

Pan Evaporation Trends in Dry and Humid Regions of the United States

JAY H. LAWRIMORE AND THOMAS C. PETERSON

NOAA/NESDIS National Climatic Data Center, Asheville, North Carolina

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ABSTRACT

Decreasing pan evaporation trends in many regions of the world have been viewed as evidence of a decrease in the terrestrial evaporation component of the hydrologic cycle. However, some researchers suggest that the relationship between pan evaporation and terrestrial evaporation depends on the environment in which the measurements are recorded and that pan evaporation trends run counter to trends in terrestrial evaporation in some climates. To determine whether evidence of this kind of relationship exists in the observational record, pan evaporation trends were compared with precipitation trends in eight regions within the United States. To the extent that warm-season precipitation can be used as an indicator of surface evaporation, these results support the view that pan evaporation and actual evaporation can be inversely related.

1. Introduction

The evaporation of water as measured from pan evaporimeters has decreased in many regions of the world over the past half-century. Peterson et al. (1995) found a correlation between decreases in seasonal averages of pan evaporation and diurnal temperature range over much of Russia and the United States. Decreasing pan evaporation trends have also been observed in India (Chattopadhyay and Hulme 1997) and Venezuela (Quintana-Gomez 1998). These studies relied on the traditional view that pan evaporation trends are assumed to mirror trends in surface evaporation, which suggests a recent decrease in the terrestrial evaporation component of the hydrologic cycle.

However, Brutsaert and Parlange (1998) contend that decreases in pan evaporation run counter to well-substantiated increases in global precipitation and cloud cover. These increases in precipitation and cloud cover could only occur if surface evaporation, as the only source of atmospheric water vapor, also increased. They attempt to resolve the apparent paradox by postulating that the ability of pan evaporation E_{pa} to represent actual evaporation E accurately is dependent on the kind of environment in which the pan evaporation measurements are taken.

From a surface in which there is abundant moisture, actual evaporation equals potential evaporation E_o and is also equivalent to the amount of pan evaporation mul-

tiplied by a "pan coefficient." Potential evaporation is defined as the amount of evaporation from a large uniform land surface with adequate moisture such that available energy is the limiting factor. In a region without adequate moisture, E_o cannot be sustained, and as a result E is less than E_o . The decrease in E is expected to have a negligible effect on net radiation; rather, it will primarily affect the temperature, humidity, and turbulence of the air near the ground (Brutsaert 1982). The energy that is not used for evaporation manifests itself as sensible heat flux and, in the absence of local oasis effects, results in an increase in potential evaporation in an amount equal to the energy given up by E with no change in the overall energy budget. This complementary relationship between actual and potential evaporation, first proposed by Bouchet (1963) and applied by Morton (1975) in estimating evaporation from climatological observations, is the basis for the Brutsaert and Parlange solution to the evaporation paradox.

Although the supply of moisture may cause a reduction in E , a lack of surface moisture is not a limiting factor on E_{pa} , and thus pan evaporation cannot necessarily be related to the actual amount of surface evaporation. Although actual evaporation decreases as the amount of available moisture decreases, sensible heat flux that provides the energy to increase potential evaporation also provides the energy to increase evaporation from water-filled pans. Just as actual and potential evaporation have a complementary relationship, actual and pan evaporation should share the same relationship.

For these reasons, Brutsaert and Parlange (1998) state that, "in non-humid environments, measured pan evaporation is not a good measure of potential evaporation." They also state that "evaporation from a pan, E_{pa} , can

Corresponding author address: Jay H. Lawrimore, National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801.
E-mail: jlawrimo@ncdc.noaa.gov

be used as a good indicator of the evaporation, E , from the surrounding environment, but only when land-surface moisture is in ample supply." This statement makes it clear that an inverse relationship between pan evaporation and actual evaporation should be found in dry regions such as those in the western United States. Even in humid regions of the eastern United States, however, it is doubtful that warm-season evaporation occurs at the potential rate at any time other than shortly after rainfall or while dew is on the surface. Therefore, if the average surface evaporation rate is less than the potential rate, an inverse relationship between pan evaporation and terrestrial evaporation may well exist throughout most areas of the United States.

2. Region selection and analysis method

To determine if this inverse relationship exists and if the humidity of the region alters the sign of this relationship, the research of Peterson et al. (1995) is extended to include analysis of pan evaporation and precipitation trends within eight regions of the United States. Warm-season precipitation is used as an indicator of terrestrial evaporation based on the assumption that increasing precipitation in large regions leads to increases in terrestrial evaporation (Brutsaert and Parlange 1998). Although the complex relationship between factors affecting evaporation (e.g., radiation, humidity, wind speed, pressure, and land-cover changes) can produce localized differences, the amount of moisture available for evaporation within large regions is determined by precipitation, runoff, and water storage (Budyko 1974). Precipitation that falls can be returned to the atmosphere through evaporation, and it can be subject to runoff and storage.

In the warm-season months, increasing insolation provides the energy to increase evaporation, often at the expense of runoff and storage. Rasmusson (1968) found an annual cycle in evapotranspiration in the eastern and central United States, with a minimum in January and a maximum in July. He also found that, as evapotranspiration increased during the warm-season months, runoff and water storage decreased, even as the average amount of precipitation increased during the same period. Others (Benton and Estoque 1954) have found similar results for the entire North American continent.

So although increases in precipitation can lead to increasing runoff (Karl and Riebsame 1989), one should also expect regional increases in precipitation to lead to increasing evaporation, especially during the warm-season months. This expectation is consistent with other studies that show increases in both precipitation and evaporation in an intensifying hydrologic cycle (Houghton et al. 1996). For these reasons, we feel confident in our central assumption that an increase in terrestrial evaporation would accompany an increase in precipitation. Likewise, we expect decreases in precipitation

to restrict further the available supply of moisture, resulting in a reduction in terrestrial evaporation.

Precipitation and pan evaporation trends were studied within eight subregions defined by selecting groups of states within regions of the country that can be characterized as dry, humid, or steppe. Five humid regions (Southeast, South, Northeast, Midwest, and Central), two dry regions (Mountains and West Coast), and one steppe region (Plains) were defined.

The predominant vegetation type in each of the humid regions is forest, and these regions receive on average more than 460 mm of precipitation during the warm-season months of May through September. The two dry regions are predominately desert but also have grassland and forested vegetation types. These regions receive less than 180 mm of precipitation during the warm-season months. The one steppe region is composed almost entirely of short and tall grass and receives on average less than 380 mm of precipitation from May through September.

A network of 493 stations having total monthly pan evaporation for the warm-season months May through September between 1948 and 1998 was used. After starting with a network of 812 stations, all stations (315) that had less than 15 yr of data were removed. Time series plots of total monthly pan evaporation for each station also were produced, and a subjective assessment about the homogeneity of each station was made. Time series that displayed obvious inhomogeneities were either truncated by removing the data prior to the inhomogeneity or were removed from the analysis entirely. Four stations were removed completely, and another 17 stations were truncated to create a homogenous time series.

The remaining 493 stations were partitioned into each of the eight regions, and a time series was calculated for each region. The first difference method (Peterson et al. 1998) was used, which involved area averaging the year-to-year differences in pan evaporation to create a first difference time series for each month between 1948 and 1998. Each regional first-difference series was then converted into an anomaly time series by cumulatively summing the area-averaged first difference values from the first year to the last. The first difference method was used because it allowed incorporation of station data with different periods of record without creating a bias in the analysis.

The traditional method for calculating anomaly time series (the anomaly method) requires all stations to have a minimum number of years during a prescribed base period. This period is typically 25 yr during the period from 1961 to 1990. The base-period years may vary (e.g., 1951–80), but, regardless of the period, all stations in the analysis must have a minimum number of years during the prescribed period. The result is that stations that may have been in operation only prior to the base period or only during a portion of the base period are excluded from the analysis. The first difference method

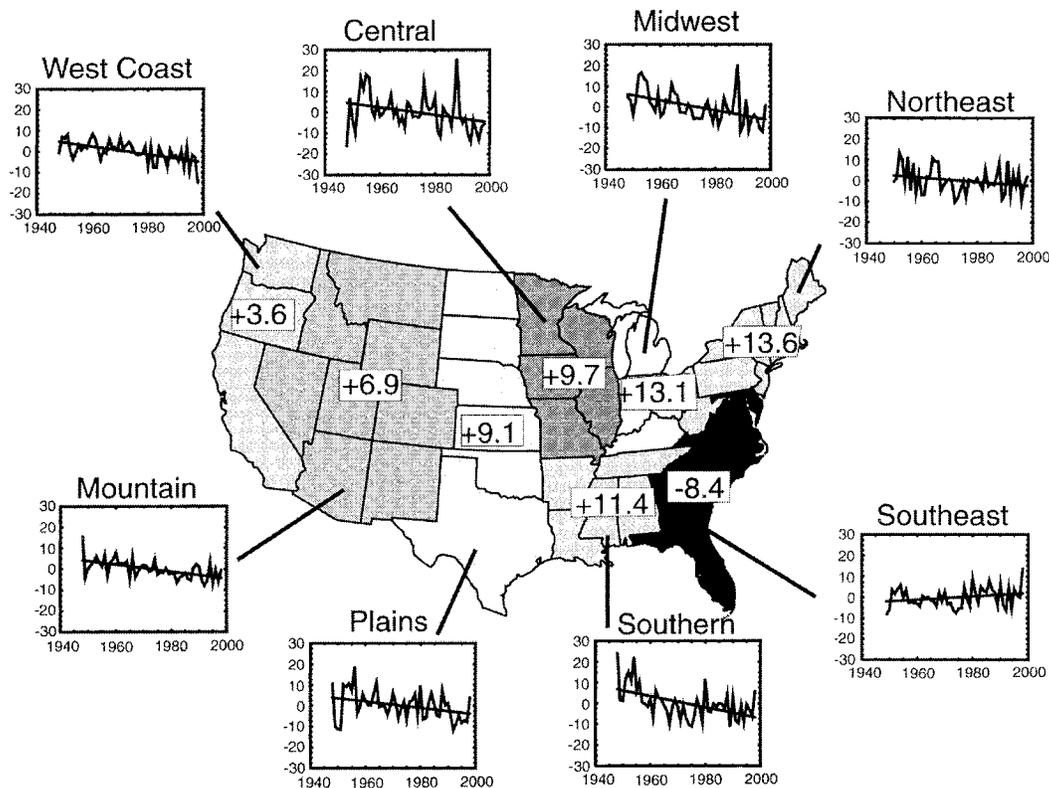


FIG. 1. Pan evaporation anomaly time series and precipitation trends for eight U.S. regions. Pan evaporation anomalies are in percent of the long-term mean for each region. Regional precipitation trends (mm decade^{-1}), calculated using the traditional anomaly method, are shown in the text box in the center of each region.

was designed to avoid this limitation. By calculating first difference values for each station and averaging the first difference values into a first difference series before calculating an anomaly series, this method avoids the requirement that all stations have data during the same base period. This freedom allows one to use, for example, stations that only have data between 1950 and 1975 and stations that only have data from 1970 to 1990.

After each time series was calculated, the anomalies were totaled over the five months of the warm season and each value of the seasonal anomaly series was converted to a percentage of the long-term mean as a method of standardizing the eight regional time series. Warm-season precipitation anomalies for the same regions throughout the period 1948–98 also were calculated using precipitation data from the U.S. Historical Climatology Network (Easterling et al. 1996), and the precipitation trend for each region was calculated.

3. Results and conclusions

The pan evaporation anomaly series and corresponding trend line for each region are shown in Fig. 1. The precipitation trend for each region (mm decade^{-1}) is also shown in the text box in the center of each region. The precipitation trends are positive in every region

except the Southeast, indicating that most regions in the United States have experienced increasing amounts of precipitation during the warm-season months between 1948 and 1998. For every region with an increasing precipitation trend, the trend in pan evaporation is negative. In the Southeast, however, where there has been a trend toward drier conditions during the warm season, the pan evaporation trend is positive.

Pan evaporation trends are significant at the 95% confidence level or higher for all regions but the Southeast and Northeast. The trends in these two regions are significant at the 90% confidence level. (Table 1 contains the regression statistics for pan evaporation in each region.) Although the trend in the South region is significant at the 95% confidence level, it is heavily influenced by large positive anomalies in the first 10 yr of the period. In the succeeding years, the trend is close to zero. Precipitation trends are significant at the 90% confidence level or greater in every region except the Southeast, South, and central. (Table 2 contains the regression statistics for precipitation.)

In the dry West Coast and Mountain regions, precipitation increased and pan evaporation decreased. As Fig. 1 illustrates, there was also an inverse relationship between trends in precipitation and trends in pan evaporation in each of the other more humid regions. Using

TABLE 1. Pan evaporation regression statistics within each region calculated from the anomaly time series (anomalies as percents, shown in Fig. 1), and the average pan evaporation totals during the warm-season months.

Region	Coefficient	Std error	<i>t</i> value	Correlation	Avg warm-season pan evaporation (mm)
South	-0.27	0.065	-4.16 ^c	-0.51	843
Southeast	0.08	0.044	1.77 ^a	0.25	821
Northeast	-0.10	0.060	-1.72 ^a	-0.24	635
Midwest	-0.24	0.061	-3.91 ^c	-0.49	719
Central	-0.18	0.077	-2.34 ^b	-0.32	823
Plains	-0.16	0.062	-2.53 ^b	-0.34	1141
Mountain	-0.17	0.035	-4.94 ^c	-0.58	1201
West					
Coast	-0.17	0.037	-4.68 ^c	-0.56	1121

^a Significant at the 90% confidence level.

^b Significant at the 95% confidence level.

^c Significant at the 99% confidence level.

the postulate that increases in warm-season precipitation coincide with an increase in terrestrial evaporation, these results support the assertion that decreases in pan evaporation can be interpreted as evidence of increasing terrestrial evaporation (Brutsaert and Parlange 1998). This result also suggests that, even in the most humid regions of the United States, the supply of moisture is not sufficient over the long term to produce evaporation

TABLE 2. Regression statistics within each region calculated from the precipitation anomaly time series in millimeters (trends converted to millimeters per decade for Fig. 1 text boxes), and the average precipitation totals during the warm-season months.

Region	Coefficient	Std error	<i>t</i> value	Correlation	Avg warm-season precipitation (mm)
South	1.14	0.767	1.48	0.21	570
Southeast	-0.84	0.744	-1.12	-0.16	655
Northeast	1.36	0.602	2.26 ^b	0.31	473
Midwest	1.31	0.513	2.56 ^b	0.34	465
Central	0.97	0.702	1.38	0.19	488
Plains	0.91	0.517	1.77 ^a	0.24	376
Mountain	0.69	0.221	3.13 ^c	0.41	176
West					
Coast	0.36	0.219	1.67 ^a	0.23	102

^a Significant at the 90% confidence level.

^b Significant at the 95% confidence level.

^c Significant at the 99% confidence level.

at the potential rate. Although potential evaporation likely occurs more often in humid regions, it does not occur with sufficient duration or frequency to make pan evaporation a good indicator of surface evaporation.

Although precipitation trends are not significant in three of the eight regions, there is strong evidence of an inverse relationship between pan evaporation and precipitation in the United States. These results support the solution of the evaporation paradox described by Brutsaert and Parlange (1998) and suggest that decreases in pan evaporation indicate an increase in terrestrial evaporation in the United States.

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