC (1998) Temperature variation in a class A evaporation pan. J Hydrol 206:75–83
Jovanovic B, Jones DA, Collins D (2008) A high-quality monthly pan evaporation dataset for Australia. Clim Change 87:517–535
Kahler DM, Brutsaert W (2006) Complementary relation between daily evaporation in the environment and pan evaporation. Water Resour Res 42:W05413. doi:10.1029/2005WR004541
Langbein WB (1949) Annual Runoff in the United State. U.S. Geological Survey Circular 5. U.S. Department of Interior, Washington D.C.
Lawrimore JH, Peterson TC (2000) Pan evaporation trends in dry and humid regions of the United States. J Hydrometeor 1:543–546
Linacre ET (2004) Evaporation trend. Theor Appl Climatol 79:11–21
Liu CM, Zeng Y (2004) Changes of pan evaporation in the recent 40 years in the Yellow River basin. Water Int 29:510–516
Liu B, Xu M, Henderson M, Gong W (2004) A Spatial analysis of pan evaporation trend in China, 1955–2000. J Geophys Res 109:D15102. doi:10.1029/2004JD004511
Liu S, Sun R, Sun Z, Li X, Liu C (2006) Evaluation of three complementary relationship approaches for evapotranspiration over the Yellow River basin. Hydrol Process 20:2347–2361
Livingston GJ (1908) An annotated bibliography on evaporation. Mon Weather Rev 36(6):186
McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (2001) Climate change 2001: working group II: impacts, adaptation and vulnerability, contribution of working group II to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
McVicar TR, Li LT, van Niel TG, Hutchinson MF, Mu XM, Liu ZH (2005) Spatially distributing 21 years of monthly hydrometeorological data in China: spatio-temporal analysis of FAO-56 crop reference evapotranspiration and pan evaporation in the context of climate change. CSIRO Land and Water Technical Report 8/05
Milly PCD, Dunne KA (2001) Trends in evaporation and surface cooling in the Mississippi River basin. Geophys Res Lett 28:1219–1222
Moonen AC, Ercoli L, Mariotti M, Masoni A (2002) Climate change in Italy indicated by agrometeorological indices over 122 years. Agric For Meteorol 111:13–27

Natsgdorj L, Jugder D, Chung YS (2003) Analysis of dust storms observed in Mongolia during 1937–1999. Atmos Environ 37:1401–1411
Nicholls N (2005) The changing nature of Australia drought. Clim Change 63:323–336
Ohmura A, Wild M (2002) Is the hydrological cycle accelerating? Science 298:1345–1346
Oroud IM (1998) Influence of heat conduction on evaporation from sunken pans in hot, dry environment. J Hydrol 210:1–10
Ozdogan M, Salvucci GD (2004) Irrigation-induced changes in potential evapotranspiration in southeastern Turkey: test and application of Bouchet's complementary hypothesis. Water Resour Res 40:W04301. doi:10.1029/2003WR002822
Peterson TC, Golubev VS, Groisman PY (1995) Evaporation losing its strength. Nature 377:687–688
Pirazzoli PA, Tomasin A (2003) Recent near-surface wind changes in the central Mediterranean and Adriatic areas. Int J Climatol 23:963–973
Quintana-Gomez RA (1998) Changes in evaporation patterns detected in northernmost South America. In: Proc 7th int. meeting on statistical climatology. Institute of Mathematical Statistics, Whistler, BC, Canada, p 97
Rayner DP (2007) Wind run changes: the dominant factor affecting pan evaporation trends in Australia. J Clim 20:3370–3394
Risbey JS, Entekhabi D (1996) Observed Sacramento Basin streamflow response to precipitation and temperature changes and its relevance to climate impacts studies. J Hydrol 184:209–223
Robinson M (1999) The consistency of long-term climate datasets: two UK examples of the need for caution. Weather 54:2–9
Robinson PJ (2000) Temporal trends in United States dew point temperatures. Int J Clim 20: 985–1002
Roderick ML, Farquhar GD (2002) The cause of decreased pan evaporation over the past 50 years. Science 298:1410–1411
Roderick ML, Farquhar GD (2004) Changes in Australian pan evaporation from 1970 to 2002. Int J Clim 24:1077–1090
Roderick ML, Farquhar GD (2005) Changes in New Zealand pan evaporation since the 1970s. Int J Clim 25:2031–2039
Roderick ML, Rotstayn LD, Farquhar GD, Hobbins MT (2007) On the attribution of changing pan evaporation. Geophys. Res. Lett. 34, L17403, doi:10.1029/2007GL031166
Sartori E (2000) A critical review on equations employed for the calculation of the evaporation rate from free water surfaces. Sol Energy 68(1):77–89
Schiesser HH, Pfister C, Bader J (1997) Winter storms in Switzerland north of the Alps 1864/1865–1993/1994. Theor Appl Climatol 58:1–19
Singh VP (1988) Hydrologic systems: watershed modeling. Prentice Hall, Englewood Cliffs
Singh VP, Xu CY (1997) Evaluation and generalization of 13 mass-transfer equations for determining free water evaporation. Hydrol Process 11:311–323
Smits A, Klein Tank AMG, Konnen GP (2005) Trends in storminess over the Netherlands, 1962–2002. Int J Clim 25:1331–1344
Snyder RL, Orang M, Matyac S, Grismer ME (2005) Simplified estimation of reference evapotranspiration from pan evaporation data in California. J Irrig Drain Eng 131(3):249–253
Stanhill G (2002) Is the Class A evaporation pan still the most practical and accurate meteorological method for determining irrigation water requirement? Agric For Meteorol 112:233–236
Stanhill G, Möller M (2008) Evaporative climate change in the British Isles. Int J Climatol 28: 1127–1137
Symons GJ (1867) Evaporators and evaporation. Br Rainfall 7:9–10
Szilagyi J, Katul GG, Parlange MB (2001) Evapotranspiration intensifies over the conterminous United States. J Water Resour Plan Manage 127(6):354–362
Tebakari T, Yoshitani J, Suvanpimol C (2005) Time–space trend analysis in pan evaporation over kingdom of Thailand. J Hydrol Eng 10:205–215
Thomas A (2000) Spatial and temporal characteristics of potential evapotranspiration trends over China. Int J Climatol 20:381–396
Trewin B, Collins D (2005) Observed climate change in Australia—what we do and do not know. In: Pan evaporation: an example of the detection and attribution of trends in climate variables. Australia Academy of Sciences, pp 24–33
Tuller SE (2004) Measured wind speed trends on the West Coast of Canada. Int J Clim 24:1359–1374
Walter MT, Wilks DS, Parlange JY, Schneider RL (2004) Increasing evapotranspiration from the conterminous United States. J Hydrometeorol 5:405–408

Wentz FJ, Ricciardulli L, Hilburn K, Mears C (2007) How much more rain will global warming bring? Science 317:233–235
Wild M, Gilgen H, Roesch A, Ohmura A, Long CN, Dutton EG, Forgan B, Kallis A, Russak V, Tsvetkov A (2005) From dimming to brightening: decadal changes in solar radiation at Earth's surface. Science 308:847–850.
Wild M, Ohmura A, Cubasch U (1997) GCM-simulated surface energy fluxes in climate change experiments. J Clim 10:3093–3110
WMO (1966) Measurement and estimation of evaporation and evapotranspiration, vol 83. Technical Report, Working Group on Evaporation Measurement, Geneva
WMO (1976) The CIMO international evaporimeter comparisons. Final Report No. 449, Geneva, p 38
Wurbs RA, Muttiah RS, Felden F (2005) Incorporation of climate change in water availability modeling. J Hydrol Eng 10:375–385
Xu J, Haginoya S, Saito K, Motoya K (2005) Surface heat balance and pan evaporation trends in Eastern Asia in the period 1971–2000. Hydrol Process 19:2161–2186
Zhang L, Hickel K, Dawes WR, Chiew FHS, Western AW, Briggs PR (2004) A rational function approach for estimating mean annual evapotranspiration. Water Resour Res 40:W02502. doi:10.1029/2003WR002710
Zhang Y, Liu C, Tang Y, Yang Y (2007) Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan plateau. J Geophys Res 112:D12110. doi:10.1029/2006JD008161
Zuo HC, Bao Y, Mang CJ, Hu YQ (2006) An analytic and numerical study on the physical meaning of pan evaporation and its trend in recent 40 years. Chin J Geophys 49:680–688 (in Chinese)