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The Cause of Decreased Pan Evaporation over the Past 50 Years

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Changes in the global water cycle can cause major environmental and socioeconomic impacts. As the average global temperature increases, it is generally expected that the air will become drier and that evaporation from terrestrial water bodies will increase. Paradoxically, terrestrial observations over the past 50 years show the reverse. Here, we show that the decrease in evaporation is consistent with what one would expect from the observed large and widespread decreases in sunlight resulting from increasing cloud coverage and aerosol concentration.

It is now well established that the surface of Earth has, on average, warmed ~0.15°C decade^{-1} over the past 50 years (*1*). One expected consequence of this 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. However, despite the observed increases in average temperature, observations from the Northern Hemisphere show that the rate of evaporation from open pans of water has been steadily decreasing over the past 50 years (*2*). This trend is general (*3*, *4*) but not universal (*5*). The contrast between expectation and observation is called the pan evaporation paradox. It is important to understand why pan evaporation has decreased despite the increases in average temperature in order to make more robust predictions about future changes in the hydrological cycle.

Two proposals for the decline in pan evaporation have been advanced: the first invokes changes in the humidity regime over the pans (*6*), whereas the second invokes reductions in solar irradiance resulting from more clouds and/or aerosols (*5*, *7*) and is generally consistent with the independent suggestion that increased pollution would weaken the hydrological cycle (*8*). The first proposal is that pan evaporation has decreased because evaporation from the environment surrounding the pan has increased (*6*). The explanation is that in water-limited environments, when the evaporation from the adjacent environment is high, the air over the pan tends to be cooler and more humid, thereby reducing evaporation from the pan. A subsequent analysis of rainfall and streamflow data from water-limited environments in both the former Soviet Union and the United States does apparently show an increase in evaporation from the environment (*9*, *10*). However, this explanation for decreasing pan evaporation is unsatisfactory for two reasons. First, it only predicts changes in pan evaporation in water-limited environments. 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 (*9*). Further, if the proposed mechanism was the important one, then the vapor pressure deficit should have decreased. However, data from the United States show that its average has remained virtually constant over the past 50 years (*10*). This implies that the second proposal, based on the decrease in solar irradiance, should be further investigated.

Any explanation of the decrease in pan evaporation must accommodate the following: (i) the widespread decrease in pan evaporation has occurred in both dry and wet environments, and (ii) the average vapor pressure deficit (D, measured in Pa) has remained more or less constant despite increases in the average temperature. Decreases in solar irradiance would be consistent with (i), and here we specifically address the second item.

The key question is: How could D remain nearly constant despite increases in average temperature? We note that D is defined by

$$D = e_s(T) - e_s(T_d), \qquad (1)$$

where e_s (measured in Pa) denotes the saturation vapor pressure at the temperature (T) and dew point (T_d) of the air. To first order, the change in D is given by

$$\delta D = s\delta T - s_d\delta T_d, \qquad (2)$$

where s and s_d are the slopes of the saturation vapor pressure–temperature relationship at T and T_d, respectively. T is larger than T_d, and s is larger than s_d. δD would be zero if $\delta T_d/\delta T$ were equal to s/s_d. Averaged over a day, s/s_d depends on both the average T and the diurnal temperature range (DTR). This ratio is typically a little greater than 2 for a sunny day with a large DTR but a little less than 2 on cloudy days with a lower DTR (Table 1). Taking a typical value of s/s_d as 2 (Table 1), it follows that δD would be zero provided that δT_d is double δT. That is important, because globally averaged measurements over the past 50 years show that while the average T has been increasing (~0.15°C decade^{-1}), the average minimum T generally has been increasing twice as fast (~0.2°C decade^{-1}) as the average maximum T (~0.1°C decade^{-1}) (*1*). When above the freezing point, the dew point will in general set a lower limit on the minimum T. Thus, the observed increase in minimum T implies that the dew point must also be increasing faster than the average T.

Table 1. Variation in the ratio s/s_d as a function of T assuming three different T_d (T_d = 5°, 15°, 25°C).

T (°C)	s/s_d
T_d = 5°C s_d = 61 Pa K^{-1}	
10	1.36
15	1.80
20	2.38
25	3.10
T_d = 15°C s_d = 110 Pa K^{-1}	
20	1.32
25	1.72
30	2.22
35	2.84
T_d = 25°C s_d = 189 Pa K^{-1}	
30	1.29
35	1.65
40	2.08
45	2.61

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That conclusion is consistent with data from the United States that show that the average dew point has generally increased much faster (~0.3°C decade^{-1} or a little greater in some parts of the United States) than the average T (*11*, *12*). Consequently, over the United States at least, δD should be very close to zero because $\delta T_d/\delta T$ is about the same as s/s_d. This would explain why the average D has remained virtually constant in the United States over the past 50 years. More generally, the widespread observed decline in the DTR (*13*, *14*), when combined with the above analysis, suggests that the changes in D should be very small in many places.

Pan evaporation is generally much more sensitive to variations in net irradiance and D than to variations in wind speed (*15*–*17*). Thus, with δD being small, a change in pan evaporation must result from a change in net irradiance. To estimate the magnitude of this change resulting from a change in solar irradiance, we use

$$(0.7)\,\lambda E_{pan} \approx 1.26\left(\frac{s}{s+\gamma}\right)R_n \qquad (3)$$

where the right-hand side of Eq. 3 is the well-known Priestley-Taylor expression for evaporation from a wet surface (*18*), and we have used the usual coefficient (0.7) to account for evaporation pans having a greater surface area for energy transfer than for mass transfer (*17*). In Eq. 3, λ (~2.4 MJ kg^{-1}) is the latent heat of vaporization of water; E_{pan} (kg m^{-2} s^{-1}), the pan evaporation; R_n (J m^{-2} s^{-1}), the net irradiance; and γ (~ 67 Pa K^{-1}), the psychrometric constant. The ratio $s/(s + \gamma)$ is calculated at the mean T and varies from 0.48 at 5°C to 0.82 at 35°C. Ignoring the change in that ratio resulting from the very small observed change in mean temperature, the change in pan evaporation resulting from a change in net irradiance can be approximated as:

$$\lambda\delta E_{pan} \approx \frac{1.26}{0.70}\left(\frac{s}{s+\gamma}\right)\delta R_n \qquad (4)$$

For an evaporation pan, R_n is nearly linearly related to the global solar irradiance (R_s, J m^{-2} s^{-1}), so that in differential form we have

$$\delta R_n \approx c\,\delta R_s \qquad (5)$$

where c is ~0.8 (*16*, *17*). Thus, the change in pan evaporation resulting from a change in global solar irradiance can be approximated as:

$$\lambda\delta E_{pan} \approx 1.44\left(\frac{s}{s+\gamma}\right)\delta R_s \qquad (6)$$

In general, measurements of global solar irradiance are not as readily available as measurements of pan evaporation. However, much of the original work reporting the decrease in pan evaporation was from the northwest of the former Soviet Union (49° to 67°N) (*2*, *9*), fortunately one of the few regions of the world where such regional measurements are available for the same period (*19*). Here we use those data, along with Eq. 6, to calculate the expected change in annual pan evaporation over a 30-year period (1960 to 1990), which is then compared with the observed change. In the region of interest, R_s decreased by 2 to 4% per decade from 1960 to 1990, and a typical annual total R_s in that region is in the range of 3000 to 4000 MJ m^{-2} per year (a^{-1}) (*19*). Assuming that R_s is 3500 MJ m^{-2} a^{-1} and is declining at a rate of 3% per decade over the 30-year period of interest, then δR_s would be –315 MJ m^{-2} a^{-1}. With $s/(s + \gamma)$ in the range of 0.48 to 0.82, the reduction in latent heat loss would be in the range (~1.44 × 0.48 × 315 to 1.44 × 0.82 × 315) of ~217 to 372 MJ m^{-2} a^{-1}, which is equivalent to a decrease in annual pan evaporation of ~90 to 155 mm a^{-1}. The observed pan evaporation at seven sites in the region show a rate of decrease ranging from 1.5 mm a^{-2} to 6.7 mm a^{-2}, and the average rate of decrease is 3.7 mm a^{-2} (*9*). Over the 30-year period of interest, this equates to a decrease in annual pan evaporation of 110 mm a^{-1}, consistent with our estimate of ~ 90-155 mm a^{-1}.

We have encountered considerable scepticism about the large reported declines in global solar irradiance. The issue is that most climate models as yet do not include the 10 to 20% reductions observed in many places over the past 50 years (*7*, *20*). However, we have a further independent check. A substantial decline in global solar irradiance as a consequence of increased cloud coverage and/or aerosol concentration should result in a decrease in the DTR, because increases in clouds and/or aerosols dampen the diurnal cycle by reducing the incident sunlight and also by reducing the net loss of long-wave irradiance from the surface at night (*8*, *21*). This was recently highlighted by the marked increase in DTR over parts of the United States from 11 September to 14 September 2001 when aircraft were grounded (*22*). Thus, the widespread longer-term decreases in DTR (*1*, *13*, *14*) are qualitatively consistent with the widespread observed decreases in global solar irradiance (*7*, *20*). Quantifying that, we estimated the expected decrease in DTR with the use of an approximate relation between the transmission of solar irradiance through the atmosphere and the DTR (*23*). Over the same part of the former Soviet Union, the change in DTR computed from the observed change in solar irradiance is ~–0.2°C decade^{-1} (see SOM Text) and is consistent with the observed changes of ~–0.1° to –0.3°C decade^{-1} in the DTR (*1*, *14*).

We conclude that the observed decrease in pan evaporation is not a paradox after all. Instead, the decrease is to be expected given the decreases in solar irradiance and the associated changes in DTR and vapor pressure deficit that have been observed. Further, the observed decrease in the DTR is itself qualitatively and quantitatively consistent with the observed decrease in global solar irradiance. These results highlight the fundamental importance of evaluating the direction and magnitude of changes in the surface energy balance resulting from greenhouse forcing as opposed to the direction and magnitude of changes resulting from aerosol loading (*8*). Such an evaluation is also important when estimating the biological and ecological impacts of changes in climate, because clouds and aerosols scatter light and thereby reduce the shade within vegetation canopies, markedly affecting the structure and productivity of terrestrial vegetation (*24*, *25*). The interactions between global solar irradiance, diurnal temperature range, and pan evaporation, which have been highlighted here, are all related to variations in the transmission of solar irradiance through the atmosphere and appear to be very general features of the climate and the climate-vegetation systems.

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Supporting Online Material

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References and Notes

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