RUSSIAN CLIMATE AND THE HYDROLOGICAL BUDGET OF THE CASPIAN SEA

by

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RÉSUMÉ

Depuis le Pléistocène, le niveau de la mer Caspienne a subi de nombreuses variations qu'on a déjà tenté d'expliquer par des mouvements tectoniques; on sait maintenant qu'elles sont liées à des changements climatiques. Ainsi, on en trouve l'explication dans l'étude comparée des différents niveaux de la mer Caspienne, de 1881 à 1940, et 1) des températures estivales, cause d'une forte évaporation au droit de la haute Volga et de la surface iranienne de la mer Caspienne elle-même, et 2) des précipitations dans son bassin nord. En effet, les trois quarts des eaux de la Caspienne lui viennent de la haute Volga et de son principal affluent, la Kama.

De 1881 à 1940, en Russie, les précipitations hivernales ont augmenté aux stations continentales, et diminuées aux stations maritimes, tandis que la température moyenne annuelle, et particulièrement d'été, s'est élevée. Toutefois, de 1935 à 1940, la continentalité du climat s'est manifestée par des précipitations de 16% sous la moyenne, et des records de température dont 3° F. sous la normale pour le bassin de la Caspienne en juillet. De 1933 à 1940, le niveau de la Caspienne a donc baissé de 161 cm. Des économistes et des hydrologues soviétiques ont voulu expliquer cette baisse de niveau, au contraire, par différents travaux de l'homme sur les cours d'eau du bassin-versant. (K.W.B. et C.L.).

INTRODUCTION

During the course of the Pleistocene, historical times and again during the last few decades appreciable fluctuations in the level of the Caspian Sea have taken place. It was once thought that these fluctuations were the result of tectonic movements. However it has not been possible to provide proof for any large-scale tectonic activity or deformations within the drainage basin of the Caspian since at least the Middle Pleistocene, possibly excepting the Apsheron Peninsula which is of no more than local importance. A. A. Kaminsky (1927, 1929) and L. S. Berg (1934) have discussed this question in greater detail and decided that climatic and not tectonic factors are of primary importance. Climate however has a very broad meaning and comprises several elements varying over a drainage basin extending between latitudes 35 and 62° N. Only a rigorous examination of the changing hydrological budget of the Caspian and its causes during the period 1881-1940 (for which we have relatively complete and reliable records) can provide a satisfactory classification of these climatic elements and their geographical distribution. Having achieved this, it may also be possible to assess the part played by increased anthropogenic interference with the Volga's waters in the sharp drop of Caspian level during the 30's. These features are of considerable interest as they can affect inland waterways, hydroelectric development, fishing resources and irrigation. The Great Lakes as well as the Great Salt Lake provide an actual counterpart in North America, so much so that a closer investigation of this mechanism of variation can also be of assistance to economic planning and development in the New World.

THE HYDROLOGICAL BUDGET OF THE CASPIAN SEA

Before commencing upon a study of the variation of climatic elements within the drainage basin of the Caspian, it is necessary to clarify the origin of the Caspian's waters. In a recent hydrological compendium, M. I. Lyvovitch (1953) has given maps showing calculated theoretical evaporation over the U.S.S.R. and the mean volume of water passing off the land surfaces. These figures are however too generalized for our purposes, and unfortunately omit all references to the southern coast of the Caspian, as all Russian articles can be expected to do. To visualize the primary sources of drainage, the present writer has calculated the amount of surplus water according to the Thornthwaite system [1] for 68 stations in the basin itself, and some two dozen along its outer periphery. This hydrological outline was not intended to represent true surface drainage and gives a much too low value. Nevertheless it employs monthly temperature and precipitation data giving consideration to more factors than most usable precipitation-evaporation-discharge formulae. The picture so obtained using the climatic normals of W. Koeppen (1939) for the period 1881-1915, M. H. Ganji (1955) for Iran, supplemented by the *World Weather Records* (Vol. 79), is given in Fig. 1. This map is merely intended to give a relative picture where the drainage waters originate. Three particular concentrations of surplus water are apparent in the Urals, the Caucasus and on the Mazanderan slopes of the Iranian Elburz. In the former two the true discharge figure is well over 80 cms., in the latter locally even over 150 cms. However of greater areal significance is the vast drainage system of the upper Volga and Kama with its large network of navigable rivers. Allowing for the winter snow cover from November to early April the chief season of runoff in central Russia and the Caucasus is spring, compared with autumn, winter and spring on the Mazanderan coast. This spring maximum is particularly pronounced on the Volga, where 27% of the annual discharge passes Stalingrad in the month of May alone (Fig. 2).

M. I. Lyvovitch (1953, p. 15) gives the following data for the annual discharge of some of the larger Caspian rivers:

River	Area of drainage basin in km²	Annual discharge in km³	Discharge in m³/sec.
Volga	1.380.000	255	8.100
Ural	220.000	11	360
Kura	188.000	18	580
Terek	43.710	11	350

Not considered are the smaller rivers of the northeastern Caucasus and the coast of Iran. From Fig. 1 these areas obviously contribute a good deal of water. Estimating the drainage area and runoff of both areas on a comparative basis with the Kura and Terek, the Kuma, Sulak, Samur and minor Caucasian coastal rivers contribute no less than 25 km^3, the Iranian coast over 20 km^3. From the sum total it can be calculated that the Volga contributes fully 75% of the annual inflow, the Ural 3%, the north Caucasian rivers 11%,

[1] Evapotranspiration in the sense of Thornthwaite (1948) comprises soil evaporation, plant transpiration and interception leading to direct evaporation. Provided sufficient water is available, a general equation $e = 1.6\ (10\ t/\ I)^a$ expresses mean monthly potential evapotranspiration e in cms., where t = mean monthly temperature in ° C, I = sum of 12 monthly values of heat index $i = (t/5)^{1.514}$, a = constant. In practice, when the annual heat index is known, monthly potential evapotranspiration can be simply read from a linear curve and be corrected according to varying length of daylight and month by a latitudinal correction factor. A hydrological budget can then be set up, whereby the surplus water (when precipitation exceeds potential evapotranspiration) can be calculated. Thornthwaite assumes 10 cm. of water is held in the root zone until transpired by the plant cover when P. E. exceeds actual precipitation. The remaining water assumedly percolates to the ground-water or runs off directly. However the small amount of theoretical surplus for the summer months is contradicted by actual measurements on the Moskva which set this figure at 20-25% of the precipitation May to October inclusive, whereas the Thornthwaite system only allows for some 7%.

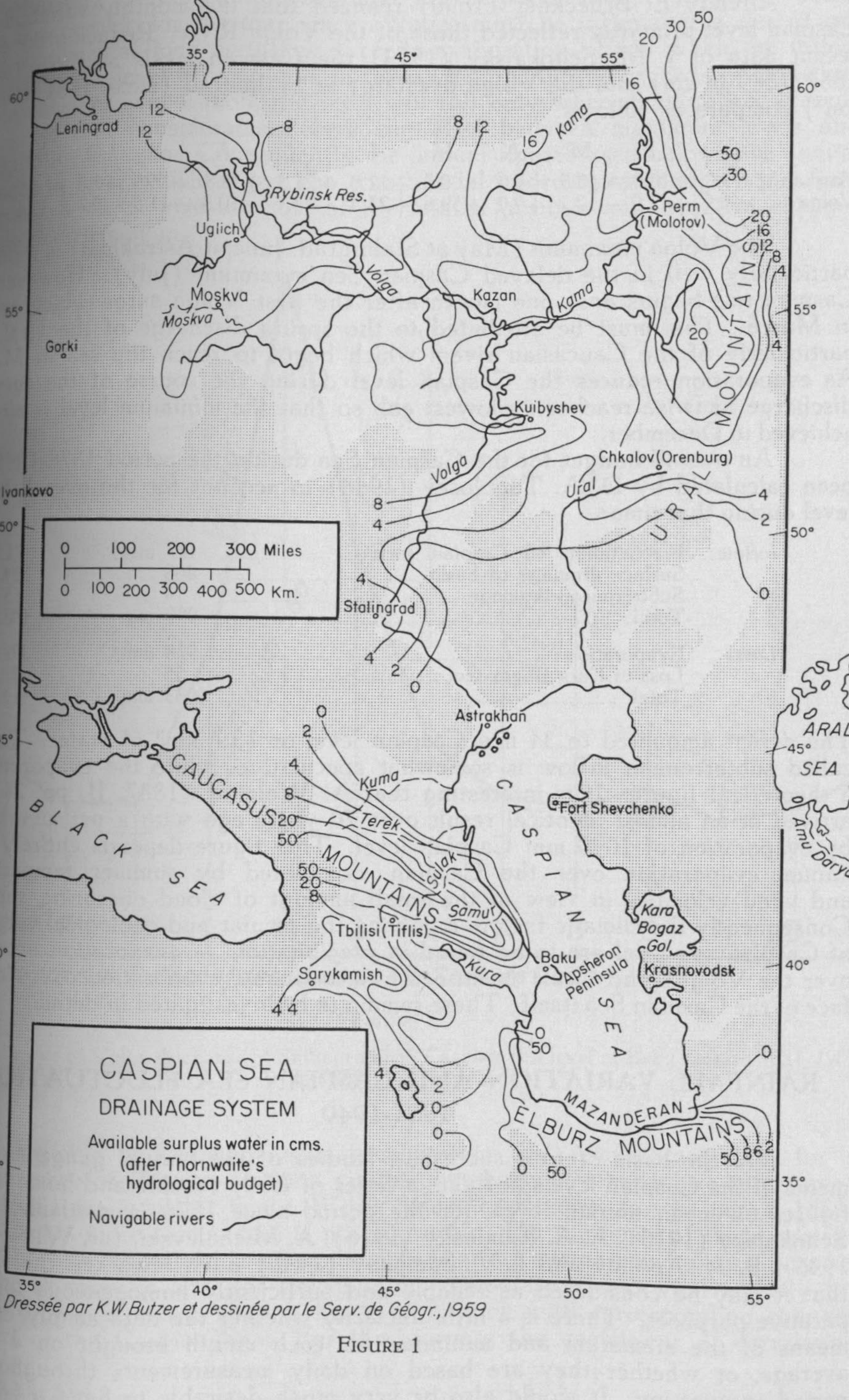

FIGURE 1

the Kura 5%, and the coast of Iran 6%. In short some 78% of the Caspian waters originate north of latitude 50°N in central European Russia.

Already E. Brueckner (1890) realized that the monthly variations of Caspian level primarily reflected those of the Volga River. Reducing the more recent data of J. M. Schokalsky (1913) the Caspian levels at Baku (mean 1887/1889 in cm) and the Volga discharge at Stalingrad (mean 1881/1909 in km³) compare as follows:

	J	F	M	A	M	J	J	A	S	O	N	D
Caspian	—9.8	—10.0	—10.5	—8.0	— 0.3	+12.8	+21.3	+14.8	+ 6.5	—2.8	— 6.5	—10.3
Volga	—6.9	—11.9	—12.1	+9.9	+59.6	+22.5	— 3.4	—10.3	—11.5	—9.7	—13.6	—11.5

The Volga maximum (May at Stalingrad, June at Astrakhan) is reflected particularly well in the delayed Caspian Sea maximum (July). However the Caspian rise begins only one month after the first Volga surge which arrives in March. This must be attributed to the spring discharge of the Ural and particularly of the Caucasian rivers which begin to reach the sea in March. As evaporation reduces the Caspian level during the course of the summer, discharge likewise reaches its lowest ebb so that the minimum level is already achieved in December.

An overall budget for the Caspian Sea during the period 1878-1945 has been calculated by D. A. Tugolosev (1948) to account for the overall fall in level during that time:

Inflow:	Precipitation on Caspian surface	177 mm	71.1 km³
	Surface drainage of basin	808	324.2
	Subterranean drainage	14	5.5
	Total	999 mm	400.8 km³
Loss:	Evaporation	978 mm	392.3 km³
	Loss to Kara Bogaz Gol	55	22.2
	Total	1033 mm	414.5 km³

The deficit amounted to 34 mm Caspian level or 13.7 km³ of water. The so-called subterranean inflow is somewhat speculative, while the evaporation is a theoretical figure. It is interesting that A. Woiekof (1887, II, pp. 261-67) arrived at an almost identical result over 70 years ago with a net annual loss by evaporation of 1090 mm Caspian level. This figure depends entirely upon annual evaporation over the Caspian, dominated by summer temperatures and wind velocities in view of the small amount of cloud obscuring sunlight. Consequently the climatic factors involving the secular and geological variations of Caspian sea level are to be found in precipitation — evaporation anomalies over the Volga (and Ural) basin or in variations of evaporation over the surface of the Caspian Sea itself. These remain to be investigated in detail.

RAINFALL VARIATION AND CASPIAN SEA FLUCTUATIONS 1881-1940

On the basis of four successive studies of the annual gauge measurements of the Caspian levels at Baku, a series of fairly reliable and homogeneous figures on mean annual levels for the period since 1878 is available. J. M. Schokalsky (1913), A. A. Kaminsky (1926), A. Michalevski, (cf. W. Koeppen, 1936), B. A. Apollov and I. V. Samoilov (1946) have reworked the data so that it may be considered as reliable and sufficiently homogeneous for comparative purposes. There is a little unclarity whether the data simply employs means of the maximum and minimum for each month brought on a yearly average, or whether they are based on daily measurements throughout the period in question. It would also be very much desirable to have a complete comparative record for another station, to avoid errors caused by wind effect or of possible local tectonic movements in the often disturbed region of Baku.

Unfortunately no better data is available for the period until 1930 and no better data is accessible for the time since. Notice must be taken that a rise of sea level continues as long as inflow exceeds evaporation. Even when the inflow diminishes, the level will continue to rise as long as inflow exceeds evaporation. Given constant evaporation, the level will fall only when evaporation exceeds inflow, so that considerable delays can arise between maximum levels and precipitation maxima. Consequently the annual figures used below give annual changes in level which reflect the true annual hydrological budget, and five-year means which give the sum of the annual positive and negative changes during that time-span.

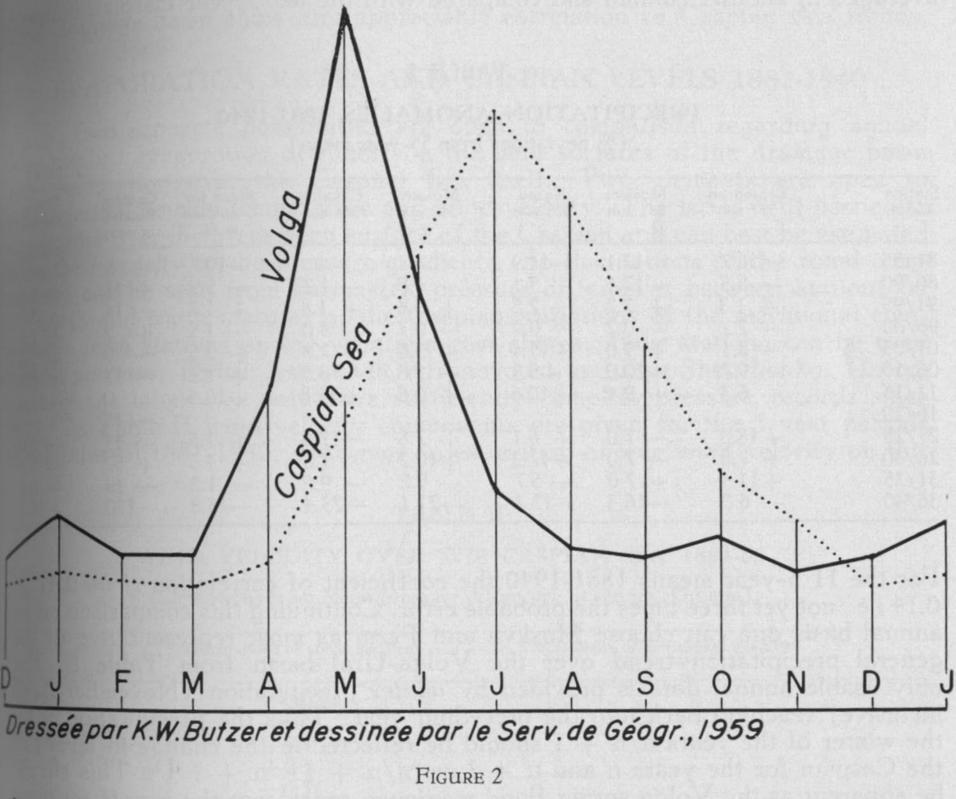

FIGURE 2

Annual curve of Volga discharge at Stalingrad and Caspian Sea level at Baku (means 1881/1909 and 1887/1909 resp.).

Reliable and homogeneous precipitation and temperature data for a good number of Russian stations (unfortunately most records are interrupted 1916-1920) are available in the *World Weather Records* for the period 1881-1940. Again more recent data is not accessible. On the basis of these records we propose to undertake a rigorous mathematical comparison, whose purpose shall be to show in how far precipitation, temperature and wind velocity for annual or 5-year means show a linear correlation with corresponding changes in level of the Caspian Sea. For this purpose the coefficient of correlation

$r = \frac{\Sigma \Delta x_1 \Delta y_1}{\sqrt{\Sigma \Delta x^2 \Delta y^2}}$ where $\Delta x_1 = X - x_1$ and $X = \frac{1}{n} \sum_{n}^{1} x_1$ gives a value with probable error $e = 0.6745 (1 - r^2)/\sqrt{n}$. To reduce the weakness inherent in using a small number of samples as is unavoidable here,[2] the coefficient of correlation r is considerably reduced by $(r')^2 = 1 - (1 - r^2)(n - 1)/(n - 2)$ which gives a usable coefficient according to V. Conrad and Pollak (1952). Conrad maintains that a minimum correlation three times the probable error e and very preferably five or more times greater than e is required for significance.

Beginning with precipitation data, Table I gives 5-year deviations from precipitation means (in %) for 5 stations representative for the main discharge zones of the Volga-Ural drainage system: Chkalov (Orenburg), Perm (Molotov), Kazan, Moskva and Leningrad. These deviations are equally averaged in another column and compared with the net 5-year Caspian budget.

TABLE I

PRECIPITATION ANOMALIES 1881-1940

(% deviations from 55-year mean)

Station Mean	Leningrad 547 mm	Moskva 583 mm	Kazan 428 mm	Molotov 582 mm	Chkalov 348 mm	Mean for 5 stations in %	Caspian Budget in cms.	Tbilisi 505 mm
81/85	—16.7	—12.1	—11.9	—	—	—10.2	— 8	—16.2
86/90	— 8.5	—12.1	— 3.1	— 4.8	— 1.2	— 5.9	+ 18	+ 9.4
91/95	+ 1.3	+ 2.2	— 2.6	+ 3.4	+ 1.8	+ 1.2	— 14	— 3.0
96/00	— 2.7	— 0.2	— 0.9	— 0.7	— 3.0	— 1.5	+ 2	+ 1.8
01/05	— 3.1	+ 9.0	+11.4	+ 3.0	— 7.8	+ 2.5	— 9	+ 5.8
06/10	— 9.2	+20.0	— 5.3	+ 3.6	— 3.6	+ 1.4	— 13	+ 5.0
11/15	— 6.3	+ 9.4	+10.6	+ 3.6	+34.8	+10.4	0	—11.0
16/20							— 15	
21/25	+18.0	— 7.0	+ 6.1	+ 7.8	—12.6	+ 2.5	— 43	— 5.0
26/30	+ 7.8	— 7.0	+12.3	+10.2	— 1.8	+ 4.3	+ 52	— 1.8
31/35	+11.4	+ 7.0	— 5.7	— 9.2	— 9.6	— 1.2	— 48	— 0.6
36/40	— 6.0	—16.3	—12.3	—21.1	—23.4	—15.8	—120	+16.2

For the 11 5-year means 1881-1940 the coefficient of correlation $r' = 0.41 \pm 0.14$ i.e., not yet three times the probable error. Continuing this comparison on an annual basis one can choose Moskva and Perm as most representative of the general precipitation trend over the Volga-Ural basin from Table I. The only usable annual data is provided by *winter* precipitation (November-April inclusive) reaching back into the preceding year. Thus the precipitation p for the winter of the years $n/n + 1$ should be reflected in the change in level l of the Caspian for the years n and n + 1 or $^{p}n/n + 1 \propto {}^{l}n + 1 - {}^{l}n$ This should be apparent as the Volga spring flood maximum represents the runoff resulting from melted snow accumulating since November of the preceding year and reaching the Caspian in the corresponding summer. For this reason a comparison of annual precipitation with annual mean level of the Caspian is senseless. The correlation coefficients so obtained for Moskva and Perm for the decade 1931/1940 are however quite poor with r = 0.22 and 0.40 respectively. For 1921/1930 they are even lower (0.30 and —0.16). A. A. Kaminsky (1926) attempted a similar correlation for the period 1891-1925 based upon 13 stations and obtained $r = 0.33 \pm 0.10$. Kaminsky tried to improve this result by shifting his coordinates by one year, i.e. assuming the winter meltwaters took over a year to influence the Caspian level effectively. However with a correla-

[2] Statistically it would be very much more preferable to use 5 or 10-year overlapping annual means. As the observational records are broken for 1916-20 recourse must be made to simpler values, as a break in the record of overlapping means cannot be tolerated for an hydrological study. The 20-year period 1921-40 is too short to apply overlapping means with much purpose.

tion coefficient only raised to 0.49, this shift of axis is statistically not fully warranted and above all not physically obvious (compare Fig. 2). It therefore appears that although annual winter precipitation does show a certain similarity to the trend of Caspian levels, it cannot be accepted as a primary cause. Winter precipitation on a 5-year basis shows no correlation whatever (r′ = 0.03) since winter precipitation has gradually increased in continental Russia during the period in question. This should discard the winter precipitation theory entirely. Overall precipitation on a 5-year basis comes somewhat closer to this desideratum, but is also statistically unsatisfactory. Lastly, Table I includes the 5-year precipitation means for Tbilisi (Tiflis) which even yield a slight negative correlation. Only longer-term precipitation anomalies over the northern Volga-Ural drainage basin show any appreciable correlation to Caspian Sea trends.

EVAPORATION RATES AND CASPIAN LEVELS 1881-1940

Two separate possibilities are open to comparison regarding annual evaporation: evaporation of runoff on the land surfaces of the drainage basin and evaporation over the Caspian Sea itself. Two elements are open to investigation, namely temperature and wind velocity. The latter is of particular importance over the great open surface of the Caspian and can best be estimated from the intensity of the pressure gradients. So fluctuations of the zonal components can be seen from barometric pressure differences between stations on the north and south margins of the Caspian, variations of the meridional components from stations on the west and east shores. Four stations can be used for this purpose: Tbilisi, Astrakhan, Krasnovodsk and Fort Shevchenko. Unfortunately the latter two only have sufficiently complete pressure records since 1921. In Table II wind velocity components are given for the 5-year periods of the interval 1881-1940. However an estimation of true wind velocity on this

TABLE II

WIND VELOCITY OVER THE CASPIAN SEA 1881-85

(Deviations from mean pressure difference at sea level in mm)

	Fluctuations of zonal gradient (N > S)	Fluctuations of meridional gradient (E > W)
81/85	—0.02	
86/90	—0.28	
91/95	+0.46	
96/00	—0.30	
01/05	—0.34	
06/10	+0.10	
	(1915-1920 no records)	
21/25	—0.27	+0.18
26/30	+0.62	+0.12
31/35	—0.10	—0.48
36/40	+0.11	+0.16

basis yields no correlation whatever. Similar useless results were obtained for evaporation according to wind velocities over the northern drainage basin. Only when direct local wind speed data for a number of stations is accessible for a few decades can further attempts be made to correlate mean wind velocity and Caspian Sea trends. So far they do not appear very promising.

Whereas winter temperatures are of no special interest to the rate of evaporation in Russia, summer temperatures are all the more important: almost all of the annual evaporation takes place during the summer months which also witness the annual rainfall maximum of the Volga-Ural basin. Consequently July temperature deviations from the 55-year mean of the same five Russian stations as above are given in Table III for the period 1881-1940 in °C. These means are averaged on an equal basis in a further column, which yields a linear correlation of r′ = — 0.60 ± 0.12 with the trend of Caspian levels. The correlation is five times the probable error, so that it is statistically significant that increased summer (July) temperatures in the Volga-Ural basin are related with negative tendencies of the Caspian Sea and conversely on the 5-year mean. Considering July and August temperatures at Krasnovodsk representative for the yearly trend of evaporation over the southern half of the Caspian, where incidentally most of the evaporation loss occurs, we can obtain an identical coefficient of r′ = — 0.60. A mean for Astrakhan and Fort Shevchenko as representative for the northern half of the Caspian is a little less favourable. Summer temperatures over the southern Caspian on the 5-year mean are then also significantly related to changes of Caspian Sea level.

TABLE III

TEMPERATURE ANOMALIES 1881-1940 FOR JULY
(Deviations from mean in ° C)

Station Mean	Leningrad 17.78	Moskva 18.07	Kazan 20.15	Molotov 18.23	Chkalov 22.25	Mean for 5 Stations in °C	Krasnovodsk (July and August) 28.68
81/85	+0.52	+1.15	+0.05	+0.43	—	+0.54	—0.54
86/90	+0.56	+0.19	+0.31	+0.91	—0.61	+0.27	—0.98
91/95	—1.02	—0.09	—0.21	—0.65	—0.47	—0.49	—0.34
96/00	+0.24	+0.69	—0.81	—0.61	—1.05	—0.31	+0.41
01/05	—1.40	—1.43	—1.05	—0.61	—0.47	—0.99	+0.29
06/10	—0.44	—0.59	—0.47	+0.13	+1.25	—0.02	+0.06
11/15	+0.68	—0.99	—0.39	—0.63	+0.11	—0.29	+0.13
16/20							—0.34
21/25	—0.18	—0.77	—0.09	—0.05	+0.43	—0.13	+0.04
26/30	+0.48	—0.27	—0.69	—0.25	+0.01	—0.14	—0.02
31/35	+1.00	+0.79	+0.99	+0.75	+0.65	+0.84	—0.14
36/40	+1.94	+2.69	+1.63	+1.47	+0.93	+1.73	+1.48

It is to be expected that annual summer temperatures over the northern drainage basin yield poorer correlations on account of the time-lag between summer evaporation and water reaching the Caspian long after the annual July maximum. All Russian stations show correlations well below 0.20 during the period 1921/40. Remarkably Krasnovodsk and Tiflis show little better linear correlations on the annual basis (r′ = — 0.17).

CLIMATOLOGICAL IMPLICATIONS OF CASPIAN FLUCTUATIONS

Analysis of the previous climatological material gives the following results in comparison with the recent variations in Caspian Sea level:

1) primary cause of Caspian Sea fluctuations is evaporation over the northern drainage basin (upper Volga, Kama and Ural) as well as over the Caspian Sea, especially over its southern half. This rate of evaporation is predominantly a matter of mid-summer temperatures;

2) secondary cause of the Caspian fluctuations is precipitation over the northern drainage basin.

Both factors are however closely related, so much so that the series of 5-year means for the five central Russian stations gives a linear correlation r′ = — 0.75 ± 0.08 which is over nine times the probable error and very significant.

Since most of the rain comes in summer one can say that cool summers are generally moist, hot summers characteristically quite dry. The meteorological explanation for this parallelism is apparent in cool and moist oceanic summers alternating with hot and dry continental summers. Several general features can be noted with respect to Russian climate during the years 1881-1940. In an earlier article (K. W. Butzer 1957c) the writer had noted the overall increase in precipitation between 30-year means for the Volga Basin. As mentioned above, winter precipitation has increased at the more continental stations as Perm (36% between 1885/1910 and 1911/1940), but decreased a little in more maritime stations as Moskva (by 9%). Lastly there has been a general rise in annual and particularly summer temperatures over the region in question. These features connected with the recent climatic fluctuation infer a weaker Siberian anticyclone in winter permitting more westerly depressions to pass through Russia during autumn, winter and spring. On the other hand continental tropical airmasses connected with a northward shift of the subtropical cells of high pressure have become more characteristic for mid-summer. Seen in the 5- or 10-year means the picture is more complicated (compare also Butzer 1957c, 1958b). The period 1891-1930 was coolest, the decades 1901-1930 wettest. Maximum oceanity was reached between 1901 and 1915. Since 1930 continentality has increased very strongly coupled with westward extensions of the asiatic high in winter, with the dominance of cT airmasses in summer. The period 1935-40 was not only calamitously dry with mean precipitation 16% below average but also extremely continental with record winter temperature minima at several stations and a mean July temperature averaging some 3°F. above normal for the entire Caspian drainage system. Some stations such as Moskva enjoyed a mean July temperature almost 5°F. above average. The use of 5-year means obscures that these bad years already began 1933, as the agricultural disasters of the 30's also emphasize in part.

The year 1933-1940 were also notorious for a fall of 161 cm in the level of the Caspian Sea. Soviet economists and hydrologists viewed the increased anthropogenic interference of the Caspian basin waters with alarm, and G. A. Taskin (1954) has reviewed the consequences of this drop recently. It was already noted that the Kura River supplies the Caspian with only 5% of its water, and a certain loss to irrigation projects there since the late 1920's will certainly not be worth the mention. What had been achieved in the Volga Basin before 1940 ? Hydroelectric stations were built at Ivankovo and Uglich, and the Rybinsk Reservoir constructed; similarly the Volga-Moskva River Canal was begun. However the great reservoirs at Gorki, Perm, Kuibychev and Stalingrad have only come into operation quite recently and played no part during the 30's. All in all the interference with Volga waters in the 30's was not what it has been claimed to be, and can in no way compare with the climatic anomalies of these years. So the increase in precipitation and cooler years since 1940 was paralleled by a greater equilibrium in the hydrological budget of the Caspian. That the great lakes dammed back behind the barrages at Stalingrad, Kuibychev, Perm and Gorki will now play a very much greater role in evaporating great quantities of Volga waters must be emphasized, but the "*precipitate fall*" of 1933-40 was overwhelmingly due to climatic phenomena. That this trend of the period 1929-1945 was not without similarity elsewhere is seen by a linear correlation of $r' = 0.28$ between annual changes in level of the Caspian and Dead Sea during that interval (Butzer 1958a) which is at least better than the annual correlations obtained for all other elements above. As precipitation certainly does not vary in phase in short-term means over the Caspian Basin and Near East, one can realize the dominant role played by temperature climate in controlling the hydrological budget of the Caspian.

The fluctuations of the recent geological past and historical times have already been discussed at length elsewhere (Butzer 1958a, also 1957a). During the Last Glaciation the Caspian rose by some 75m to overflow into the Black Sea immediately following upon the 15m interglacial transgression, i.e. this Early Chvalyn stage occurred before an appreciable lowering of planetary temperatures during the moist Early Glacial. Consequently one must assume that changes of precipitation were also at times of greater importance. It is known that rainfall increased through the drainage system at this time, probably during a period of cool maritime summers (Butzer 1957b). A 50% increase of precipitation over the surface of the Caspian would alone account for a rise of 10 cm a year provided all other elements remain constant and in equilibrium. Dating from the maximum of the glacial interval, the Main Chvalyn shorelines only lie some 28m above the present Caspian level. This period was cold and continental in Russia, and the reduced vapour density of the air will have excluded greater precipitation. In Late and Post-Glacial times, probably until the end of the thermal maximum, a gradual drop of the Caspian must also be ascribed to temperature, just as the high levels of the 9.-10th and 17.-19th centuries A. D. were associated with a cool climatic anomaly. A branch of the Amu Darya reached the Caspian across the Sarykamish Depression during several intervals in prehistoric times, particularly during the Würm. The total discharge of the Amu is 42 km³ which would suffice to raise the level of the Caspian some 10 cm per year provided all of its waters flowed into the Caspian. However the Aral Sea would then have fallen considerably as the Amu contributes over 75% of the Aral Sea waters. Since the Aral also stood a few meters higher during the Last Glacial, one must assume that only a small part of the Amu's waters followed the bifurcation at Khiva westwards.

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