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Evaporation changes over the contiguous United States and the former USSR: A reassessment

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Abstract. Observed decreases in pan evaporation over most of the United States and the former USSR during the post-WWII period, if interpreted as a decrease in actual evaporation, are at odds with increases in temperature and precipitation over many regions of these two countries. Using parallel observations of actual and pan evaporation at six Russian, one Latvian, and one U.S. experimental sites, we recalibrate trends in pan evaporation to make them more representative of actual evaporation changes. After applying this transformation, pan evaporation time series over southern Russia and most of the United States reveal an increasing trend in actual evaporation during the past forty years.

Introduction

Five years ago we reported a post-WWII decrease in pan evaporation over a significant portion of the extratropical land area of the Northern Hemisphere [*Peterson et al*., 1995]. Pan evaporation, that is, evaporation from the open water surface of the evaporation pan, is a complex function of the surface radiation balance and vertical turbulent heat fluxes. Pan evaporation, E_p, is assumed to reasonably approximate (or at least is proportional to) latent heat flux under conditions of saturated soils [*Konstantinov*, 1963]. When soil is not saturated, actual evaporation, E, is significantly less than E_p and less than potential evaporation, E_0. Potential evaporation describes a climatic variable that characterizes the evaporation that would occur if soil moisture were not a limited factor under the "same" climatic/atmospheric conditions [*Thornthwaite*, 1948]. The use of this fictitious variable, which is closely related to the surface radiation balance, although its ambiguity was well understood from the beginning [*Budyko*, 1956; *Brutsaert*, 1982], allowed to link climatologically the energy and water balances of the land surface on the monthly basis everywhere in the world using available meteorological and hydrological data [*Atlas of Heat Balance*.., 1963; *World Water balance*… 1974]. Due to the instrument design, E_p can be considered (with some restrictions) as an estimate of potential evaporation rather than of actual evaporation. Figure 1 shows that over a large part of the globe both the absolute values and the geographical pattern of potential and actual evaporation are quite different. Leaving aside obvious situations in subtropical deserts with absolute maximums of potential (and pan) and absolute minimums of actual evaporation, let us note that over the most of the Northern hemisphere south of 50°N even the derivatives $dE/d\varphi$ and $dE_0/d\varphi$, where φ is latitude, have opposite signs and when E is increasing with the latitude, E_0 is going up and vise versa. In reaction to *Peterson et al* [1995], *Brutsaert and Parlange* [1998] demonstrated how trends in pan evaporation and actual evaporation may well be opposite. Therefore, the objective of this paper is (a) to reveal climatic zones where the multidecadal changes in evaporation and pan evaporation are parallel and where they are negatively correlated; and then (b) to update and re-assess our pan evaporation time series in order to revise conclusions about actual evaporation over the former Soviet Union (FSU) and the United States.

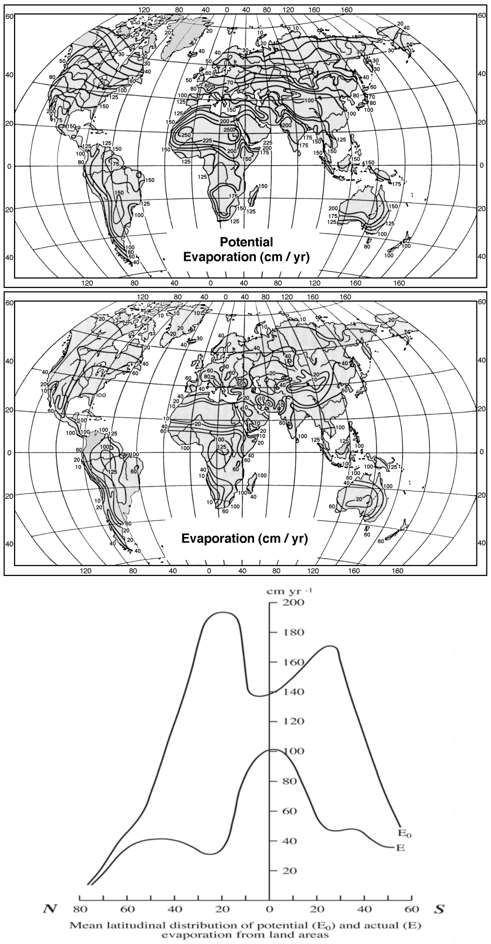

Figure 1. Annual potential and actual evaporation estimates (adapted from *Zubenok* [1976]) that were used to construct *World Water Balance Atlas* [1974].

This paper discusses the changes in evaporation in the warm season over the contiguous U.S. and the FSU during the past forty to fifty years. The background of these changes (i.e., changes in other climatological variables in the same season) are: a significant increase in surface air temperature over the former USSR (but not over the contiguous U.S.); a

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* Prof. Golubev has passed away on January 27, 2001.

Table 1. Estimates of Pan and Actual Evaporation Changes in Russia and Latvia.

Site	Lat.	Lon.	R	Climatic zone	Sign of trends in evaporation		Ratio of trends
					Actual	Pan	
Volgograd	49N	44E	1.76	Dry steppe	+	-	-0.7
Kamennaya Step'	51N	40E	1.29	Tall grass steppe	+	-	-0.5
Nizhnedevitskaya	52N	38E	1.00	Forest-steppe	+	-	-0.6
Kostroma	57N	41E	0.85	Forest	+	-	-0.6
Pribaltiiskaya	57N	26E	0.79	Forest	+	-	-0.4
Dry years			0.87		+	-	-0.8
Wet years			0.67		-	-	0.0
Coshocton, Ohio	40N	82W	0.76	Forest			
Valdai	58N	33E	0.67	Taiga	-	-	0.7
Kandalaksha	67N	32E	0.56	Taiga	-	-	1.4

Seven water balance stations and meteorological stations with enhanced observational program across European Russia and Latvia have carried co-located observations of pan and actual evaporation during the post WWII period. Coordinates, the radiation index of dryness, climatic zone, and signs of trends in evaporation for these sites are presented. All linear trends in pan evaporation are statistically significant at the 0.05 level or higher. This allows us to use the ratio of actual to pan evaporation trends as a scale conversion. Location of the U.S. site (Coshocton) in this table sorted by the R-index values is also shown.

significant increase in precipitation over most of the contiguous U. S. and the European Russia, and a significant precipitation decrease in East Siberia; increase in low cloud cover over the contiguous U.S. and a decrease over the FSU; and a general increase in the frequency of convective cloudiness and heavy precipitation over both countries *[Lettenmaier et al* ., 1994; *Georgievsky et al*., 1996; *Karl and Knight*, 1998; *Groisman et al*., 2001; *Sun et al*., 2001].

Parallel Observations of Pan and Actual Evaporation

The relationship between pan and actual evaporation was initially tested using the unique network of water balance stations and special field studies spread over the meridional transect of the European part of Russia and Latvia from 49°N to 67°N. In the seven locations along this transect (Table 1), climate conditions vary from dry steppe to taiga. The radiative index of dryness, R (ratio of potential evaporation to precipitation introduced by *Budyko* 1956]) varies at these locations from 1.8 in dry steppe to less then 0.6 in the northernmost taiga site. *Budyko* [1956] shows that $R < 0.7$ for most of the Russian territory, while $R > 0.7$ for most of the contiguous United States. For example, this index is close to 0.85 for New Orleans and St. Louis, and it is much above 1 throughout the entire Western U.S. R is ≤ 0.7 only in the northern tip of the northeastern U.S., the northwestern part of the Washington State, and the northern part of the Great Lakes area.

At each location in Russia, time series of both pan evaporation and actual evaporation were available for several decades during the period from 1950 to 1990. Actual evaporation was measured by large weighing lysimeters from undisturbed natural surfaces at five locations. The water balance method [Golubev et al., 1989] was used to estimate evaporation at the most southern and northern locations (at Volgograd and Kandalaksha). Time series of actual evaporation and pan evaporation are shown in Figure 2A for these locations. In five locations (except taiga) actual and pan evaporation are negatively correlated with r^2 in the range from 0.2 to 0.5. A thorough assessment of these correlations in the humid part of the forest zone (Pribaltiiskaya) revealed a strong negative correlation only for "dry" years, that is, when the annual precipitation was below its long-term mean value. For "wet" years (annual precipitation above this value) a zero correlation was detected (Figure 2B). We found systematic and statistically significant trends in pan evaporation in all seven locations and in actual evaporation in the steppe and forest-steppe climatic zones, at the central Russia forest site in Kostroma, and at the northernmost taiga site in Kandalaksha. We also found that, south of the taiga climatic zone, the signs of the evaporation trends are opposite to trends in pan evaporation (Table 1). Table 1 indicates that collinear trends in pan and actual evaporation occur only in areas with $R < 0.7$, while for regions with $R \geq 0.8$, an inverse relationship exists between pan and actual evaporation.

This notion is supported by intercomparison of pan and actual evaporation time series in Coshocton, Ohio (40°N, 82°W; $R = 0.76$; Figure 2A). Observations of weighing lysimeter and evaporation pan in this agricultural area of the forest zone reveal opposite trends, although the increasing trend in pan evaporation was not statistically significant. The weighing lysimeter in Coshocton has never been used to represent the undisturbed natural land surface. During the post-WWII period a variety of grass crops (orchard grass, birdsfoot trefoil grass, and alfalfa) were grown and cut a few times during the warm season [*Malone et al*., 1999]. Therefore, efforts were made to account for any inhomogeneity introduced by different grass crops and harvesting practice at this site during the post-WWII period using a suite of supplementary information (precipitation, percolating lysimeter data with a consistent vegetation cover, and the station metadata). After the contribution of non-meteorological factors into weighing lysimeter data were eliminated, we found (a) no statistically significant trends in the post-WWII period and (b) a zero correlation with precipitation and pan evaporation data at this site. We sorted the Coshocton data into two groups of years, "wet" and "dry", using the annual precipitation data at the site. The wet years are characterized by R less than 0.7 (~ 0.65) while in the dry years R is above 0.8. Within each group of years, pan and actual evaporation show noticeable correlations of opposite signs in line with those revealed in Russian and Latvian locations (Table 1; Figure 2B). The Coshocton data, however, cannot be directly used for the recalibration described below, because the pan evaporation trend at this site is statistically insignificant.

The instruments/methods used for actual and pan evaporation measurements/evaluation are different and the values are incomparable. Therefore, absolute values of trends in these variables are incomparable too. Consequently, we reduce them to relative values (percent of the long-term mean) and estimate the ratio of their relative changes for each climatic zone (Table 1). These ratios, RAT, at the sites with non-zero trends in E_p, provide the rough estimates of changes in E: $\Delta E = \text{RAT}\,\Delta E_p$, where ΔE and ΔE_p are relative changes in E and E_p respectively. With this procedure, the relative changes in actual evaporation can be assessed with the help of more numerous pan evaporation data grouped by climatic zone for the FSU and the contiguous U.S.

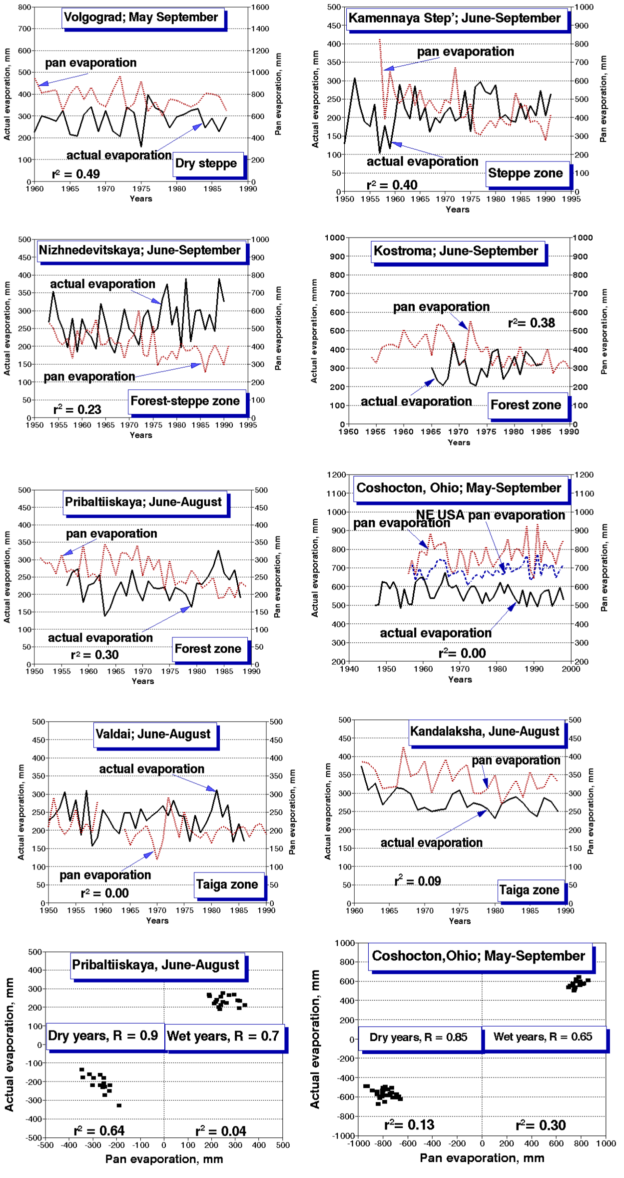

Figure 2. Upper four lines of plates. Variations in actual and pan evaporation as observed/estimated at seven locations along the meridional transect of the European part of Russia and Latvia from dry steppe to taiga climatic zones and in one U.S location at Coshocton, Ohio. Bottom line of plates. The anticorrelation between pan and actual evaporation in the humid forest climatic zone sites with R ≤ 0.8 (Pribaltiiskaya, Latvia and Coshocton, USA) is confined solely to "dry" years (the annual precipitation totals below the long-term mean value). To distinguish the values for "dry" years in the correlation graph of pan and actual evaporation for these sites, these values were multiplied by –1.

Reassessment of Trends in Pan Evaporation

Two zones each were selected in the European and Asian part of the FSU: the zone of sufficient humidity in the north coincides with the taiga and tundra climatic zones. The zone of dry climate comprises the most southern region of each part of the FSU. In three of the four zones pan evaporation significantly decreased during the second half of the 20th century [*Peterson et al.*, 1995]. In regions with R>0.8 we believe this should be interpreted as an increase in actual evaporation. By multiplying the ratio of trends (Table 1) to the pan evaporation trends, we estimate an increase in actual evaporation of approximately 5 %/decade in the southern section of the European part of the FSU. In the north of the Russian Federation where R < 0.7 we suggest a decrease of actual evaporation by approximately 2 to 4 %/decade. Most of the Asian part of Russia (Siberia) is covered by taiga but in its southern part along the Kazakhstan border a relatively narrow strip of steppe and forest-steppe climatic zones is located. Here, according to our recalibration, an increase of actual evaporation has occurred.

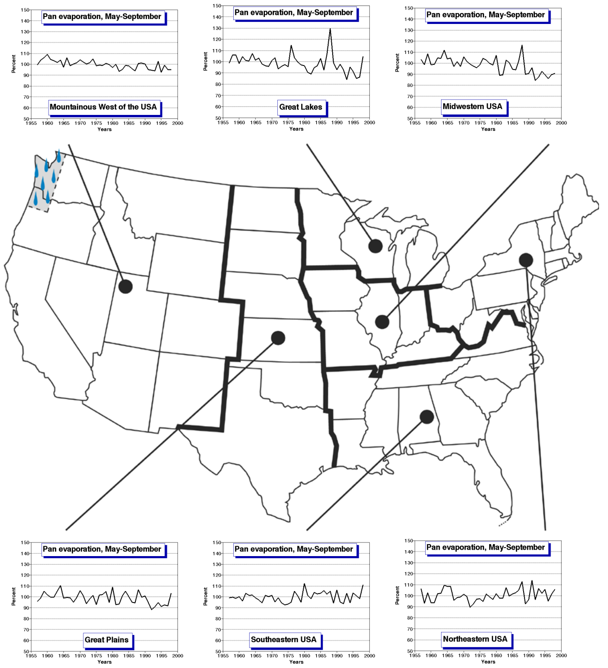

Figure 3. Pan evaporation changes (percent of the long-term mean regional values) over the contiguous United States during the past forty years (1957-1998). The number of stations used for evaluation of area-averaged time series of regional pan evaporation varies from 12 in the Great Lakes area to 198 in the Mountainous West of the contiguous U.S. (total number = 491).

The contiguous U.S. was divided into six climatic zones (Figure 3). The Budyko radiation index of dryness is about 0.7 or less only in New England and in a few areas in the north and northwest. Only in these regions may pan and actual evaporation trends (if they present) have the same sign. R is above 0.8 over the western U.S., Great Plains, Midwest, and Southeast and these trends, where they exist, should have opposite signs. Analysis of Figure 3 shows a gradual increase in the two eastern zones and a strong decrease in pan evaporation in the four other climatic zones (Table 2). These changes should now be interpreted as an *increase* in actual evaporation over most of the country with the exception of the Southeastern USA (where evaporation has been decreasing), the Northeastern USA, and the Great Lake region. In the last two regions, which include areas with $R<0.8$, the sign of changes in E remains uncertain. Here, (at Coshocton, Ohio) actual evaporation (a) shows no systematic trend during the past 40-50 years and (b) does not correlate with E_p or precipitation. The northwestern tip of the western United States (west of 122°W, north of 45°N) is, in fact, a humid region (with $R = 0.6$). Therefore, we analyzed and interpreted the tendencies in pan evaporation over this region separately. We found an increase in pan evaporation of 3%/decade and in precipitation of 1%/decade in this region confirming our notion about the increase of actual evaporation during past several decades over the entire western United States including this humid region. After recalibration, the sign of actual evaporation changes coincides with that of the summer precipitation changes over the contiguous United States [*Karl and Knight*, 1998, *Lawrimore and Peterson*, 2000] and Russia [*Georgievsky et al.,* 1996; *Sun et al.,* 2001].

We build our conclusions about the pan evaporation trend interpretation solely on the analysis of the data from eight locations in steppe, forest-steppe, boreal forest, and taiga climatic zones. We realize that this generalization of the field results from eight experimental sites to the two large countries requires a leap of faith and warn the reader about this matter (especially for the sites / wet years with $R < 0.7$, where correlations between E and E_p were low). For most of the regions assessed, our results support the explanation by *Brutsaert and Parlange* [1998] about the opposite signs of the pan and actual evaporation changes on the multidecadal time scale.

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Table 2. Trends in Pan Evaporation Based on the Entire Pan Evaporation Observational Network and Their Interpretation

Region	Period	Trend in pan evaporation %/10yrs	Interpretation of trend for actual evaporation
North of the European Russia (taiga)	1951-1990	-5.8**	Decrease by ~3-4 %/10yrs
South of the European part of FSU (steppe, forest-steppe, and forest)	1951-1987	-8.9**	Increase by ~4-6 %/10yrs
Siberia (taiga)	1951-1988	-3.0**	Decrease by ~2 %/10yrs
Siberia (steppe & forest-steppe)	1951-1988	-1.8	Increase
Central Asia and Kazakhstan (steppe, semi-desert, desert)	1952-1989	0.2	No change
Northeastern USA	1957-1998	0.8	Uncertain
Southeastern USA	1957-1998	0.8	Decrease
Great Lakes zone	1957-1998	-2.1*	Uncertain
Midwestern USA	1957-1998	-3.4**	Increase by 1 to 2 %/10yrs
Great Plains	1957-1998	-1.6**	Increase by ~0.8 %/10yrs
Mountainous West	1957-1998	-2.1**	Increase by ~ 1%/10yrs
USA west of 122°W; north of 45°N	1961-1998	3.0	Increase

The boundaries of the U.S. regions are shown in Figure 3. Trends statistically significant at the 0.05 level are marked by * and those statistically significant at the 0.01 level are marked by **. Quantitative interpretation of evaporation trends is very approximate for northern Russia due to the weak correlation of pan and actual evaporation in the taiga zone.

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