A Comparison of Trends in Potential and Pan Evaporation for the Canadian Prairies

Article *in* Canadian Water Resources Journal · September 2006

DOI: 10.4296/cwrj3103173

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Abstract: Comparisons are made between potential evaporation trends and pan evaporation trends for a collection of sites on the Canadian Prairies. Trends are analyzed using the non-parametric Mann-Kendall test. There are many similar trend results, but most of these indicate no trend for either measure of evaporation. Seven cases (out of 53 in total) show matching significant trends, six of which are decreasing trends. One case shows opposing significant trends with an increasing pan evaporation trend and a decreasing potential evaporation trend. Despite the opposing trends, time series plots of pan and potential evaporation show similar timing of maximum and minimum values. Wind speed exerting an influence on potential evaporation and not on pan evaporation was the most common explanation for discrepancies between pan and potential evaporation trends.

Résumé : Des comparaisons sont établies entre les tendances d'évaporativité et les tendances d'évaporation-bac pour un certain nombre d'endroits des Prairies canadiennes. Les tendances sont analysées à l'aide du test non paramétrique de Mann-Kendall. Il existe de nombreux résultats semblables, mais la plupart n'indiquent aucune tendance pour l'une ou l'autre des mesures d'évaporation. Sept cas (sur 53 en tout) révèlent des tendances importantes correspondantes, dont six sont des tendances décroissantes. Un cas révèle d'importantes tendances contraires qui s'accompagnent d'une tendance d'évaporation-bac croissante et d'une tendance d'évaporation potentielle à la baisse. Malgré ces tendances contradictoires, des graphiques chronologiques de l'évaporation-bac et de l'évaporation potentielle font état d'une séquence semblable de valeurs maximales et minimales. L'explication la plus courante fournie quant aux écarts entre les tendances d'évaporation-bac et d'évaporation potentielle est la vitesse du vent, laquelle exerce une influence sur l'évaporation potentielle mais non pas sur l'évaporation-bac.

Introduction

Human-induced climate change is hypothesized to have potentially serious impacts on the hydrological cycle and the earth's water resources (IPCC, 2001). In particular, there has been speculation that global warming will lead to an intensification of the hydrological cycle possibly resulting in increased precipitation and increased evaporation (Trenberth, 1998; Douville *et al.,* 2002; Labat *et al.,* 2004; and

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Submitted April 2006; accepted July 2006. Written comments on this paper will be accepted until March 2007.

Huntington, 2006). However, analyses of trends in evaporation have resulted in decidedly mixed conclusions as to whether evaporation is increasing or decreasing. Increasing trends in pan evaporation have been documented in Israel by Cohen *et al.* (2002) and in northeast Brazil by da Silva (2004) while decreasing trends in pan evaporation were reported in the United States and the former Soviet Union by Peterson *et al.* (1995), in India by Chattopadhyay and Hulme (1997), in China by Liu *et al.* (2004), in Australia by Roderick and Farquhar (2004) and in Thailand by Tebakari *et al.* (2005). A long-term series of potential evaporation for Oxford, England, calculated using the Thornwaite method (Burt and Shahgedanova, 1998), indicates an increasing trend; however decreases in potential evapotranspiration (PET) have been reported by Chattopadhyay and Hulme (1997) for India, where PET was calculated using the Penman equation, and by Moonen *et al.* (2002) for a site in Italy based on PET calculated using the method of Hargreaves (1975).

Due to the conflicting results from studies of evaporation trends, there have been numerous attempts to explain the apparent paradox between observed and expected trends in evaporation. Brutsaert and Parlange (1998) argue that there is an inverse relationship between pan evaporation and actual evaporation. Lawrimore and Peterson (2000), Golubev *et al.* (2001) and Hobbins *et al.* (2004) support this argument through results showing that a decreasing trend in pan evaporation can imply an increasing trend in actual evaporation. Roderick and Farquhar (2002) postulate that increasing evaporation results in a cooler, more humid climate over an evaporation pan, resulting in reduced pan evaporation. Walter *et al.* (2004) determined that evapotranspiration, calculated using a water balance approach, is increasing for the conterminous United States. Gedney *et al.* (2006) show that increased CO_2 in the atmosphere results in reduced plant transpiration leading to increased soil moisture and river flow. Labat *et al.* (2004) indicate that intensification of the hydrological cycle can be explained in terms of more intense evaporation over oceans in conjunction with either increased or decreased evaporation over the land surface.

It is important to gain a better understanding of the likely future trends in evaporation resulting from climate change. This requires an improved understanding of: i) the nature of evaporation changes on a local, or regional, scale; and ii) the mechanisms responsible for the observed changes. This paper explores and compares trends in pan evaporation and estimated potential evaporation (PE) for 11 sites on the Canadian Prairies. In addition to identifying and quantifying trends in evaporation, the meteorological processes that may be responsible for the trends are explored.

The Canadian Prairies are an important food production area and decreases in water availability could thus lead to considerable economic hardship. Akinremi *et al.* (1999) examined precipitation trends on the Canadian Prairies and found that there was a significant increase in the number of precipitation events and also a significant increase in the amount of precipitation, largely resulting from an increase in the amount of rainfall. Akinremi *et al.* (1999) suggested that these changes may be related to climate change. Sauchyn *et al.* (2002) examined an aridity index, defined as the ratio of precipitation to PET, for the Canadian Prairies. They used paleoclimatic records and General Circulation Model (GCM) projections to determine that, under future climate conditions, the aridity index is likely to reflect drier conditions than present day aridity. McGinn *et al.* (2001) examined GCM projections for precipitation and evaporation for the Canadian Prairies. They found evidence suggesting an intensification of the hydrological cycle with increases in precipitation and both increases and decreases in evaporation.

Methodology

Estimation of Evaporation

Potential evaporation is estimated in this study using Meyer's formula (Martin, 2002)

$$PE = 7.58(V_w - V_a)(1 + 6.21 \times 10^{-2} W)(1 + 3.28 \times 10^{-5} A) \quad (1)$$

where PE is the monthly potential evaporation (mm); V_w is the monthly saturated vapour pressure corresponding to the estimated monthly mean water temperature (mbar); V_a is the actual monthly mean vapour pressure in the atmosphere at 7.62 m above ground level (mbar); W is the monthly mean wind speed at 7.62 m above ground level (km/hr); and A is the elevation above mean sea level of the ground level (m).

From Equation (1), PE at a site is affected by the difference between water surface vapour pressure and air vapour pressure (vapour pressure deficit, VPD), wind speed and the elevation of the site. The latter factor results in a roughly 1% increase in PE for every 300 m increase in elevation and reflects the decrease in air density, and hence an increase in the potential for evaporation, with an increase in elevation. Martin (2002) estimates the monthly saturated vapour pressure based on water temperature, which is estimated from monthly mean air temperature. This relationship was developed for moderate sized water bodies and allows widely available air temperature data to be used to estimate the required water temperature values. The actual monthly mean vapour pressure in the atmosphere is estimated from monthly mean dew point temperature. Trend analysis is therefore conducted in this research for air temperature and dew point temperature, along with vapour pressure deficit and wind speed, to investigate possible causes for trends in evaporation.

Available daily measurements of pan evaporation were summed to calculate monthly evaporation. Missing daily values were estimated using the average daily evaporation determined from the existing daily evaporation values within the month. If more than nine daily measurements were missing, the monthly evaporation estimate was deemed to be unreliable and was considered to be missing. The value of nine missing measurements was chosen as a threshold as this ensured that the number of missing values was less than one-third of the monthly total. Other threshold values could have been selected, but the results are unlikely to be sensitive to the value selected.

There are shortcomings to both of the measures of evaporation used in this work. Meyer's formula is an example of the mass transfer technique for estimating PE and is an empirical formula. Martin (2002), and references contained therein, describe the development and use of Equation (1) for sites on the Canadian Prairies. Equation (1) has been found to provide useful estimates of PE for moderate sized water bodies on the Canadian Prairies (Martin, 2002). Pan evaporation generally overestimates the evaporation from an open water body due to the small size of the evaporation pan, boundary effects, and wind effects resulting from the pan itself. Pan evaporation is thus typically adjusted using a pan coefficient to estimate evaporation from an open water body. In spite of the shortcomings noted above for both measures, they are widely used as an indication of the potential for evaporative losses from a water body. Trends in time series of evaporation values are therefore of interest for the design of a variety of water resources infrastructure.

Trend Analysis

Time series of pan evaporation and PE, and the predictors of PE in Equation (1), were analyzed for trends using the Mann-Kendall non-parametric (rank-based) test (Mann, 1945; Kendall, 1975). The version of the trend test used incorporates a correction, developed by Yue *et al.* (2002), for serial correlation in the data. The calculated trend statistic can be used to determine the significance of a trend in a data set. Further details on the trend detection methodology can be found in Burn *et al.* (2004).

Trend Attribution

Input variables were examined for any unusual patterns or trends and comparisons were made between variables to identify possible causal mechanisms for trends in PE and pan evaporation. Correlations between variables were also determined to help identify possible causal mechanisms. Temporal patterns in meteorological variables were examined using exploratory data analysis to ascertain the overall pattern, or tendency, which is often difficult to visualize as a result of the natural variability in the data.

Study Area and Data

Comparisons were made between trends for pan and potential evaporation for 11 sites on the Canadian Prairies for the months of May to September inclusive. Pan evaporation sites were chosen based on data availability and with a goal of providing a comparison with potential evaporation sites that displayed increasing, decreasing and no trends in PE. Analysis periods for the pan evaporation data vary with location with several stations and months containing gaps in the data record. Table 1 outlines the most commonly used analysis period for each station. Each station in Table 1 has a potentially unique analysis period and the analysis period will sometimes differ from month to month for a given location. It was therefore not practical to adopt a common analysis period as has been done in some previous trend studies (Burn *et al.*, 2004). The inconsistencies in the available analysis periods arise from the limited availability of pan evaporation data. Trends in PE data were, for every case, calculated for the same analysis period as was used for the pan evaporation data.

trends for each evaporation measure and for the months of May through September. Also included is the total number of increasing and decreasing trends, which is the sum of the monthly values. Data were not available for the month of May for Calgary or Norway House. June and July are the months with the largest number of evaporation trends, especially for PE. In May, very few trends are observed while in August, there are no pan evaporation trends, but four of the 11 PE sites (36%) exhibit a trend.

Table 1. Time periods and months used for comparing pan and potential evaporation.

Pan Evaporation Station	PE Station	Months Compared	Analysis Period
Altawan	Medicine Hat	May to September	1966-2003
Calgary Intl A	Calgary	June to September	1964-1994
Estevan A	Estevan	May to September	1962-2003
Morden CDA	Portage La Prairie	May to September	1963-1998
Nipawin A	Nipawin	May to September	1974-2003
Norway House Forestry	Norway House	June to September	1971-1999
Regina A	Regina	May to September	1963-1995
Swift Current CDA	Swift Current	May to September	1960-2003
Weyburn	Regina	May to September	1962-2003
Winnipeg Intl A	Winnipeg	May to September	1962-1994
Wynyard	Wynyard	May to September	1967-2003

Figure 1 shows the locations of the pan and potential evaporation stations listed in Table 1. In Figure 1, the square symbol represents locations for which the pan and potential evaporation sites are coincident and the other pairs of symbols denote the locations of a pan evaporation/PE station pair. As can be seen from the figure, only three station pairs are not coincident. For these three station pairs, the maximum separation between a pan evaporation site and the corresponding PE site is approximately 100 km. Regina is used both as a PE site to match with a pan evaporation site (Weyburn) and as a pan/potential evaporation pair.

Results

Comparison of Trends

Trends were identified using the Mann-Kendall trend test with a significance level of 10%. Table 2 shows the number of stations with increasing and decreasing

Figure 2 presents box plots that compare the trend slopes for pan evaporation and PE. The box plots in Figure 2 give the five, 25, 50, 75 and 95 percentiles of the 53 slope values for each measure. It is apparent from Figure 2 that the median slope for PE is slightly lower than for pan evaporation and both are negative, indicating a preponderance of decreasing trends. Figure 2 also indicates that there are more negative slopes for PE than for pan evaporation with the 75 percentile for PE slopes below zero. There is also a wider range of slope values for pan evaporation than for PE.

Table 3 summarizes the trend results showing both the results for each evaporation measure (in the column and row labeled as total) and showing the agreement and disagreement between trends in pan evaporation and trends in PE. Table 3 reveals that pan evaporation shows 12 significant trends, eight decreasing trends and four increasing trends, while PE shows 22

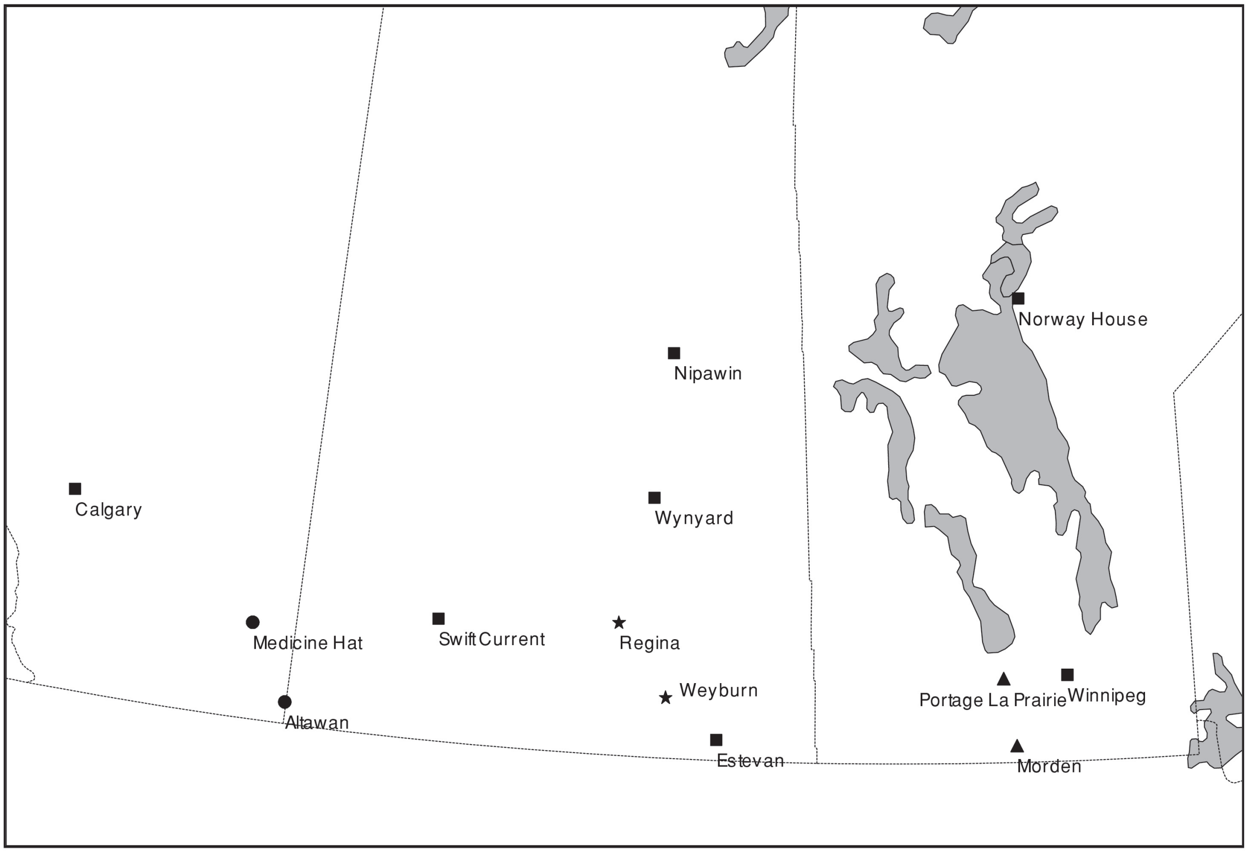

Figure 1. Location of the sites used for the comparison of pan and potential evaporation. ■ represents locations for which the pan and potential evaporation sites are coincident. ●, ★, and ▲ denote the locations of a pair of stations.

Table 2. Number (percentage) of stations showing a significant trend in evaporation at the 10% significance level.

Month	Potential Evaporation Decreasing		Potential Evaporation Increasing		Pan Evaporation Decreasing		Pan Evaporation Increasing	
May	0	(0%)	1	(11%)	0	(0%)	1	(11%)
June	5	(45%)	0	(0%)	3	(27%)	2	(18%)
July	8	(73%)	0	(0%)	4	(36%)	0	(0%)
August	3	(27%)	1	(9%)	0	(0%)	0	(0%)
September	3	(27%)	1	(9%)	1	(9%)	1	(9%)
Total	19	(36%)	3	(6%)	8	(15%)	4	(8%)

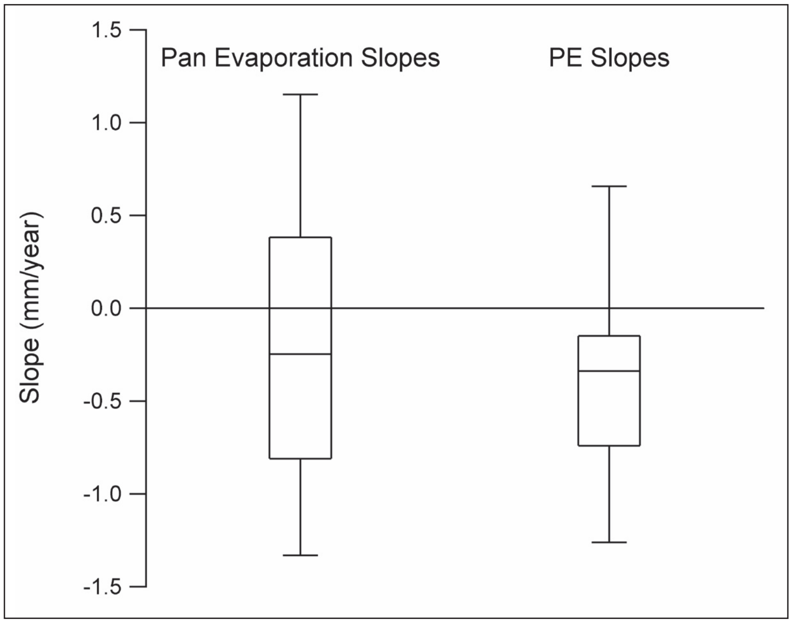

Figure 2. Box and whisker plots of monthly trend slope values for pan evaporation and potential evaporation.

significant trends, 19 decreasing and three increasing. Cases where the trend results are in agreement are on the diagonal of the table that goes from the lower left to the upper right. This occurs for 34 out 53 cases, although 27 of these are cases where neither measure shows a significant trend. There are seven agreements in significant trends, six decreasing trends and one case where both display an increasing trend. The off-diagonal entries in the table indicate cases where there is a disagreement in the trend results; there are 19 such cases. The majority of the disagreements indicate one measure with a significant trend and the other with no trend. There is, however, one case where there is an increasing trend in pan evaporation and a decreasing trend in PE. The largest category of disagreement is a decreasing trend in PE and no trend in pan evaporation (12 cases).

Figure 3 is a plot of the probability level associated with the trend test for both evaporation measures. A probability level of 0.05 or less indicates a decreasing trend, a probability level of 0.95 or greater indicates an increasing trend and values between 0.05 and 0.95 indicate no trend (based on the 10% significance level). Figure 3 thus provides further detail on the level of agreement between the trend results for pan evaporation and PE and supplements the information summarized in Table 3. Figure 3 reveals that in addition to the one case of an increasing trend for both evaporation measures, there are two cases that are close to agreement (one case where pan evaporation has a significant increasing trend and PE is very

Table 3. Comparison of trend results for PE and pan evaporation at the 10% significance level.

	Pan Evaporation			
Potential Evaporation	**Decreasing Trend**	**No Trend**	**Increasing Trend**	**Total**
Increasing Trend	0	2	1	3
No Trend	2	27	2	31
Decreasing Trend	6	12	1	19
Total	8	41	4	53

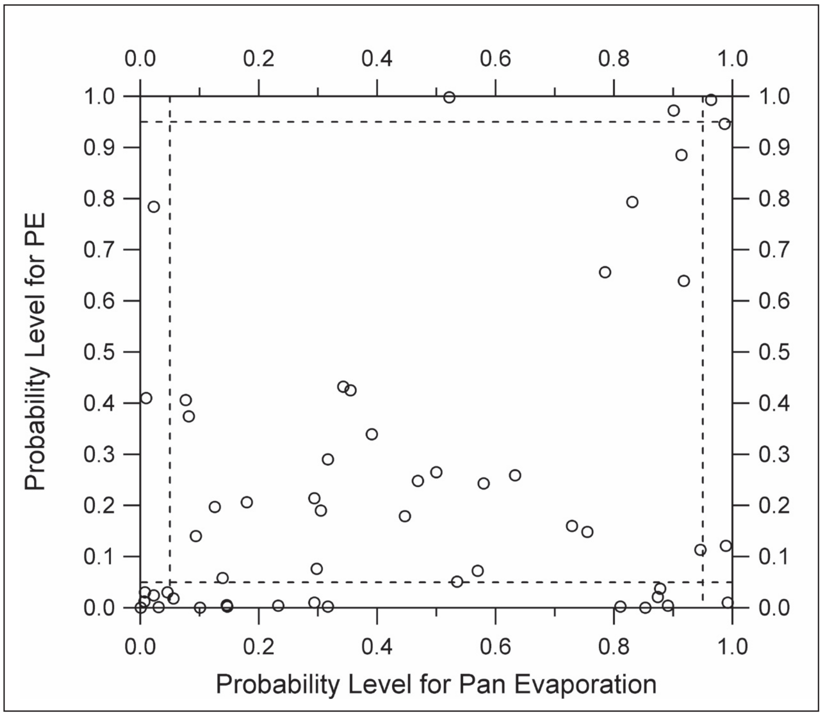

Figure 3. Probability level associated with trends in pan and potential evaporation.

close to significant, and one case where the PE trend is significant and pan evaporation is close to being significant). There are also cases where there is close to an agreement in terms of decreasing trend behaviour (see the lower left portion of the figure). However, in addition to the further evidence for agreements from Figure 3, there is also evidence for lack of agreement in the two evaporation measures. Consider the 12 cases where PE indicates a significant decreasing trend and pan evaporation indicates no trend. These events are located in the bottom centre "box" in Figure 3 and indicate that there is no pattern in terms of the trend tendency for pan evaporation for these cases in that the probability level for pan evaporation varies from close to 0.05 to almost 0.90. Similarly, the 27 cases where there is not a significant trend in either evaporation measure are not distributed evenly around the 45° line, as might be expected.

Figure 4 is a time series plot for evaporation at Estevan (Saskatchewan) for July. Figure 4 shows the observed pan evaporation, the observed PE and a smoothed representation of the observed values obtained using the LOWESS technique (Cleveland, 1979). The July evaporation for Estevan exhibits a significantly decreasing trend in both pan evaporation and PE (significance level < 1%). The correlation between pan evaporation and PE is 0.90. Clearly there is a strong correspondence in the observed trend behaviours for this case implying that the two evaporation measures are responding to similar meteorological forcing factors. Figure 5 shows a similar plot for Morden pan evaporation and Portage la Prairie (Manitoba) PE for the month of June. Pan evaporation shows a significant increasing trend while PE shows a significant decreasing trend (both at the 1% significance level). The correlation between pan evaporation and PE, while smaller than observed for Estevan, is 0.64, a value that is highly significant. This implies that while there are similarities in the meteorological factors responsible for the pan evaporation and PE values, as inferred by the large correlation value, there are also differences, as implied by the difference in trend direction for the two measures. The nature of these similarities and differences are explored below.

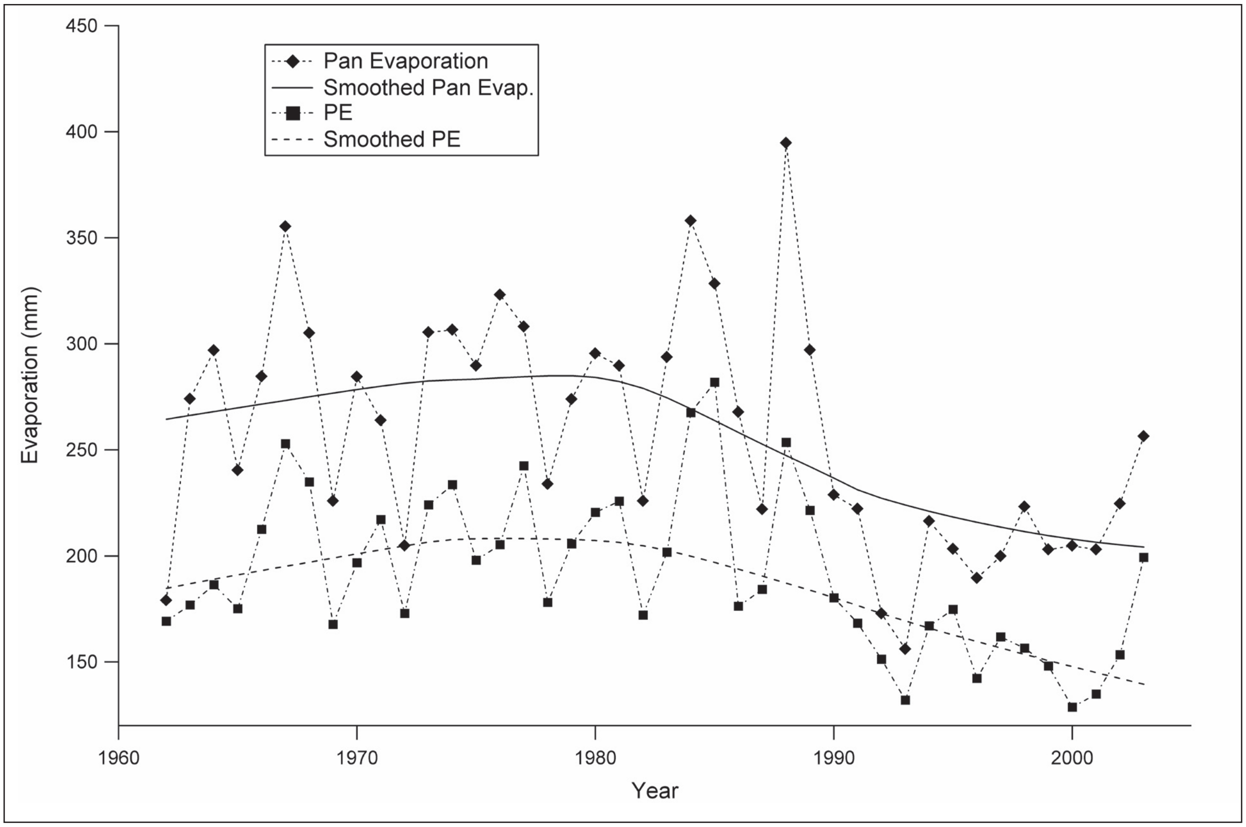

Figure 4. Raw data and smoothed trend lines for pan evaporation and PE at Estevan (SK) in July.

Trend Attribution

To further investigate the possible origins of the trends in pan evaporation and PE, trends in input variables were evaluated and correlations were calculated between input variables and both pan and potential evaporation. High correlations with pan evaporation were found at most stations for air temperature, water vapour pressure and VPD. Negative correlations with pan evaporation were common for dew point temperature and air vapour pressure. Air temperature typically displayed the highest correlation with pan evaporation; however several cases demonstrated stronger correlation with VPD than with air temperature. The majority of the stations show weak correlations between pan evaporation and mean wind speed; the highest correlations do not exceed 0.6 and negative correlations are found in several cases. Potential evaporation correlations with VPD are stronger for PE than those observed for pan evaporation. Wind speed correlations are also much higher with PE than with pan evaporation. Dew point temperature and air vapour pressure exhibit correlations that are more negative with PE than with pan evaporation. Air temperature has, in most cases, a lower correlation with PE than with pan evaporation.

Possible causal mechanisms for PE trends were investigated by considering the trends in wind speed, VPD, air temperature and dew point temperature (the latter two variables are related to water vapour pressure and air vapour pressure, respectively). Table 4 summarizes the results for wind speed and VPD (relevant results for air temperature and dew point temperature are summarized below). Table 4 reveals significant increasing VPD trends in May, June and September, significant decreasing trends in July and no significant trends in August. Wind speed exhibits a preponderance of significant decreasing trends in all months. Comparing the PE trends with trends in VPD and wind speed reveals that the three increasing PE trends all occur at the same station (Nipawin) and are attributed to increasing wind speed (one case) or increases in both VPD and wind speed (two cases). One of the increasing trends in VPD (in May) can

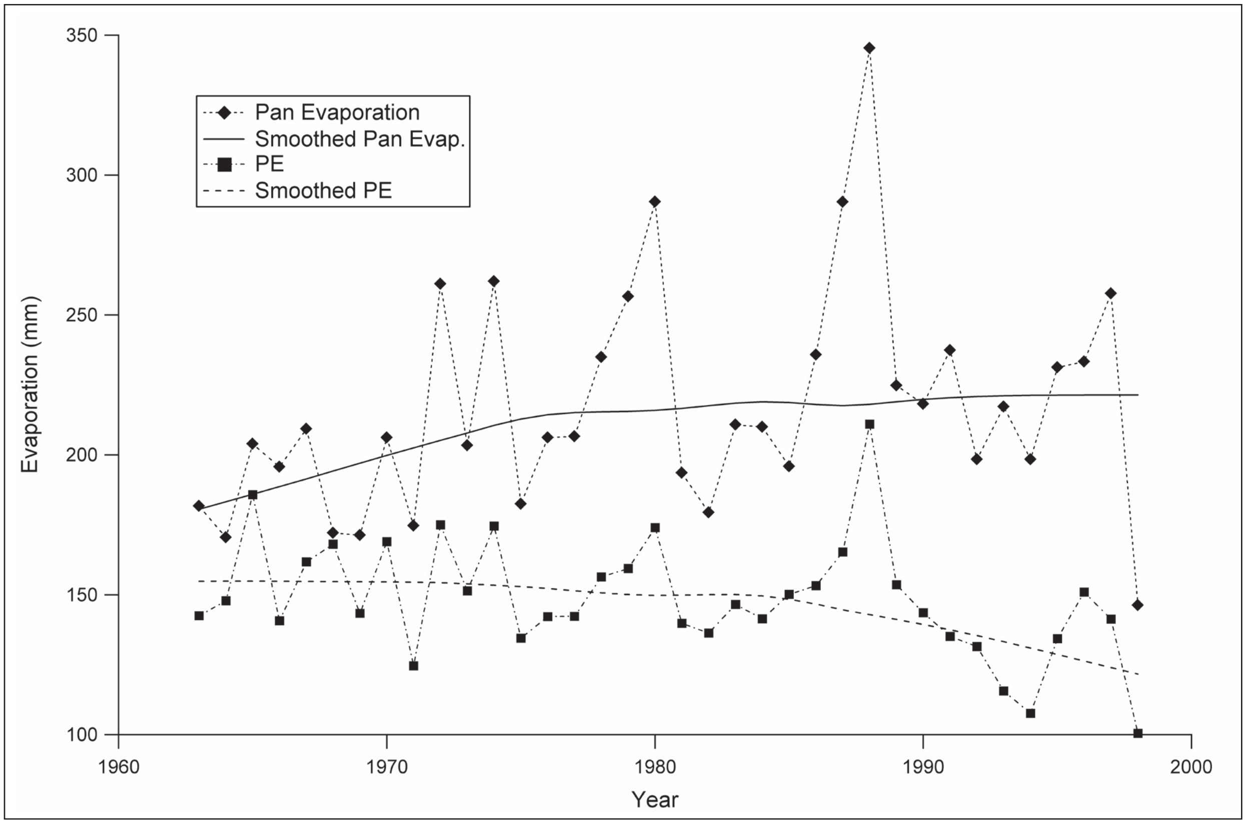

Figure 5. Raw data and smoothed trend lines for pan evaporation at Morden (MB) and PE at Portage La Prairie (MB) in June.

Table 4. Number (percentage) of stations showing a significant trend in VPD and wind speed at the 10% significance level.

	Vapour Pressure Deficit		Wind Speed	
Month	**Decreasing**	**Increasing**	**Decreasing**	**Increasing**
May	0 (0%)	3 (27%)	6 (67%)	1 (11%)
June	0 (0%)	1 (9%)	8 (73%)	1 (9%)
July	5 (45%)	0 (0%)	9 (82%)	0 (0%)
August	0 (0%)	0 (0%)	8 (73%)	0 (0%)
September	0 (0%)	1 (9%)	9 (82%)	1 (9%)
Total	5 (9%)	5 (9%)	40 (75%)	3 (6%)

be attributed to decreases in dew point temperature, implying the atmosphere is becoming less humid in May at this location. The other increasing trend in VPD (in September) can be attributed to an increasing trend in air temperature resulting in an increase in water vapour pressure. The decreasing trends in PE can be attributed to decreasing trends in wind speed (in June, August and September) and decreases in both VPD and wind speed in July. The decreasing trends in VPD in July can be attributed to increasing trends in dew point temperature (atmosphere becoming more humid), decreasing trends in air temperature (reduced water vapour pressure) or increasing trends in air temperature that are less than the increasing trends in dew point temperature (atmosphere more humid and water vapour pressure reduced).

Identifying possible causal mechanisms in pan evaporation trends was less straightforward and relied on correlation with the meteorological variables and the trends observed in the meteorological variables (see Table 4). For the four cases of increasing trends in pan evaporation, one can be attributed to an increasing trend in VPD, one to an increasing trend in wind speed, one to an increasing trend in both VPD and wind speed and the fourth has no clear cause for the observed trend. The eight decreasing trends can be attributed to: a decreasing trend in wind speed (four cases); a decreasing trend in VPD (one case); a decreasing trend in both VPD and wind speed (two cases); and one case with no discernible cause for the trend. In comparison with the results for PE, there is a greater influence from VPD and less of an influence from wind speed, as could be expected given the lower correlation with wind speed noted above. Interestingly, there are no trends in either pan evaporation or VPD in August.

Cases were examined in greater detail where: i) there is a common significant trend; ii) there is an opposing significant trend; and iii) one measure exhibits a significant trend but the other does not. The seven cases of common significant trends tended to be characterized by comparatively strong correlations between wind speed and pan evaporation with wind speed often being either the sole causal mechanism for the trend in pan evaporation or one of the causes. The one site where there are opposing trends (see Figure 5) has a very low correlation (0.183) between wind speed and pan evaporation. The 14 cases where there is a trend in PE but not in pan evaporation are characterized by very low (often not significant) correlations between wind speed and pan evaporation. For the four cases where there is a trend in pan evaporation but not in PE, there are no obvious patterns in terms of causal mechanisms or correlations with meteorological variables. It should be noted that one of these four cases is very close to an agreement as the probability level for the PE trend is 0.946.

These results suggest that the varying influence of wind speed is the main source of the discrepancies between pan and potential evaporation trends. For the cases where there is an agreement in the significant trends, the correlation between wind speed and pan evaporation is higher than other cases. For cases where there is either an opposing significant trend or a trend in PE only, the correlation between wind speed and pan evaporation is lower and the difference between the magnitude of the correlation between wind speed and pan evaporation and wind speed and PE is greatest.

Conclusions

Pan and potential evaporation exhibit both significant decreasing trends and significant increasing trends. For both evaporation measures, there are more significant decreasing trends than significant increasing trends, although potential evaporation exhibits more decreasing trends than does pan evaporation. The preponderance of decreasing trends in evaporation for the Canadian Prairies is consistent with studies conducted in other parts of the world. Significant decreasing trends are concentrated in June and July for both pan and potential evaporation. There are both agreements and disagreements when comparing the two evaporation measures for individual stations and months, although most of the agreements are cases where neither evaporation measure exhibits a significant trend. The largest number of disagreements occurs for cases where there is a significant decreasing trend for potential evaporation but no trend for pan evaporation.

Trends in potential evaporation can be explained by trends in wind speed, VPD or both variables. Pan evaporation trends showed less of an influence from wind speed and a greater influence from VPD. Potential evaporation also showed stronger correlations with wind speed in comparison to pan evaporation. Trends in VPD were found to result from trends in both air temperature and dew point temperature or solely air temperature. Most of the discrepancies between pan and potential evaporation are due to wind speed exerting an influence on PE but not on pan evaporation. Several cases were also identified where pan evaporation is being influenced by air temperature resulting in a difference between pan and potential evaporation trends. Matching significant trends between pan and potential evaporation show similar causal mechanisms of VPD or both VPD and wind speed.

Acknowledgements

This research was financially supported by Agriculture and Agri-Food Canada. Additional support was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC). This support is gratefully acknowledged. The authors appreciate the support and assistance provided by Gord Bell and the assistance, advice and data provided by Fred Martin (both with Agriculture and Agri-Food Canada). The paper has benefited from constructive comments from two anonymous reviewers. The first author thanks Dr. Slobodan Simonovic for assuming editorial duties for this paper.

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