Is Mongolia's groundwater increasing or decreasing? The case of the Kherlen River basin

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Abstract The average area-wide underground terrestrial water storage in the Kherlen River basin, a relatively pristine area in eastern Mongolia where human impacts have been minimal so far, has undergone a marked decline in the past decade; nevertheless, there is no evidence that any unusual or systematic long-term storage change has taken place over the past half century. This result follows from an analysis of daily streamflow records measured at three gauging stations on the river, namely at Baganuur, Undurkhaan and Choibalsaan. This absence of a clear trend in long-term groundwater storage is generally consistent with findings in previous studies regarding trends of other components of the hydrological cycle in Mongolia and neighbouring regions at similar latitudes, namely in northern Inner Mongolia to the east and Xinjiang to the west, and even further in the same direction in the adjacent areas of southern Central Asia of the Russian Federation and of Kazakhstan.

Key words groundwater storage; climate trends; baseflow; drought flows; East and Central Asia; Mongolia

Les eaux souterraines de Mongolie s'accroissent ou décroissent-elles? Cas du bassin versant de la Rivière Kherlen

Résumé Le stockage hydrogéologique moyen dans le bassin versant de la Rivière Kherlen, une région relativement vierge de la Mongolie orientale où les impacts anthropiques ont été minimaux jusqu'à présent, a souffert d'un déclin marqué au cours de la dernière décennie. Il n'y a cependant aucune preuve d'un quelconque changement accidentel ou systématique lors du dernier demi-siècle dans le stockage à long terme. Ce résultat est basé sur une analyse des données d'écoulement journalier mesurées en trois stations de jaugeage sur la rivière, à Baganuur, Undurkhaan et Choibalsaan. Cette absence de tendance nette vis-à-vis de la ressource en eau souterraine à long terme est compatible avec les tendances préalablement observées pour d'autres composantes du cycle hydrologique en Mongolie et dans les régions voisines de latitudes similaires, à savoir la partie nord de la Mongolie Intérieure vers l'est et le Xinjiang vers l'ouest, et encore plus loin dans la même direction dans les zones adjacentes du sud de l'Asie Centrale de la Fédération Russe et du Kazakhstan.

Mots clefs stockage d'eau souterraine; tendances climatiques; écoulement de base; étiages; Asie Orientale et Centrale; Mongolie

INTRODUCTION

The grasslands of Mongolia, which are among the few more pristine ecosystems remaining on Earth, have been the home of nomadic herdsmen since time immemorial. However, for the past fifty to sixty years many aspects of this traditional land use and way of life have been giving way to those of a less itinerant and less migratory society with a more organized economy, causing widespread overgrazing and land degradation. It is generally agreed that this degradation has increased the risks of desertification and has put increasing stresses on the available water supplies in rural areas. In these areas groundwater is often the main, if not the only source of water, especially in winter when surface waters are frozen. In addition, over the past decade or so, the country has been suffering serious drought conditions, which have exacerbated this situation, and have caused a marked reduction in groundwater levels; this has resulted (e.g. Davaa *et al.*, 2006; Fig. 10) in the drying up not only of wells and springs, but also of some rivers and lakes. A number of groundwater observation wells have been put into operation (e.g. Davaa, 2007), which suggest recent average groundwater table declines of the order of 0.05 m/year. However, these well records are only a few years long and too short to allow quantitative conclusions. Although much of the available information is still anecdotal and based on short records, it is a general perception in the country that these declining water tables over the past decade are unusual and

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result from climate change (e.g. NSO, 2000; United Nations, 2006). The relative importance of human impacts and possible climate change is still unclear.

In light of this uncertainty, it is the main objective of the present study to assess the recent groundwater downtrend relative to the long-term evolution of groundwater storage in those parts of this semi-arid region where human impact has been minimal, and to put this within the broader framework of current global climate change concerns. This task is achieved by relating groundwater storage with available streamflow data, for which much longer and more reliable records are available than for well observations, and by then tracking the resulting storage values, from the middle of the last century until the present. The Kherlen River basin was selected for this purpose, because conditions there have remained relatively pristine so far and direct human impacts have been minimal; thus changes detected in this basin can be used as a baseline to assess changes observed elsewhere in Mongolia where human effects have been more pronounced. The results will be shown to be consistent with findings in other studies regarding general changes in the hydrological cycle in regions with a similar semi-arid climate in central and eastern Asia. The present study was also motivated and conceived in part as a further development of the RAISE project (Sugita *et al*., 2007), whose purpose was to gain a better understanding of the water cycle in general, and its relation with the lower atmosphere and ecology of eastern Mongolia. It is a truism that no terrestrial water budget of a region can be complete without a thorough knowledge of the changes in underground water storage, both in the short and in the long term.

THE RELATIONSHIP BETWEEN BASEFLOW AND GROUNDWATER STORAGE

The streamflow resulting from groundwater outflows in a river basin, in the absence of precipitation or artificial storage release, is referred to as baseflow; it can also variously be called low flow, sustained flow, dry-weather flow or fair-weather flow. Such flows have been of interest because of their relevance for problems of water supply, river water quality during drought periods, and overall basin drainage. A commonly used equation to describe low flows, whose form goes back at least to the pioneering work of Boussinesq (1877), is of the following form:

$$Q = Q_0 \exp(-t/K) \tag{1}$$

where Q is the volumetric rate of flow in the river [L^3 T^{-1}], Q_0 is its value at the (arbitrarily) chosen reference of time, i.e. $t = 0$, and K is a characteristic time scale of the catchment drainage process [T], also referred to as the storage coefficient.

Once the baseflow characteristics of a river are known, the rate of change of underground water storage volume per unit catchment area, dS/dt, in the upstream contributing aquifers of the catchment can be determined directly from the storage equation; thus, if Q can be assumed to result from groundwater outflow only, in the absence of any inflows into the system, this can be written as:

$$Q = A \frac{dS}{dt} \tag{2}$$

in which A is the area of the catchment [L^2]. Integration of equation (2) upon substitution of equation (1), that is:

$$S = -Q_0 \int_t^\infty e^{-t/K} dt / A \tag{3}$$

produces immediately the desired relationship:

$$S = KQ / A \tag{4}$$

in which the storage S can be visualized as the average thickness of a layer of water above the zero-flow level spread over the area A.

Equation (4) shows how the temporal trend in terrestrial storage can be estimated from the baseflow trend in the river basin. However, this requires knowledge of the characteristic drainage time scale K. Over the years several procedures have been developed to estimate K for any given river from streamflow measurements. One among them, which allows the treatment also of nonlinear aquifer behaviour, was proposed in Brutsaert & Nieber (1977); it consists of first putting equation (1) in differential form, namely:

$$\mathrm{d}Q / \mathrm{d}t = -KQ \qquad (5)$$

Ideally, the value of K is then directly determined from the lowest envelope of a logarithmic plot of $(-\mathrm{d}Q/\mathrm{d}t)$ data *versus* the corresponding Q data; this procedure will be illustrated below.

In the course of any year, the terrestrial water storage in a basin goes through highs and lows depending on the antecedent precipitation inputs over the region. A reliable and objective way to track the long-term evolution of this storage over many years is to monitor its lowest level each year, that is, when it reaches the non-depleted reserve, which is available and can be depended upon for future years. Since storage is related to flow rate by equation (4), the long-term storage trend can in principle be derived from the trend of the lowest daily flows for each year of the period of record. But because such daily flows are normally subject to error and other uncertainties, it was decided to use the annual lowest seven-day daily mean flows, namely Q_{L7}, as a more robust measure for this purpose.

THE KHERLEN RIVER BASIN

The Kherlen River is about 1250 km long and it has its headwaters in the Khentii Mountains at a height of some 1750 m a.m.s.l. in northeastern Mongolia; it first flows southward for some 250 km and then gradually turns to a more northeasterly direction to reach the autonomous region of Inner Mongolia, where it ends up in Hulun Lake at 540 m a.m.s.l., some 170 km further to the northeast. In wet periods this lake may overflow and become part of the Argun-Amur (or Ergun-Heilongjiang) River system. As an illustration of the flow regime, Fig. 1 shows the annual mean flow rates at Choibalsan, the station with the longest record; during the period 1947–2006, the average of these flow rates was 19.98 $\mathrm{m^3\ s^{-1}}$ or 8.81 mm year^{-1}. Maps showing the general location and course of the river can be found at the following sites:

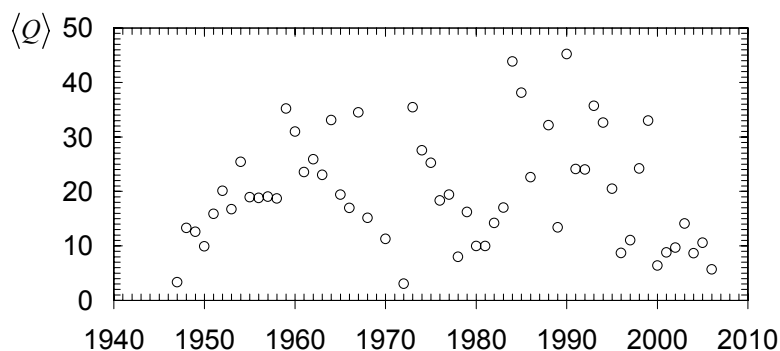**Fig. 1** Annual mean flow rates $\langle Q \rangle$ at Choibalsan (in $\mathrm{m^3\ s^{-1}}$). Over the 60-year period of record (1947–2006), the average of these flow rates was 19.98 $\mathrm{m^3\ s^{-1}}$, or 8.81 mm year^{-1}, and the trend over this same period $\mathrm{d}\langle Q \rangle / \mathrm{d}t = -0.01834$ $\mathrm{m^3\ s^{-1}}$ year^{-1}, or roughly -0.00809 mm year^{-1}. The upstream drainage area at this gauging station is $A = 71\ 500\ \mathrm{km^2}$.

The Kherlen River basin is a region of complex geology (Academy of Sciences MPR *et al*., 1990; Mineral Resources Authority of Mongolia, 1999). In brief, the small mountainous area of the river's headwaters displays a mixture of Mesozoic and Palaeozoic granites, and Carboniferous rocks; however, further downstream all the way to the outlet, the right-hand hilly ridge areas of the basin to the south consist mainly of Mesozoic rocks, whereas those on the left hand side to the north are more complex consisting of areas of Mesozoic rocks and Palaeozoic granites. The broad flood plains along the river itself are covered with Quaternary deposits which form the unconfined aquifers, feeding the low flows of interest in this study.

The long-term average precipitation over this basin is of the order of 200 mm per year (e.g. Natsagdorj, 2000). The average temperatures in the basin are below freezing from November to March and above freezing between April and October. At Choibalsan, the major station in the area located at a height of about 750 m a.m.s.l, the long-term (1961–1990) mean temperature is of the order of 0.66(±15)°C, ranging between a monthly mean of +19.8°C in July and –20.5°C in January. Over the second half of the 20th century, the recorded average temperature rise has been of the order of nearly 2°C (Oyunjargal & Sarantuya, 2001; also Jacoby *et al*., 1999).

This river basin was selected as a suitable area for the objectives of the present study and also of the earlier RAISE project because its environment is in a relatively original state without significant urban and industrial intrusions. Nevertheless, over the past 50 years some logging has taken place in the mountainous areas of the headwaters, and the grasslands have been subjected to increasingly intense grazing; the effects of these activities on the regional hydrology are largely unknown, but they can generally be assumed to be small (e.g. Davaa *et al*., 2006)

AVAILABLE STREAMFLOW DATA

The discharge rate of the Kherlen River is being recorded by the Institute of Meteorology and Hydrology (2000) of Mongolia, and long-term daily data are available for three gauging stations, namely at Baganuur since 1951, at Undurkhaan since 1959, and at Choibalsan since 1947; the respective drainage areas of these three stations are $A = 7350$, $39\,400$ and $71\,500$ km^2. Their respective elevations are $H = 1297$, 1033 and 738 m a.m.s.l., and the respective distances from the river mouth at Hulun Lake are: $L = 940$, 829 and 390 km. Normally, no data are available for the winter season, when the river stops flowing due to freezing. For the purpose of the present study, to avoid the possibility of ice conditions, use was made only of the river discharge data recorded between 1 May and 30 September. Whenever data were missing during this warm season, the entire year was designated as missing. By this criterion, for Baganuur, 40 years were available for analysis from the 56 years of record; for Undurkhaan this number was 45 years out of the 48 years of record, and for Choibalsan it was 57 years of the 60 years of record. For convenience of comparison the daily flow rates were divided by their respective drainage areas A, namely as $y_{L7} = Q_{L7}/A$, and expressed in mm d^{-1}.

ANALYSIS AND RESULTS

For each year of record the lowest 7-day daily mean flow was determined, as the lowest value of the 7-day running averages. The temporal trends of these annual low flows can be directly calculated by simple linear regression from which the trends of the annual groundwater storage can be estimated by means of equation (4); but this requires knowledge of the characteristic drainage time scale K. In large basins the parameter K is known to be relatively insensitive to drainage area. Indeed, as shown elsewhere (Brutsaert, 2008), over larger areas many of the controlling effects will "average out" and/or compensate one another; thus K values in different basins within a similar climate can be expected to be of a similar order of magnitude and to vary within a relatively narrow range, independently of drainage area A or terrane. Nevertheless, for the present study it was decided to calculate K anew for each of the three gauging stations.
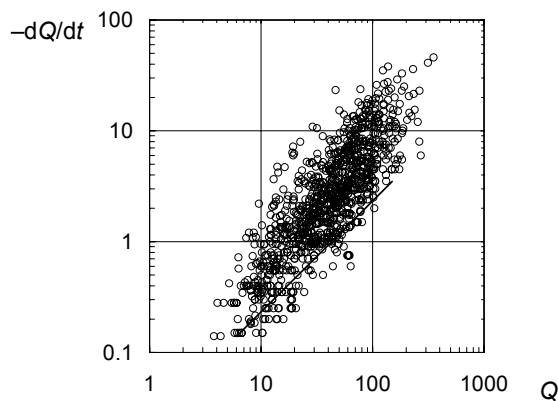
Fig. 2 Data points $-dQ/dt$ plotted against Q observed on the Kherlen River, during hydrograph recessions at Undurkhaan, Mongolia; the lower envelope line has a unit slope, in accordance with equation (5), and a value of the drainage time scale parameter $K = 43$ d. The upstream drainage area at this gauging station is $A = 39\,400$ km^2.

Accordingly, equation (5) was applied separately to daily flow data measured at Baganuur, Undurkhaan and Choibalsan, following the method of Brutsaert & Nieber (1977; also in Brutsaert, 2005). The method was implemented by plotting values of $(Q_{i-1} - Q_{i+1})/2$ against Q_i (in which the subscript refers to the flow on the ith day) during recessions of the daily flow time series. Ideally in this method, flows which are not strictly baseflow, that is, flows during and immediately following precipitation, must be eliminated. However, in basins of this size the raingauge network density would never be sufficient to capture all events everywhere in the basin. To maximize the likelihood of selecting flows during recessions that constituted "pure" drought flow, the following criteria were used in the selection process: eliminate all data points with positive and zero values of dQ/dt, and also sudden anomalous ones; eliminate two data points after the last positive and zero dQ/dt, and three data points after major events; eliminate two data points before dQ/dt becomes positive or zero; eliminate data points in a drying sequence, which are suddenly followed by a data point with a larger value of $-dQ/dt$. This procedure resulted in the cloud of points and the straight line lower envelope shown in Fig. 2, as an example for the case of Undurkhaan. To make some allowance for the unavoidable error in these data points, the lower envelope was established by keeping roughly 5% of the points below it. The straight line shown in Fig. 2 has a unit slope in accordance with equation (5) with a value of the storage coefficient $K = 43$ d. With this procedure, the value obtained for Baganuur was $K = 41$ d and for Choibalsan $K = 48$ d. The procedure, used here to estimate K, admittedly has some subjective aspects; but then, so does every other method currently available in the hydrological literature to estimate K. In light of this uncertainty, it was decided to use the average for all three stations, namely $K = 44$ d as a more robust value in the calculations. Note that this K value is roughly of the same order as values observed in many large river basins in other parts of the world (e.g. Brutsaert & Lopez, 1998; Brutsaert, 2008); this confirms that over larger areas K is indeed a relatively stable parameter. Note also that the three values of K appear to be correlated with several features of the gauging station locations, viz. A ($r = 0.971$), H ($r = -0.978$) and L ($r = -0.996$). The strongest is with the distance from the end L; while it is hazardous to draw conclusions from just three data points, this may suggest that the small variability of K is mostly affected by the travel time of the open channel flow of the river, and less so by groundwater flow characteristics; this would again confirm the relative robustness of the drainage time scale K.

With the value of $K = 44$ d the trends of groundwater storage S were calculated as:

$$\frac{dS}{dt} = K\frac{dy_{L7}}{dt} \qquad (6)$$

for the three stations on the river; this was done for different periods, in order to allow not only

Table 1 Groundwater storage trends (in mm year^{-1}) for different periods, as derived from low-flow measurements at the three main gauging stations of the Kherlen River.

Period / Station	1947–2006	1951–2006	1959–2006	1950–2000	1979–1994
Baganuur	NA	−0.00825	−0.0517	NA	−0.0300
Undurkhaan	NA	NA	−0.0127*	NA	+0.00532
Choibalsan	+0.000704	−0.00241	−0.00819*	+0.00246	+0.0286
	(−0.00809)	(−0.0480)	(−0.0958)	(+0.0254)	(+0.555)

* Slope values for which null hypothesis (of being equal to zero) may be rejected on the basis of a *t*-test at the 0.05 significance level.
Trends of the mean annual flow rates at Choibalsan are shown between brackets in mm year^{-2}.

comparison of the trends of the flows obtained at the three stations over their respective periods of record, but also possibly comparison with the trends of other hydrological variables published in the literature. The results of the trend calculations are shown in Table 1.

It can be seen that all the trends are very small and difficult to distinguish from zero. In fact for only two of these regression coefficients can the null hypothesis be rejected in a *t*-test at the 0.05 level, which means that most of them cannot be assumed to differ from zero. This is also brought out by the fact, that positive or negative trends are obtained depending on which period is considered. This is especially striking in Table 1 for the case of Choibalsan, the station with the longest and most complete record. This is also illustrated in Fig. 3, which shows strongly positive and negative regression lines for different 20-year periods, although the regression line for the entire 60-year period of record is nearly horizontal; it also shows that the pronounced negative trend in groundwater storage during the most recent 20 years is hardly steeper than that observed during 1964–1983. The trends at the three stations agree in sign although not in absolute value for each of the different time periods of record; that the absolute values are widely dispersed is no doubt due to several factors; these are that: (i) different years were missing at each station, and especially at Baganuur; (ii) low flows close to zero are notoriously subject to error and their temporal gradients even more so; and (iii) at the three stations the Kherlen River drains different, albeit overlapping, areas covering different groundwater conditions resulting from different precipitation input events.
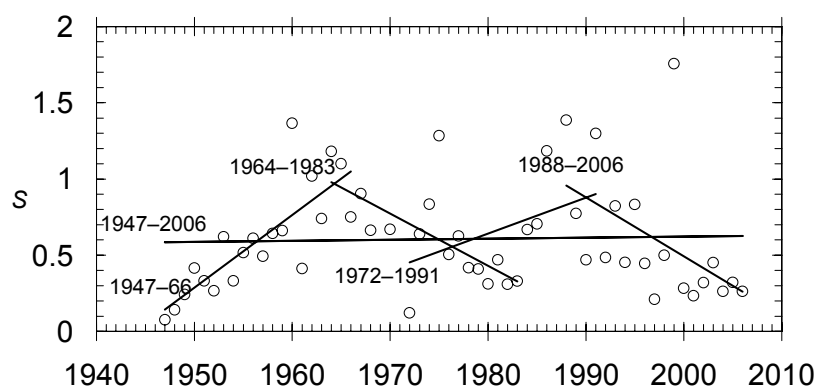

Fig. 3 Evolution of the annual lowest groundwater storage *S* (in mm) above the zero-flow level for the past half century upstream of Choibalsan (with $K = 44$ d). The straight line segments are the regressions over the indicated periods. The upstream drainage area at this gauging station is $A = 71\,500$ km^2.

TRENDS IN OTHER HYDROLOGICAL VARIABLES IN THE REGION

The trends in groundwater storage can be compared with the trends of other components of the hydrological cycle during the same period in this region. Precipitation is undoubtedly the most

important variable to consider, since it essentially drives the entire hydrological cycle. Precipitation trends over China and Mongolia during 1951–1990 were the subject of a study by Yatagai & Yasunari (1994); over the northern part of this region no clear trend in annual precipitation was found; in fact, in their Figure 3a the zero-trend line can be seen to run through the Kherlen basin. Summer precipitation in Mongolia during 1960–1998 was studied by Endo *et al.* (2006) in greater detail. The results displayed in Figure 5a of Endo *et al.* (2006) show both positive and negative trends in total summer precipitation over the general area of the Kherlen River, depending on location, with no obvious spatial pattern; but most of the trends shown are small, roughly around ±0.5 mm year^{-2}, ranging between ±1.0 mm year^{-2} and not statistically significant. Liu *et al.* (2005) analysed precipitation data in adjacent northern China for the period 1960–2000. The trends shown by these authors in their Figure 2 for the northeast climatic region, which comprises eastern Inner Mongolia and the lower reaches of the Kherlen River, indicate that the 45th parallel is a transition zone between small positive values to the north and negative values to the south.

The mean annual discharge in the river is also closely related to the groundwater storage changes analysed here. The trends of the mean annual discharges of the Kherlen River (including also the cold season flows) at Choibalsan, the station with the longest record, are shown between brackets in Table 1, where they can be compared with the trends in groundwater storage for different periods. These trends have mostly the same sign as the trends of the groundwater storage; this is not surprising since both are derived from the daily runoff data, which reflect the dry and wet episodes in the region. Again, however, the absolute values are not very large and the trend is nearly zero for the entire period of record starting in 1947.

In a different approach, Pederson *et al.* (2001) drew on tree-ring chronologies in the Kherlen River region to extend the available records and to produce annual time series of precipitation and streamflow from 1651 to 1995. They concluded that the hydrometeorological variations during the period 1948–1995, as reflected in the tree-ring record, were not unusual and well within the range of those observed over the previous 345 years; they also noted that the trend during the period of record was not exceptional compared to the previous three centuries.

Evaporation from pans is another variable of interest which may provide some information about recent trends in the hydrological cycle. Apparently, no studies are available for Mongolia itself, but several were carried out with data in neighbouring China. The results calculated by Liu *et al.* (2004) for the period 1955–2000, and presented in their Figure 3, indicate that the northeast climatic region, comprising eastern Inner Mongolia and the lower reaches of the Kherlen River, has the smallest trend in pan evaporation in all of China, namely –0.77 mm year^{-2}; this is considerably smaller than –3 mm year^{-2}, the average value for China, which is also typical for other parts of the world (e.g. Brutsaert, 2006). In a study of pan evaporation trends in China for the somewhat shorter period 1971–2000, Xu *et al.* (2005) obtained very similar results: their Figure 14 indicates that the zero trend contour line runs roughly from northeastern Inner Mongolia, westward through Mongolia to Xinjiang; the Kherlen basin lies slightly to the north of this contour, again suggesting only a small negative trend. Actually, according to the analyses by Peterson *et al.* (1995) and Golubev *et al.* (2001), this zone of no-to-very-little change in evaporation appears to extend even further to the west at roughly the same latitude into central Asia of the Russian Federation and Kazakhstan.

The results of all these previous studies are generally consistent with those obtained herein, namely that the Kherlen basin lies in a region in which hydrological variables, though extremely variable, have remained statistically stationary over the past 50–60 years and perhaps even longer. One discordant result is the relatively large trend of +2.5 mm year^{-2} for the period 1979–1994 obtained in an analysis of the country-wide average soil moisture storage in the top 1 m in Mongolia by Robock *et al.* (2000, Figure 6); while the sign of this trend is the same as those of the more complete records listed in Table 1 for groundwater storage and for annual streamflow at Choibalsan, its absolute value is several orders of magnitude larger. In light also of the small trends in rainfall (cf. Endo *et al.*, 2006) and in evaporation (cf. Liu *et al.*, 2004; Xu *et al.*, 2005) in this region, this discrepancy is not easy to explain, and will require further investigation.

CONCLUSIONS

The most recent decade has seen sharply decreasing groundwater levels, with some of the lowest values on record, in the Kherlen River basin, a relatively pristine area in northeastern Mongolia. Nevertheless, at this time, there is still no evidence that this development has been unusual or exceptional, compared to longer term variations observed in this basin over the past half century and probably even longer. This result is in contrast with the general acceleration of the hydrological cycle observed in some other parts of the world. However, the present findings are consistent with the small trends observed for several other measures of hydrological cycle activity during the past 50 years in this general area of eastern and central Asia at similar latitudes, namely precipitation, average annual streamflow, tree ring widths and pan evaporation. An explanation for this result will have to await a better understanding of the changes in atmospheric dynamics in this specific region and of the effects of its proximity to the Tibetan Plateau on these changes.

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