Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary?

Michael T. Hobbins and Jorge A. Ramírez
Civil Engineering Department, Colorado State University, Fort Collins, Colorado, USA

Thomas C. Brown
Rocky Mountain Research Station, U.S. Forest Service, Fort Collins, Colorado, USA

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[1] Pan evaporation (ET_{pan}) has decreased at 64% of pans in the conterminous U.S. over the past half-century. Comparing trends in ET_{pan} and water budget-derived actual evapotranspiration (ET_a^*), we observe the so-called "Pan Evaporation Paradox," which we confirm is no more than a manifestation of the complementarity between actual evapotranspiration (ET_a) and potential evapotranspiration (ET_p). Examining trends in the components of ET_a—the radiative energy and regional advective budgets—we show that both components must be considered together to explain the relationship between ET_{pan} and ET_a^*. *INDEX TERMS:* 1818 Hydrology: Evapotranspiration; 1833 Hydrology: Hydroclimatology; 1655 Global Change: Water cycles (1836); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Hobbins, M. T., J. A. Ramírez, and T. C. Brown (2004), Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary?, *Geophys. Res. Lett.*, *31*, L13503, doi:10.1029/2004GL019846.

1. Pan Evaporation "Paradox"

[2] The decreasing trend in ET_{pan} observed in several countries [e.g., *Chattopadhyay and Hulme*, 1997; *Peterson et al.*, 1995; *Golubev et al.*, 2001; *Lawrimore and Peterson*, 2000] has captured attention, especially because the trend seems contrary to concurrent increasing trends in ET_a^* [*Szilagyi et al.*, 2001], GCM-based estimates of evapotranspiration [*Manabe*, 1997], temperature [*Folland and Karl*, 2001], and precipitation and cloudiness [*Karl et al.*, 1996]. All else equal, one expects evapotranspiration to increase with increases in temperature, and increasing evapotranspiration is necessary for increases in precipitation and cloudiness. This apparently contradictory behavior has led to talk of a "pan evaporation paradox," which has been cited as evidence of "climate alarmists' illusionary world of 'unprecedented' global warming" [*CSCDGC*, 2001, 2003].

[3] As theorized by *Brutsaert and Parlange* [1998], the solution to the paradox turns on the relation of ET_{pan} to ET_a. Depending on moisture availability in the region around the pan, these two variables may be nearly identical or very different, but they are nevertheless related: to understand the changes in ET_{pan}, one must look at changes in ET_a, or at the variables influencing ET_a. As a recent editorial in Science [*Ohmura and Wild*, 2002] stated, "...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." The editorial further called for an examination of ET_a in the context of its two driving components: the radiative budget and the advective budget. These budgets have been addressed previously [*Szilagyi et al.*, 2001; *Roderick and Farquhar*, 2002; *Milly and Dunne*, 2001], but separately.

[4] We examine trends in both ET_{pan} and ET_a for the conterminous U.S., obtaining estimates of ET_a observationally (ET_a^*) as precipitation minus runoff for 655 relatively undisturbed basins (Figure 1). We explain trends in ET_a^* as functions of combinations of trends in the radiative and advective budgets, and show that both components must be considered together; neither in isolation explains the paradoxical-seeming behavior observed in ET_{pan} and ET_a^*.

2. Trends in ET_{pan}

[5] Limiting analyses to pans that reported at least 20 complete years or warm seasons (May through October) within the period 1950–2002 produces sets of 1248 data at 44 pans from which annual trends were derived (Figure 2a); and of 7064 data from 228 pans for warm-season trends (Figure 2b), where a datum is a single year's or season's observation at a single pan. The data were homogenized to account for abrupt shifts in ET_{pan} measurements resulting from changes in pan location or type, or other changes that could otherwise artificially bias our results [*Peterson et al.*, 1998]. (For each ET_{pan} time-series, a homogeneity analysis was performed to detect abrupt changes across the entire period of record as indicated by the metadata accompanying the raw data or by statistical tests—i.e., T-test and double-mass curve analyses—indicating statistically significant abrupt shifts at the 95% level. The time series of 172 pans were homogenized around 326 abrupt data-shifts: 280 shifts due to changes in pan location, the rest due to unspecified changes. In this manner 43% of the annual data and 55% of the warm-season data were homogenized.)

[6] Of the 44 annual pans, 64% show the decreasing ET_{pan} trend reported widely in the literature [e.g., *Chattopadhyay and Hulme*, 1997; *Peterson et al.*, 1995; *Brutsaert and Parlange*, 1998; *Roderick and Farquhar*, 2002]; of the 12 pans with significant trends (at the 90% level using the *F*-statistic of the trend slope), 75% are decreasing. Of the 228 warm-season pans, 60% show decreasing ET_{pan}; of the 43 pans with significant trends, 84% are decreasing. Warm-season ET_{pan} has decreased

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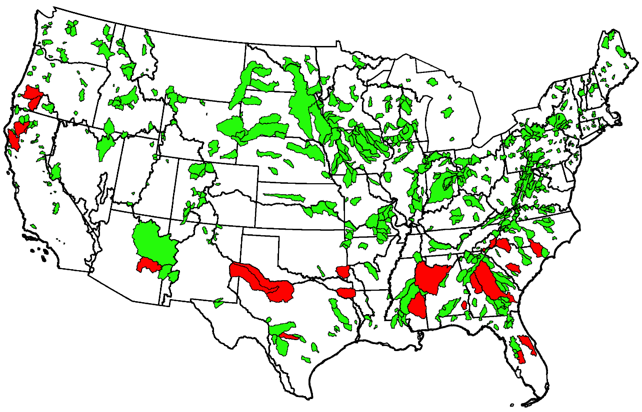

Figure 1. Locations of the 655 test-basins. The basins were selected from the Hydroclimatic Data Network (HCDN) [*Slack and Landwehr*, 1992]. ET_{pan} and basin-derived ET_a^* from the basins shown in red were used to generate the comparison in Figure 3.

across most of the conterminous U.S., but there are significant exceptions in the Northwest, the Northeast, regions around the Gulf of Mexico, South Carolina, and southern Florida. Lumping ET_{pan} data spatially over a continental scale obscures these spatial differences, confusing examination of the driving dynamics of trends.

3. Complementary Relationship

[7] The relationship between ET_{pan} and regional ET_a^* is apparent in Figure 3, which contains 192 data pairs, each consisting of an annual measure of ET_{pan} and an annual measure of ET_a^* from the surrounding test-basin (in red in Figure 1) containing the pan(s) for each year in the period WY 1953–1994 for which an ET_{pan} measure was available. The highest values of ET_{pan} occur at the left of the graph, in water-limited environments, and are matched with the lowest values of ET_a^*. Moving to the right, precipitation increases, the water-limitation on the evaporative process gives way to an energy-limitation, and ET_{pan} decreases as ET_a^* increases. In general, ET_{pan} and ET_a^* rates converge in the wettest basins; the evaporation rate in purely energy-limited basins is referred to here as wet environment evaporation (ET_w).

[8] The noise in the data may reflect the fact that ET_{pan} data are gathered at single points whereas ET_a^* data arise from hydrologic integrations over the basins containing the pans. The former therefore represent a limited sample of a population; the latter more closely represent its mean.

[9] Figure 3 closely matches the theoretical shape of the complementary relationship between regional-scale ET_p and ET_a. In this hypothesis [*Bouchet*, 1963], all available energy not taken up by ET_a goes to heat and dry the overpassing air, driving ET_p above ET_w by the amount that ET_a falls below it. This relationship is expressed by:

$$ET_a = 2ET_w - ET_p. \tag{1}$$

[10] That the independent observations of ET_{pan} and ET_a^* in Figure 3, which represent ET_p and ET_a, so closely display complementarity provides strong evidence for the complementary relationship hypothesis.

4. Trends in the Components of Evapotranspiration

[11] Figure 3 depicts the behavior that has been characterized as paradoxical—wherein decreasing ET_{pan} is matched by increasing ET_a^*. The effects of trends in the driving components of ET_a^* (or ET_a) and ET_{pan} (or ET_p) are indicated in Figure 3 by the labeled arrows. In theory, a decreasing radiative budget (Q_n)—due to increasing cloudiness, for example—lowers the dashed lines representing both ET_a^* and ET_{pan}, while increasing Q_n raises them; a decreasing advective budget (indicated by the drying power of the air, E_A)—due to increasing precipitation, for example—moves a datum pair convergently to the right along their respective dashed lines, upwards for ET_a and downwards for ET_{pan}, whereas increasing E_A moves a datum pair divergently to the left, downwards for ET_a and upwards for ET_{pan}.

[12] To understand trends in ET_{pan}, we would ideally observe trends in Q_n and E_A estimated from measurements taken at the locations of the pans. However, measurements

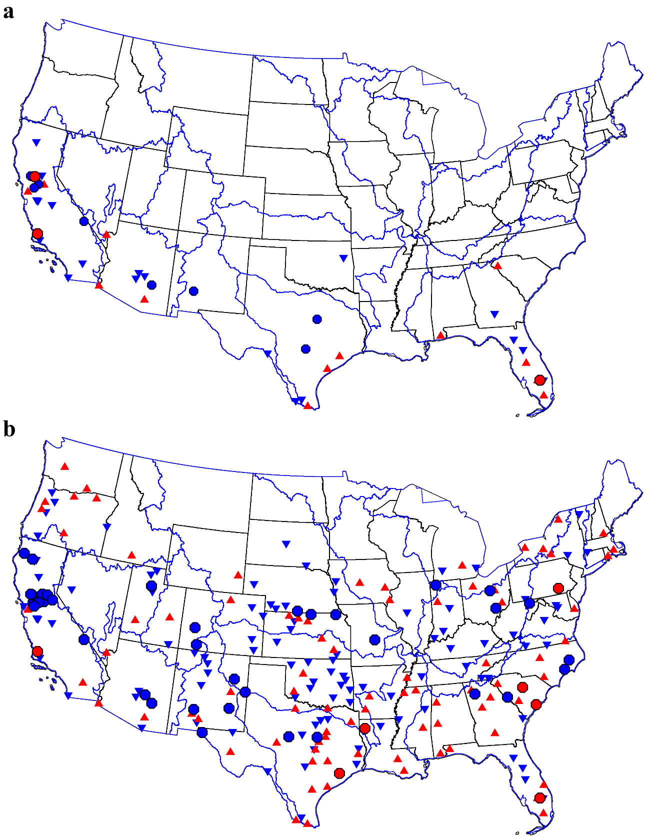

Figure 2. Trends in ET_{pan} across the conterminous U.S. (a) and (b) show the annual pans over the period WY 1951–2002 and warm-season (MJJASO) pans over the period CY 1950–2001, respectively. Increasing trends are represented by symbols in red, decreasing in blue; circles represent trends significant at 90%, triangles represent trends not significant at 90%. The ET_{pan} data were drawn from NCDC Summary of the Day and NCDC Summary of the Month.

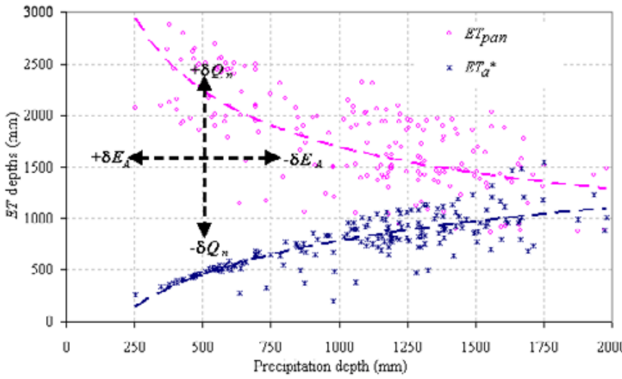

Figure 3. Point annual depths of ET_{pan} and basinwide annual depths of ET_a^*. Data for a single basin-pan pair line up vertically. Arrows marked "δE_A" and "δQ_n" indicate the effects on ET_a^* and ET_{pan} of trends of the indicated signs in their vapor transfer (E_A) and energy budget (Q_n) components, respectively. ET_a^* is calculated for each basin as the difference between precipitation and runoff, the former data being predicted by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) [*Daly et al.*, 1994] and the latter extracted for USGS gages listed in the Hydroclimatic Data Network (HCDN) [*Slack and Landwehr*, 1992].

for these variables are rarely coincident with the pans. Instead, to understand trends in ET_{pan} we examine trends in ET_a^* (the complement to ET_{pan}, as indicated in Figure 3) in terms of trends in both Q_n and E_A, mindful that ET_a is the hydrologic flux of primary interest [*Ohmura and Wild*, 2002].

[13] ET_w and ET_{pan} may be expressed as functions of Q_n and E_A as:

$$ET_w = f(Q_n) \text{ and } ET_{pan} \equiv ET_p = f(Q_n, E_A). \qquad (2)$$

[14] The temporal trend in ET_a (denoted by δET_a) can then be expressed as a combination of trends in its component budgets—δQ_n representing the time-rate of change in the radiative energy budget and δE_A representing that in the advective or vapor transfer budget (i.e., in the regional drying power of the air)—as follows:

$$\delta ET_a = \left(2\frac{\partial ET_w}{\partial Q_n} - \frac{\partial ET_p}{\partial Q_n}\right)\delta Q_n - \frac{\partial ET_p}{\partial E_A}\delta E_A. \qquad (3)$$

[15] In equation (3) all ordinary differentials are observable; the partial derivatives depend on the equations used for ET_w and ET_p—typically, some variation of the Priestley-Taylor equation and Penman equation [e.g., *Brutsaert and Stricker*, 1979], respectively. In traditional paradigms, ET_a is estimated as a monotonically increasing function of ET_p or of ET_{pan} and moisture availability, implying that trends in ET_a are a positive function of trends in ET_p, and therefore similarly in the drying power of the air E_A. However, as shown in equation (3), this is not the case. The E_A term not only drives ET_a (wherein more moisture potentially evaporates into the air as a result of the air being drier), but also reflects the effects of ET_a on regional advection (the regional drying power of the air increases when there has been less evaporation).

[16] Incident solar radiation (R_t) provides the major energy input to any evaporative process, and is an excellent estimator of Q_n. Averaged across the conterminous U.S. for WY 1953–1994, we observe a decrease in R_t of 0.298 watts/m^2/yr, for a 42-year decrease of 12.52 watts/m^2 or 14.4% of the mean, lending indirect support to the findings of *Roderick and Farquhar* [2002] and *Gilgen et al.* [1998]. On a distributed basis (Figure 4a), R_t decreased over 98% of the conterminous U.S. The western Great Lakes region and the inland Pacific Northwest are exceptions to this general decrease.

[17] Humidity is a key factor in E_A. As measured by the vapor pressure deficit (V_{dif}), humidity increased over most of the eastern U.S., but across the West the pattern is heterogeneous (Figure 4b). V_{dif} decreased over 75% of the conterminous U.S.; the spatial mean trend is a decrease of 0.012 hPa/yr, for a 42-year decrease of 0.504 hPa or 10.1% of the mean. However, in order for V_{dif} to reveal anything about ET_{pan} or ET_a it must be multiplied by a functional measure of the speed of the overpassing air, generally in the form of an empirical function of wind speed $f(U_2)$, revealing E_A, the advective budget. Thus, trends in E_A can be due to trends in wind speed U_2, V_{dif}, or some combination of both

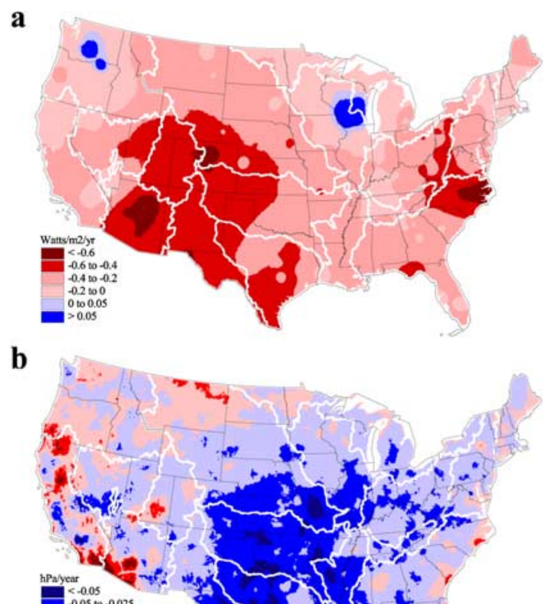

Figure 4. Trends in mean annual incident solar radiation R_t (a) and vapor pressure deficit V_{dif} (b), spatially interpolated from monthly time-series (WY 1953–1994) of observations and expressed in (a) watts/m^2/yr and (b) hPa/yr, as the slope of a linear fit to the annual time series at each 25 km^2 pixel. R_t data were drawn from the SOLMET, SAMSON, and NCDC Airways Solar Radiation datasets and are corrected for local topographic effects. V_{dif} data were derived from air temperature data extracted from NCDC Summary of the Day and dew-point temperature data from NCDC Surface Airways and SAMSON datasets.

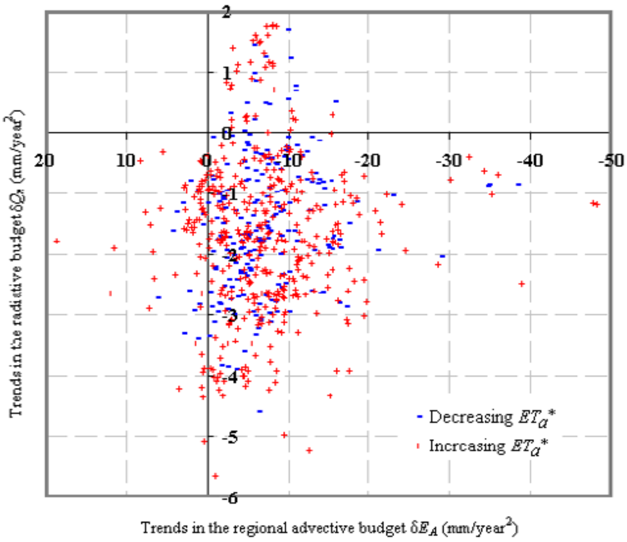

Figure 5. Slope parameters for the Q_n and E_A components of trends in annual ET_a^* over the period WY 1953–1994 for the test-basins indicated in red in Figure 1. Red "+" symbols indicate increasing ET_a^* rates, blue "–" symbols decreasing ET_a^* rates. Trends are plotted orthogonally, with δE_A plotted in reverse (positive left, negative right). Basin values for Q_n and E_A were computed by averaging across all 25 km^2 pixels in a basin.

(in this paper we examine only trends in V_{dif} in order to compare our results to those of *Roderick and Farquhar* [2002]).

[18] To show how the trends in ET_a and its component budgets are related, we examine the trends in annual ET_a^*, Q_n, and E_A at the 655 test-basins with data for WY 1953–1994 (Figure 5). The distribution of negative and positive ET_a^* trends across the quadrants of Figure 5 reflects the spatial distribution and direction of trends in R_t and V_{dif} (Figure 4). Overall, 92% of basins lie below the x-axis, reflecting the predominantly decreasing R_t (and hence decreasing Q_n); and 89% of the basins lie to the right of the y-axis, reflecting the fact that most test-basins are located in the central and eastern U.S. where decreasing V_{dif} (and hence decreasing E_A, all else equal) predominates.

[19] In the lower-right quadrant, where 528 of the basins fall, the directions of the component trends conflict in their effects on trends in ET_a^*: the decrease in E_A tends to reflect increasing regional ET_a^*, whereas the decrease in Q_n tends to decrease local ET_a^*. Consider a test-basin from the far right of the graph, representing USGS gage 10263500 located in the northern Mojave Desert of Southern California, which exhibits a decrease in depth-equivalent Q_n of 1.168 mm/yr^2 and a decrease in depth-equivalent E_A of 47.685 mm/yr^2. These component trends have opposing effects on ET_a. Taking into account the relative difference in trend magnitudes between the two (the trend in E_A far exceeds that in Q_n), one would expect ET_a to increase and, indeed, this is the case: annual ET_a^* increased at 0.262 mm/yr^2.

[20] Figure 5 also helps explain the relation of ET_{pan} to ET_a^*. ET_{pan} should be decreasing in basins in the lower-right quadrant of Figure 5, where both Q_n and E_A decreased. Because ET_a^* increased in about half (276) of the basins of this quadrant, decreasing ET_{pan} is clearly not an indication of decreasing ET_a^*. To the contrary, decreasing ET_{pan} is often associated with increasing ET_a^*. That ET_a^* increased in these 276 basins, where the effect of decreasing E_A outweighs the effect of decreasing Q_n, can only be explained in the context of the complementary relationship. (*Roderick and Farquhar* [2002] claimed that V_{dif} has not changed across the conterminous U.S., asserting instead that the complementary relationship plays little part in determining trends in ET_{pan} and that such trends are due solely to trends in R_t. However, accounting spatially for changes in V_{dif} (Figure 4b), combining V_{dif} with the wind function in a formulation of E_A, and using E_A with Q_n in a common model for ET_a [*Hobbins et al.*, 2001], we find that the portion of the conterminous U.S.-wide trend in ET_a attributable to trends in E_A amounts to an increase of 3.0 mm/yr^2, whereas that attributable to the trend in Q_n amounts to a decrease of 1.8 mm/yr^2.) An estimation procedure that ignores the complementary effects of regional advection would fail to represent the physical processes involved in a trend in ET_a, and may misdiagnose the cause of the trend. Although ET_{pan} is a very useful concept, it can be misleading if used by itself to indicate climatic trends.

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T. C. Brown, Rocky Mountain Research Station, U.S. Forest Service, Fort Collins, CO 80526, USA.

M. T. Hobbins and J. A. Ramírez, Water Resources, Hydrologic and Environmental Sciences Division, Civil Engineering Department, Colorado State University, Fort Collins, CO 80523-1372, USA. (ramirez@engr.colostate.edu)